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Nondestructive Testing of a Rare Crusader Sword
by O. Golan, K. Raphael and D. Ashkenazi

Introduction
A well-preserved iron sword, said to have been discovered in the northern Sinai Peninsula, was recently acquired by a private collector and is now exhibited at the Israel Museum in Jerusalem (Figure 1). The aim of this article is to try to confirm both the authenticity and the alleged provenance of the sword, as well as its method of production and the components of the metal. Its type and date were verified according to similar swords found in excavations and collections in Europe. The method of production, provenance and the properties of the metal were studied using archaeometallurgical nondestructive techniques, including radiography and X-ray fluorescence (XRF) analyses.

Sword Description
The sword was one of the primary weapons of both Crusader knights and their Muslim rivals. It is thus to some extent surprising that 12th and 13th century swords are so poorly represented in museum collections and archaeological excavations in the Levant region. Although there have been a number of large-scale...
excavations, very few weapons have been found: numerous iron arrowheads, one spearhead and fragments of a crossbow mechanism (Ben-Dov, 1975; Dean, 1927; Johns, 1933; Johns, 1936; Roll and Tal, 1999). Two Crusader swords were found during underwater excavations off the coasts of Dor and Atlit. While one had a thick layer of shells and sediment that showed only a crude outline, the other, although corroded, was in relatively good condition. Their exact archaeological and historical context is not entirely clear; to the best of the authors’ knowledge, analyses of the two swords were never published.

One sword is displayed at the Nahsholin Museum at Kibbutz Nahsholim (Israel Antiquities Authority [IAA] no. 94-1705), the other at the National Maritime Museum, Haifa (IAA no. 86-1001).

The sword described is a two-edged iron sword with a tapered blade and missing point. The length of the blade is 845 mm (33.27 in.), width is 55 to 26 mm (2.17 to 1.02 in.) and thickness is 3 to 4 mm (0.12 to 0.16 in.). In reconstructing the line of the blade, the point was probably narrow and quite sharp rather than wide and rounded. The fuller (a shallow channel along the center), runs along approximately two-thirds of the length of the blade. It is, however, difficult to see without looking at the X-ray photograph. The hilt is short (98 mm [3.86 in.]), allowing the fist a neat and tight grip and making it difficult to grasp the sword with two hands, unlike the large and heavy German swords of the 13th and 14th centuries, which have a longer grip. The cross is a short plain bar, round in section and wide at the edge, with a length of 140 mm (5.51 in.) and diameter of 10 to 15 mm (0.39 to 0.59 in.). A neat octagonal pommel, with a length of 44 mm (1.73 in.), width of 42 mm (1.65 in.) and height of 35 mm (1.38 in.), is threaded onto the hilt’s tang. The current weight is 1.06 kg (2.34 lb); there has been considerable loss of weight due to corrosion. In general, flat broad cutting blades date to the period before plate armor was introduced in the mid-14th century (Oakeshott, 1992). They did, however, continue to be used long after. If well made and looked after, a sword’s life span could stretch across a number of generations. Despite pommel forms, the dimension and shape of the blade may indicate the period it belonged to; it is important to note that swords were often made by small local workshops to fit the needs and size of a particular person as well as his pocket.

British amateur historian Ewart Oakeshott describes similar swords as type XII in his sword classification. The three main characteristics of this type are: a noticeable tapering of the blade that ends with a point; a short grip, “never of a hand and a half;” and the fuller runs only along two-thirds of the length of the blade. There are, however, many variations within this class. Although he clearly states that many of the characteristics continue throughout the entire medieval period, most of the swords belonging to this type date from the 12th and 13th centuries. Similar swords have been found all over Europe, including Spain, Denmark, England, Italy, Germany and even Hungary. There is no evidence of one singular place of production (Nicolle, 1999; Oakeshott, 2007). Within the eastern Mediterranean the only place where such swords of the same type have been (dated 14th century) were acquired by the Mamluks and stored in the arsenal at Alexandria, Egypt. Some no doubt were taken as booty, others bought from European merchants; most carry an Arabic inscription (Tekeli, 1996).

Background of the Metallurgical Analysis

Iron and steel weapons have been the focus of numerous typological and archaeometallurgical studies (Ehrenreich et al., 2005; Hošek and Košta, 2006; Mapelli et al., 2007; Nicodemi et al., 2005; Pense, 2000; Pertulla, 2001; Pertulla, 2004). Ferrous alloys contain a mostly iron component with carbon as a secondary element and other elements as additives. For relatively pure iron manufacturing, a reduction process should be applied at a temperature of approximately 1200 °C (2192 °F) (which is in the solid-state phase), turning the iron ore into a spongy mass called bloom (Tylecote, 1962). The bloom is then hammered in order to eliminate the ceramic slag. It is then transformed into wrought iron that has less than 0.1 wt% C (Tylecote and Black, 1980). A forge-welding process is applied at a temperature of half the melting point, allowing an intensive diffusion process (Barrena et al., 2008; Murray et al., 1993).

