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Improving Heat Treating Flexibility for Wind Turbine Gear Systems Through Carburizing, Quenching and Material Handling Alternatives

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract
Part handling and processes for heat treating large gears have created challenges for decades. Growth in wind energy technology has focused more attention on this issue in recent years. The vast majority of installations processing such large parts utilize conventional methods via pit furnace systems. Such equipment has inherent limitations with respect to quench flow and part handling, making true improvements in areas such as distortion control difficult due to physical limitations of this processing approach. This presentation will explain alternative methods for heat treating large components that allow part distortion to be minimized. Benefits will be quantified regarding cost savings to produce such gearing and quality.

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Introduction

Commercial size wind turbines shown in Figure 1 and their gearboxes Figure 2, are designed to survive in extreme environmental conditions, most notably high wind forces, desert heat and arctic cold. However robust the design and use of materials, the typical gearbox struggles to meet their design life. Studies by the National Renewable Energy Laboratory (NREL) [1] have shown that on average a gearbox’s time to repair can be as short as five years give or take when the economic payback model requires 20 years. Many failures seem to occur first in the bearings, also outlined in the NREL report. Studies are continuing to identify the root causes for these and other failures. Other preliminary studies indicate that the gearbox and or planetary carrier systems are subjected to higher-than-anticipated stresses and that the materials used may not have the strength to resist the stresses encountered. Contaminated lubrication has also been targeted as a potential problem area. Since ferrous alloys are the most economical choice for drive train components, heat treating is a major consideration when designing for material strength and fatigue resistance.

Historically pit furnaces and the pit quench have been employed to case harden these and other large gears because for treaters there just has been no other choice. They are used primarily because they exist and alternative equipment has not, and there is the comfort factor - we’ve always done it that way. There are some who will say that pit furnaces offer a higher quality product but that's not so, as data presented later will show. In addition, pit furnaces can be energy hogs especially when carburizing cycles of 35 hours and longer are common.

Figure 1. Commercial size wind turbine
Easy site preparation

Common sense suggests that eliminating the need for a pit is a very desirable concept, offering more freedom for heat treat site selection. Often the deep excavations needed for pit furnaces and quench tanks pose environmental issues in brown as well as green field sites. Further, if expanding an existing facility is contemplated, what facilities engineer hasn’t experienced a flooded pit or power outage trying to install a pit? Who wants to accommodate an extra-high bay and additional large crane? Lower installation costs are achieved by reducing the overall furnace equipment height and using a pitless quench tank. Emerging economic realities for commercial as well as captive heat treaters dictate that the need for a more flexible and cost effective method of carburizing and quenching is overdue for large gears. Wind energy has attracted the attention of commercial heat treaters but they don’t want to put all of their eggs in one basket, like a pit furnace; they need equipment flexibility if the wind turbine market fails to live up to expectations.

Cost effective material

Case hardening is necessary to achieve the tooth strength and wear resistance in ferrous alloys and the process allowing the most economical use of materials is carburizing. Adding carbon to the wear surfaces of bearings and gear teeth can be more cost effective than induction hardening where the entire part contains the alloy, even areas that play no role in the stressed application. Both processes require quenching to achieve the hardness necessary and both result in distortion that must be corrected by grinding to bring the part to operating dimension.

Anyone associated with manufacturing and heat treating precision drive systems knows grinding is a necessary process required to obtain final size and surface finish after quenching. In addition, grinding remedies minor machining errors resulting from manufacturing very large gears. Grinding, although a critical requirement, is very expensive and can be minimized if quench distortion can be controlled and held to a minimum. If distortion can be predicted then designers can plan for it, thereby providing only the amount of material to be removed. Helical bevel gears are especially troublesome because of their tendency to “unwind”. The unwinding if predictable can be accommodated in the design and machining.

Quenching options

Obviously quenching is a very difficult process to control and one that can ruin a perfectly successful carburizing process. Only recently with the development of sophisticated computerized fluid dynamics (CFD) has liquid quenching, specifically oil quenching, been targeted for investigation; maybe that’s because most heat treaters wish it would just go away - no chance. Since heat treating ferrous material began eons ago, oil has no match for the range and control of quenching response. No other medium works better than oil when correctly applied knowing its limitations.