A combat sword, as opposed to a ceremonial weapon, must have the following properties: high yield strength, excellent fracture toughness and impact resistance, hardness and ductility.

In order to achieve these properties, it was necessary to increase the amount of carbon. This could be done by carburization techniques and hardening heat-treatments. Clay mixed with charcoal was used to coat the blade; thus, the carbon defused into the blade increased its strength. According to 15th century sources, the sword was then dipped in a bizarre mixture, including animal residues (Jordanim, 2002). In some swords, a core was made of a pure iron bar that was wrapped in high carbon steel (Mapelli et al., 2007). Another way of achieving the desired strength was by using thin layers of alternating carburized steel that were carefully layered (Wadsworth and Lesuer, 2000).

Experimental Techniques

The current investigation used nondestructive testing (NDT) archaeometallurgical techniques in order to verify the sword’s authenticity and provenance. The metallurgical evaluation included digital radiography (Figure 2) and XRF analyses.

The sword was tested by a digital radiography NDT technique, using 100 kV for 0.5 to 5 min (Figure 2a). The digital...
flat panel was composed of a gadolinium oxysulfide scintillator and an array of amorphous silicon (a-Si) photodiodes (Pincu and Kleinberger, 2008). The X-ray tube sends beam photons through an object. The photons that have not been absorbed by the object reach the a-Si flat panel and strike the layer of scintillating material, which, in turn, converts them into visible light photons. The light photons reach the photodiodes and convert them into electrons that activate the pixels in the a-Si. The electronic data generated from this process is converted to a digital signal that is received by the computer, and the software converts this information into a high quality image (Cornell and Schwertmann, 2003).

A second type of chemical analysis was done using handheld XRF. This specific apparatus includes a 50 kV X-ray tube with a geometrically optimized large area drift detector, 80 MHz real-time digital signal processing and dual embedded processors for computation, data storage, live video processing and communication. The irradiation area is circular, 8 mm (0.32 in.) in diameter, and measurements are taken by means of the characteristic secondary X-rays emitted from a material as it is bombarded with high-energy X-rays. The XRF analyzer contains three excitation filters (light range, low range and main range) for optimizing sensitivity and allowing greater precision in calculations of the elemental content.

**Results**

The sword is relatively well preserved. The radiographic image of the sword exposed the internal lines (Figure 3). The difference in the shading indicates the various densities of the metal. When X-rays pass through dense and solid materials, the result is white shading. Dark shading indicates cavities, porosity and less dense areas, whereas shades of gray indicate different levels of density. The X-ray images are the result of the combination of various factors, such as density, porosity and oxidation.

The radiographic images of the sword (Figures 3 and 4a) revealed that the pommel and the cross are solid homogenous
This results in a uniform bright hue with comparison to the other parts of the sword. The blade and hilt show patches of white, gray and black, which are evidence of different densities. Furthermore, the blade and hilt are one continuous piece, as shown by similar macrostructure (Figure 4b, red arrows). The fuller runs into the hilt. The 3D surface mesh from radiography revealed the fuller topography, since the fuller appears to be less dense than the other parts of the sword (Figure 3d). This fuller is difficult to distinguish without the radiography technique because the degradation oxides fill and cover the empty fuller channel.

The density of common iron oxides is ~4.9 to 5.2 g/cm³ (0.18 to 1.9 lb/in.³) compared to 7.8 g/cm³ (0.28 lb/in.³) of pure iron (ASM, 2004). Thus, the corrosion, oxidation or porosity appears in darker shades.

The spots on the blade (Figures 2b and 4) are products of corrosion and oxidation. The blade had to be strengthened; therefore, it was carbonized to steel-form and then heat-treated to attain optimal mechanical properties. These processes are known to decrease the environmental resistance of the materials in atmospheric conditions. In contrast, the pommel and cross do not require similar strength to that of the blade;
it is thus plausible that they were made from wrought iron. The lack of carbon and heat treatments improve corrosion resistance.

The radiography clearly revealed how the sword was constructed (Figures 4a and 5). The blade and hilt are one piece. The radiography also shows the internal contour lines of the blade and hilt within the cross and the pommel, respectively (Figures 4a and 5b). The high voltage radiography image of the pommel clearly defines the pommel lines from the hilt. The separation lines between the continuous hilt-blade and the cross, which was assembled discretely, can be seen in Figures 4a and 5c. The cross was assembled later and finally the pommel.

The processing of the radiographic image (Figure 5d) shows the blacksmith’s direction of work. The lines are oriented at 45° from the fuller to the outer borders of the blade. The uneven lines along the blade indicated it was handmade. The shaping process included a multi-cycle of heating and hammering until the sword achieved its complete form.