- Polymer has been tried and in some applications it can provide acceptable results in smaller...
gears but concentration maintenance is an issue and it too has disadvantages, creating a need for more investigation into controlling distortion.

- Salt is a great quenching medium but has found almost no application with large gears. Historically, however, salt has been used extensively to reduce distortion in smaller gears.

- Helium high pressure quenching is very good at controlling distortion but cannot match the quench severity of liquid that's required for very massive parts.

- Press quenching with oil is the most accepted and practiced method for distortion control with gears and bearing cups & cones, but to date it has seen little if any application for smaller wind turbine gears.

- IntensiQuench® is a patented high intensity water quench method designed to impart compressive stresses onto the part surface in addition to allowing the use of lower alloy steels. Proprietary software computes the quench time to form martensite and the time required for the core heat to temper the martensitic case when the part is raised from the water then re-immersed into the water for final quenching.

Although diverse in their markets and application, all of the above quenching options can be implemented by AFC-Holcroft's modular heat treating system: EZ-Lynks.

Unlike smaller automotive drive trains, large gear components by necessity employ very high hardenability steels due to their size. However, high hardenability is a two-edged sword, easier to harden but at greater risk of distortion in quenching. Again, a better solution would allow several quenching techniques as documented above. Open pit oil quenching and the required fixturing offer little in the way of flexibility for quenching options. Many gears can be press quenched or otherwise individually quenched but not from pits where the awkward hanging fixture makes it impossible to remove individual parts.

Large is a relative term when applied to gears and for this paper is defined as 24” to 36” diameter planetary gears and up to 65” to 84” diameter spur gears. Quenching sun gears, shafts, pinions and planetary gears by their vertical orientation can be controlled somewhat easier but still requires attention to flow uniformity and velocity. In many applications, fairly large gears can be press quenched with oil or water but only if the furnace type and material handling can provide the access for removal.

The IQ furnace has been the preferred furnace for commercial and captive heat treaters alike, primarily due to the flexibility offered in process, load size and efficiency. With electric as well as gas fired radiant tubes, the IQ furnace has provided unmatched utility and quality for all industrial, aerospace and military markets worldwide. AFC-Holcroft's UBQ series of IQ furnaces are the preferred product for many of the world's largest drive train suppliers. Today AFC-Holcroft's batch furnace as shown in Figure 3 is carburizing and quenching planet gears used by a major wind turbine manufacturer. Flame Metals Processing Corp. in Rogers, MN is a certified heat treat supplier meeting all of the AGMA and wind turbine quality requirements. Even though AFC-Holcroft has sold IQ furnace designed for very large loads, up to 72” (1829 mm) square and 12,000 lbs (5454 kg), they have not been applied to large gears probably because of rear handler (RH) capacity restrictions and the quench tank design. EZ-Lynks, AFC-Holcroft's alternative heat treating system shown in Figure 4a, Figure 4b and Figure 4c eliminates the pit disadvantage and overcomes the material handling concerns by separating the material handling from the furnace proper allowing more flexibility in the hot zone and quench tank designs.
The EZ-Lynks cell illustrated in Figure 5a and Figure 5b consists of multiple hot zone modules, enclosed floor mounted oil quench tank, wash, temper and transfer shuttle. All equipment is rated to 16,000 lbs (7,272 kg). A manufacturer or heat treater with an existing facility does not have to invest in a pit or extra high bay to accommodate EZ-Lynks. Doors can be designed to open sideways, radiant tubes can be removed from the rear and quench tanks can rest on the floor. Process flexibility is the result of a traversing and rotating transfer car, Figure 6, capable transferring loads automatically throughout the cell according to a preconfigured recipe.
The Achilles heel of pit quenching is the huge flame created when the load is immersed in the oil. Flames rage to engulf the crane, cables and truck and risk igniting the soot-covered ceiling. Figure 7 and Figure 8 illustrate the typical pit quenching of gears. Who hasn’t been tempted to run for the exits when pit quenching a massive load in oil? A more common sense solution like that provided by EZ-Lynks would protect the building from oil ignition within an enclosure much like the IQ furnace. A pneumatic elevator can provide consistent motion into the oil even during an electrical interruption.
Recipe driven quench distortion control

Martensite, the transformation product providing the hardness and strength required in ferrous alloys, creates a volumetric expansion that contributes to distortion especially when formed at unequal rates in the carburized case. A major key to controlling distortion is creating a heat transfer rate uniformly over the part surface, in this case over the gear teeth profile and root profile. In addition, and perhaps as important, is the heat transfer over the gear hub or side areas that can cause oil canning and bore tapering. Typically in pit quenching fixtured gears are stacked with little or no space between them, resulting in trapped oil vapor and creating slower cooling than at the top or bottom of the gear stack, Figure 9.

Traditional pit quench systems circulate oil from bottom to top leaving the oil between gears to stagnate, vaporize and reduce heat transfer. A typical method to counteract or reduce the differential cooling effect of vapor in pit quenching is to reduce the overall agitation which increases rather than reducing oil vapor over the entire gear or stack of gears in an attempt to reduce distortion by slowing the heat transfer of the entire gear. Only due to the high hardenability of expensive alloys can heat treaters even consider this approach. Unfortunately this technique fails to account for the exposed top of the part surface that is free to release the oil vapor via gravity. CFD modeling studies by others have shown that with little or no agitation, the top surface of quenched parts cools faster due to the gravity effect of vapor bubbles releasing. In addition, depending on the gear web design vapor can be trapped under the gear, further causing nonuniform cooling. A new approach to more uniform quenching is needed. Oil can be circulated from side-to-side, flushing the oil vapor from between gears or from under gears, Figure 10. Vertical oil flow works well for and is required for pinions, sun gears and stacked planetary gears where vertical straightness is critical. EZ-Lynks’ quench system shown in Figure 11a and Figure 11b
can provide recipe-selected oil flow in either direction, side-to-side or vertical, or a combination according to process requirements. For improved OD roundness control while employing side-to-side flow, gears can be rotated 360° exposing the entire OD to very uniform and high velocity oil flow directly at the gear teeth. This feature also assures the maximum quench penetration into the tooth profile and root. As a result, any problematic NMTP can be eliminated.

Carburizing, as stated above, is the most cost-effective process for improving the wear resistance and strength of ferrous alloys, especially gears. Atmosphere (endothermic) carburizing is the most applied process throughout the world simply because it is so predictable even without advanced simulation models. However, with off-line and on-line case profile modeling the process is almost foolproof. Still, due to the very high vested cost of large precision gears, current wind turbine specifications demand that samples be removed from the pit furnace and evaluated. At strategic intervals during the carburizing process prior to quenching, three (3) samples are hand quenched and checked for case depth and hardness to offer the chance to save the load if the hardened properties don’t meet expectations. Thus is the fear of failure in heat treating – using pit furnaces. It’s the out-of-sight/out-of-mind mentality. Other than shim stock tests to calibrate oxygen probes, no other carburizing market requires the evaluations of samples to confirm process success. Public transportation applications such as aerospace gear manufacturers have the majority of their drive train components carburized in UBQ furnaces – hundreds at a time - without the need for periodic in-process sample evaluation.
**EZ-Lynks retains the best of UBQ technology**

For those who say only pit furnaces can successfully carburize wind turbine gears, Flame Metals Processing Corp. of Rogers, MN (mentioned above) has been an approved supplier for wind turbine gears for several years. The argument by some against refractory lined furnaces (furnaces without the stainless steel retort) was the inability to carburize gears without excessive IGO. ISO standard 6336 part 5 issued 2002 (Calculation of load capacity of spur and helical gears - part 5: Strength and quality of materials), outlines the acceptable IGO limits depending on carbide distribution. Flame Metals utilizing the 36 x 72 x 54 (914 mm x 1829 mm x 1372 mm) UBQ batch furnace can meet or exceed the applicable standards as referenced in the 6336-5 specifications. Figure 12 contains a photo of a carburized and oil quenched planetary gear load. Typical results from such a load are shown in Figure 13a, Figure 13b and Figure 13c. [2]