The XRF chemical analysis was taken from four points along the sword: pommel, hilt, cross and blade (Figure 6); the XRF results reveal chemical compositions that do not exist in modern steel (ASM, 1993; ASTM, 2004). The alloy of the sword was probably made of ancient steel,
Manufactured by a process called bloomery. This ancient manufacturing process (using charcoal) reduces the iron-oxide ore particles into a spongy iron mass called bloom. This sponge iron is then hammered in order to break and remove the brittle oxides or slag from the substance. This is done in a solid-state, that is, not cast, resulting in an unalloyed iron. Modern smelting of steel is based on a continuous casting process, involving casting and rolling. However, the casting of iron requires a temperature of approximately 1600 °C (2912 °F). This was not possible until 1500 A.D., when the blast furnace appeared (Agricola, 1950; Williams, 2003).

All the plain carbon steels produced during the past two centuries contain manganese (0.3 to 1.0 wt%) in addition to carbon (ASM, 1993; ASTM, 2004). The absence of the manganese element in the present sword (except very small concentrations in the pomme) is sufficient evidence for the authenticity of the sword. The chemical composition (XRF) of the blade (Figure 6d) is relatively homogenous; four samples were taken from the blade every 150 mm (5.91 in.). The reading of the chemical composition was identical; therefore, it has not been incorporated here.

Figure 6. The sampling positions of the X-ray fluorescence analyzer in different parts of the sword: (a) pomme; (b) hilt; (c) cross; and (d) blade.

Figure 7. The sampling positions of the X-ray fluorescence analyzer revealing the presence of arsenic.
made separately. The difference in the chemical composition between the blade and hilt is very interesting. The hilt was the only part that contained arsenic 0.5 wt% (Figure 7). This may be due to colored leather or cloth around the hilt. The sediments of silicon, aluminum, calcium, chlorine, sulfur, cobalt and titanium on the sword surface may indicate the geographical origin of the sword. The rich silicon and calcium elements point to sand and loess soil, respectively (Rögnér et al., 2004). Sand and loess soils are widespread in the northern Sinai Peninsula, both in coastal areas and in internal dunes. The high concentration of minerals such chlorine and magnesium indicate conditions with higher salinity (Hassan, 2002; Yousef and El Shenawy, 2000). Cobalt and titanium are very rare elements but can be found in the Sinai (Andel-Karim, 2009; Rögnér et al., 2004).

Discussion and Conclusion
A well-preserved, doubled-edged iron Crusader sword discovered in the Sinai Peninsula was studied using typological analysis and archaeometallurgical nondestructive techniques, radiography and XRF analyses. The results demonstrated that this sword could not have been made by modern production and, thus, is authentic. The pommel, which contains manganese, may well have been added at a later period. It is important to note that its style and shape are rare. It was also confirmed that this sword belonged to the Crusades period. The conclusions are well based on the digital radiography and XRF analysis that revealed the manufacturing processes and the chemical composition respectively:
- The chemical composition of the sword does not exist today. This composition probably belongs to ancient steel and was initially made by a bloomery process.
- The sediments of silicon, aluminum, calcium, chlorine, sulfur, cobalt and titanium on the sword surface indicate the original site where the sword was found – northern Sinai.
The digital radiography proved that the blade and the hilt are continuous and had been made of one piece. It also revealed that the fuller continues from the blade to the hilt, maintaining the same proportion.

The pommel, cross and blade have dissimilar composition, which indicates that they were made separately.

The morphology of the blade shows that it was handmade and was not manufactured using modern technologies.

AUTHORS
O. Golan: Department of Mechanical Engineering, Afeka Academic College of Engineering, Tel Aviv, 69107, Israel; e-mail golano@afeka.ac.il.
K. Raphael: Institute of Earth and Science, Hebrew University, Givat Ram, Jerusalem, 91905, Israel.
D. Ashkenazi: School of Mechanical Engineering, Tel Aviv University, Ramat Aviv, 69978, Israel.

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Nondestructive Testing Exhibit Opens on Mare Island
by TNT Editor Toni Kervina

Recently, a new exhibit on nondestructive testing (NDT) has been unveiled in the Mare Island Museum, in Vallejo, located in the northern part of the East Bay region of the Bay Area in Central California. Though officially open, the Mare Island NDT exhibit is a work in progress as new items are continually added. This exhibit represents the culmination of many years of effort between Mare Island Museum officials and individuals like longtime ASNT member George Henke and members of ASNT’s Golden Gate Section.