**Figure 12. Flame metals planetary gear load 750 lb (341 kg) each**

IGO has long been a point of contention in carburizing wind turbine gears since fatigue stress is a significant factor affecting traditional gear life because general practice has been to grind the tooth flank but not the tooth root. Since the tooth root retains its virgin surface, IGO becomes a potential failure risk. Having said that, it's been reported that no tooth roots have been identified as initiating gearbox failure sites. If gears have failed, it is presumed to be caused by bearing wear resulting in accelerated tooth wear from misalignment of the gearbox and/or carrier. It follows that there needs to be more intensive auditing of the bearing heat treating process and material selection. Assuming that bearing failures will eventually be eliminated or at least reduced the next weak link then may well be tooth fatigue failure and to address those issues a stronger tooth hardened case profile will be required.

To further illustrate the point regarding IGO and its causes, we conducted our own internal investigation at AFC-Holcroft (in addition to data provided by Flame Metal on 18CrNiMo7-6) to determine the effect steel chemistry has on IGO formation. We conducted a series of bench scale tests with three (3) common U.S. carburizing steels listed as a, b and c:

a. 20MnCr5, C-0.2%, Si-0.25%, Mn-1.25%, Cr-1.15%, S-<0.25%

b. 9310, C-0.10%, Si-0.22%, Mn-0.55%, Cr-1.20%, S-<0.35%, Mo-0.10%, Ni-3.25%

c. 8620, C-0.20%, Si-0.31%, Mn-0.82%, Cr-0.50%, Mo-0.20%, Ni-0.52%

d. 18CrNiMo7-6, C-.18%, Si-0.20%, Mn-0.70%, Cr-1.65%, Ni-1.55%, Mo-0.30%

Table 1 is a description summary of the test parameters, Simultaneously all samples were carburized at 926°C (1700°F) for 24 hours with endothermic gas with varying concentrations of carbon monoxide (CO) and carbon potentials resulting in the following tabulation. These steels were chosen for testing because they represent a large hardenability range and where higher manganese, an inexpensive but IGO contributor and an alternative to moly and nickel for hardenability is gaining interest to reduce material cost.

To investigate further the effect temperature has on IGO formation since high temperature carburizing is gaining favor due to finer grain steels, a carburizing test was conducted using the bench set up on steels a, b, and c at 1.04% CP for seven (7) hours at 1850°F (1010°C). Although the IGO depth is greater, it's not significantly so. The exception and perhaps an anomaly is the depth for 20MnCr5 that is less than the 24 hour test and that's extremely unlikely and will be re-evaluated. Carburizing at 1850°F for seven (7) hours will produce approximately the same case depth as carburizing 24 hours at 1700°F. Carburizing at elevated temperatures provides the most dramatic reduction in time of any process control parameter.
Figure 13a. Typical flame metals planetary gear process report
Figure 13b. Typical flame metals planetary gear process report
Figure 13c. Typical flame metals planetary gear process report
Table 1. Test parameter summary

<table>
<thead>
<tr>
<th>Steel</th>
<th>Carburized for 24 hrs @ 1700°F (925°C)</th>
<th>Carburized for 4.5 hrs. @ 1700°F (925°C)</th>
<th>Carburized for 7 hrs @ 1850°F (1010°C)</th>
<th>Carburized for 38 hrs @ 1725°F (940°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO 18.3% CP 0.82% (Alloy)</td>
<td>CO 14.8% CP 1.16% (Alloy)</td>
<td>CO 18.3% CP 1.04% (Fiber)</td>
<td>CO 18.3% CP 1.05% (Fiber)</td>
</tr>
<tr>
<td>20MnCr5</td>
<td>23</td>
<td>20</td>
<td>22.9</td>
<td>25.4</td>
</tr>
<tr>
<td>9310</td>
<td>18</td>
<td>12.7</td>
<td>12.7</td>
<td>15.2</td>
</tr>
<tr>
<td>8620</td>
<td>25</td>
<td>25</td>
<td>24</td>
<td>22.8</td>
</tr>
<tr>
<td>18CrNiMo7-6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:**
25.4 microns = 0.001”

To complete the investigation a short 4.5 hour carburizing test at 1700°F (925°C) was conducted at 0.75% CP to try and establish when IGO penetration became a significant risk factor. There’s some thought that a major portion of IGO is formed at the beginning of carburizing. Results of the 4.5 hour test are shown above.

From these short term tests, one could argue that indeed well over half the depth of IGO can form in certain steel grades but more testing will be required to identify a trend.

In addition to comparing a steel grade’s propensity to form IGO, we wanted to know if furnace construction had any bearing on IGO formation. As we all know, the traditional pit furnace has alloy retorts that separate the refractory from the load and carburizing atmosphere. Thereby, it is felt in some circles that this represents a more pure environment resulting in lower IGO values. Still others believe that the endo atmosphere alone causes IGO formation. These theories were evaluated by (1) conducting the test in the alloy pipe simulating the alloy retort. (2) Adding ceramic fiber and IFB into the alloy pipe within the cold to hot transition simulating the refractory in conventional carburizing furnaces. The results above speak for themselves. No difference in IGO penetration regardless of the presence of ceramic fiber or IFB refractory.

**Commentary by Flame Metals Processing Corp. [3]**

Flame Metals Processing Corporation, being a commercial heat-treating facility, had approached the problem of unacceptably deep IGO penetration in a series of deep-case carburized products. Considering the need to maintain flexibility and economical competitiveness, Flame Metals decided not to invest in specialized equipment and technology but rather to improve on the carburizing process based on existing flexible-purpose IQ furnaces and economically feasible natural gas generated atmosphere.

Because the total carburizing times for each product were already optimized in terms of process temperature and that of the sequence of the boost and diffuse cycles, the slow IGO growth was inevitable and had to continue within the prescribed carburizing time. However, Flame realized that the large portion of the IGO growth is produced during the initial stage of the process and is driven by the events that could be controlled and improved such as loading procedure and bringing the load to the heat. In other words, the main thrust of the effort was directed at reducing the initial oxidation. The effort paid off resulting in dramatic decrease in IGO penetration depths.

Total furnace time in both cases was 6 hours longer and included the identical procedures involving charging the load into furnace (0.5 hours), heating to the carburizing temperature (3 hours), and cooling down to lower temperature before quench (2.3 hours). In general, the heating time to the temperature may be reduced but in this case slow, controlled heating was applied in order to reduce distortion of the parts.

The steel alloying plays some role in IGO development in long-time carburizing process, but it
seems to be relatively minor when compared to the other factors. For example, after 34.5 hours of carburizing process conducted under the same conditions as given above, the IGO depth measured on 18CrNiMo7-6 steel was 24 μm and 28 μm on 8620 steel (see Figure 14).

It is our conviction at Flame Metals that the major event influencing development of IGO occurs in the initial stage of process. When the parts are loaded into the furnace, inevitably oxygen is introduced as well. Flame Metals was able to reduce the oxidation risk by purchasing exceptionally gas-tight IQ furnaces and implementing special bringing up to heat procedures. As a result, the steel surface exposure to the oxidation by residual oxygen at high temperatures is minimized.

Historically, pit furnaces, from the writer’s perspective based on decades working in the heat treating industry, have been known as soot generators due to the difficulty in accurately controlling carbon potential. Currently the only way pit furnaces in the U.S. and Europe used for wind turbine carburizing can be successfully managed even employing the sampling method referenced previously is with very expensive process control systems with multi-gas analysis. Costing several hundreds of thousands of dollars all by themselves, these control systems manage pits for the same reason computers keep the B2 bomber in the air – from an aerodynamic standpoint they can’t fly.

EZ-Lynks brings a cost effective common sense approach to carburizing large awkward components to the heat treating industry. As with the UBQ batch furnace cell, EZ-Lynks can be programmed to automatically retrieve loads without manual intervention, transfer to the available furnace, quench, wash and temper the load and transfer the load to the output queue, all the while tracking the load location within the cell and trending process data for archiving to an industrial-strength computer with automatic dual hard-drive back up.

Batchmaster II® standard control system developed by AFC-Holcroft manages the carburizing process with PLC logic providing consistent and repeatable results. Associated software tracks all loads through the cell providing real-time in/out data plus appropriate information to a company’s host allowing SPC analysis if required.

Operating complexity and cost when considering lean manufacturing is becoming an important parameter in the purchase decision for captive and commercial heat treaters as utility costs continue to rise. Both depend on operating efficiency and up-time to achieve the lowest possible cost per pound processed per square foot occupied. Pit furnaces in principle seem to be fairly simple devices (the furnace alone can be the lowest cost invested) until all of the associated components are considered to process with just one pit furnace. Table 2 is a comparison of items required for pit and EZ-Lynks operation.

![IGO penetration graph](image)

**Figure 14.** Flame metals (IGO) graph depth vs. time and material
### Table 2. EZ-Lynks and pit item comparison

<table>
<thead>
<tr>
<th>Item requirement</th>
<th>Pit system</th>
<th>EZ-Lynks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very expensive multi-gas process control system</td>
<td>Yes</td>
<td>No, standard controls only</td>
</tr>
<tr>
<td>High capacity bridge crane systems</td>
<td>Yes</td>
<td>No, only for single part loading</td>
</tr>
<tr>
<td>Anti-sway crane capability</td>
<td>Yes, to make loading easier</td>
<td>No</td>
</tr>
<tr>
<td>Inner and outer alloy retort replacement cost</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Water-cooled lid seal maintenance</td>
<td>Yes</td>
<td>No, water cooling required</td>
</tr>
<tr>
<td>Hanging fixture assembly</td>
<td>Yes, can consume 30% of gross load weight</td>
<td>No (tray only or no tray required)</td>
</tr>
<tr>
<td>Seal maintenance, depending on how the retort ends are sealed – sand or expansion joints</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Elaborate washing systems</td>
<td>Yes</td>
<td>No (standard washer)</td>
</tr>
<tr>
<td>Quench tanks that lack versatility plus open tank fire hazard</td>
<td>Yes, open tank fire hazard</td>
<td>Enclosed tank with flexible quench</td>
</tr>
<tr>
<td>Extra high facility bay</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Elaborate fire suppression systems</td>
<td>Yes</td>
<td>No, vestibule can be nitrogen purged</td>
</tr>
<tr>
<td>Large and deep pit required</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Finally, to further the comparison, from an economic standpoint, Figure 15a and Figure 15b highlights an operating cost comparison between a typical pit system and EZ-Lynks when carburizing a maximum load to 3.3 mm ECD at 940°C (1725°F). This cycle represents a typical case depth for a 2 to 2.7 megawatt (MW) wind turbine 24" (609 mm) diameter planetary gear and other gear components in the turbine gearbox. Calculations shown in the Excel worksheet take into account the average utility costs for natural gas, electricity and nitrogen in Ohio and Michigan. EZ-Lynks can be supplied with electric or gas heat, but this comparison uses gas heating with metallic alloy radiant tubes. The pit furnace is calculated with electric heat since most systems used throughout the U.S. and especially Europe are electrically heated. In addition, the typical pit furnace fixture whether hanging or bottom supported is very substantial and contributes about 30% of the gross weight of the pit load. This is an obvious disadvantage since the fixture is quenched with the load and as such has a useful life of about three (3) years under ideal conditions. EZ-Lynks in contrast employs a standard tray system and is subjected to much less overall stress during carburizing and quenching.

As stated in the opening of this paper, wind turbine gearbox failures may have less to do with gears and more the result of premature bearing wear, lubrication issues and environmental forces still not fully understood. However, if gearbox wind turbines are to ever attain the popularity once envisioned, these problems must be overcome. Rare-earth magnet wind turbines although more expensive may see more offshore applications but they too will employ heat treated bearings among other components. No matter what direction the alternative energy industry takes, gears and/or bearings will be heat treated and manufacturers and heat treaters by economic necessity will benefit from a large component flexible heat treating system.
Figure 15a. Operating cost comparison between a typical pit system and EZ-Lynks
Figure 15b. Operating cost comparison between a typical pit system and EZ-Lynks
References

1. National Renewable Energy Laboratory (NREL), Kathleen O’Dell, July/August 2009, p. 22.