Background
Part of the Mare Island Historic Park Foundation, the museum features a wide array of memorabilia from when the Island was active. Equipment failure being a normal part of most any industrial or shipyard setting, Mare Island saw its share of maintenance and testing issues throughout its time as an active base, so it seems only natural to now house an exhibit dedicated to the testing that helped keep so many men and woman safe over the years, especially during World War II. With the integration of NDT as part of the regular maintenance program, the hope has been that tragic events, like the sinking of the *U.S.S. Squalus* in 1939, can be avoided in the future (Rohrs, 2014).

Historically, Mare Island became the first U.S. Naval base on the Pacific Ocean when it was opened in 1854, although it had been an active port for sailors for a century prior to that. The first U.S. warship and dry dock constructed on the West Coast were also built there (NPS, 2014). Over the years, Mare Island witnessed the testing of hundreds of ships and submarines until it was closed in 1996.

While still active, the NDT unit was housed in Building 676. Some of the testing methods employed at Mare Island included radiologic testing (RT), ultrasonic testing (UT), electromagnetic testing (ET), magnetic particle testing (MT) and liquid penetrant testing (PT). These methods were employed in a number of applications, from routine submarine and ship inspection to ordnance and weaponry testing (Figure 1). Many innovations realized at the base were later incorporated into commercial NDT equipment, and techniques were developed as necessary to cover problems that arose when no solution was apparent. The 1950s to 1980s in particular saw many technological advances.

![Figure 1. Vehicles like this riverboat were routinely tested on Mare Island as part of its regular maintenance program.](image)
The Golden Gate Section

Based out of San Francisco, the Golden Gate Section has been involved in the Mare Island NDT exhibit since the beginning. Members helped clean and prepare the donated equipment, as well as create the informational signs for each item (Figure 2). In addition, for the past two years the Section has been holding its annual Christmas event on the Island, the proceeds of which go to preservation of the Mare Island Museum.

Section member George Henke was instrumental in spearheading the project (Figure 3). Henke’s longstanding career in NDT, enthusiasm for the Section and a penchant for collecting helped spark the idea and encourage interest in other likeminded collectors. Golden Gate Section Chair Dan Kerr added, “If it was up to anyone else, it wouldn’t have happened. That’s the bottom line.” The project was first started 15 years ago, when Henke realized that he and some 20 other Section members had amassed a stockpile of NDT items and wanted a place to publicly display it all. So, he contacted the president of the Mare Island Museum and, through some negotiations, agreed on the creation of an exhibit that would house mostly items purchased or used on the base, along with some additional, rare items of interest. Between 1999 and 2008, there was a lull in progress, but as Henke attested, “it was about four years ago that things started to get in place.” Now open to the public, the museum is a testament to Henke’s longstanding vision and a reminder of the thousands of hours of work he put in. Kerr said, “Henke can talk on the subject of NDT for hours and can describe the dimensions and setup of the museum exhibit in minute detail” (Figure 4).

The Exhibit

The exhibit comprises many different types of equipment and items, such as MT systems, X-ray units, gamma ray cameras and radiographs, all of which tell the story of how these technologies were created and changed over time. Some of these advances include miniaturization, the shrinking of equipment that was once too large to be truly portable, but is now oftentimes small enough to fit into a technician’s hand. Kerr added, “Vastly improved electronics make things possible now that couldn’t be done 50 years ago. For example, portable phased array UT and electromagnetic

Figure 2. Example of nondestructive testing equipment and informational placard.

Figure 3. George Henke is shown with books on nondestructive testing from his own personal library.

Figure 4. George Henke describes one of the pieces of nondestructive testing equipment on display.
acoustic transducer UT units, and enhanced smart pigging for pipeline inspections.” Visitors won’t find these types of items at the Mare Island exhibit because of how new they are, but with the speed at which technology is progressing, they too may become part of the future donations to the exhibit.

Much of the current exhibit focuses on the advancements that came about during the 1950s to 1960s, in which industry really started to take quality assurance and control measures more seriously. The majority of the collection originates from when the base was most active, with production slowing down in the mid- to late-1980s, and thus showcases what equipment was available at the time.

Items for the permanent exhibit were collected from an eclectic variety of sources, with donations from companies, local schools such as Contra Costa Community College and personal collectors like Henke. Many of the collectibles passed through the hands of several owners and were acquired from Bay Area companies that had closed or relocated. Others sat around for many years collecting dust under a desk or on a shelf.

Ultrasonic Testing

One area that the exhibit highlights is UT. Many examples of the original equipment once used are now on display (Figure 5). Kerr described one example: “There was a technique called resonance testing, which set up a continuous (versus pulsed) reverberation wave in a part. When you tuned it to get a resonance, you could see on a scale the thickness matched that resonance. The equipment dimensions were about 3 × 3 × 3 ft. That was one way UT thickness was measured until the ’60s. Nowadays you can do that same measurement much faster with something about the size of a cell phone.”

Looking Ahead

In addition to providing a way for technicians to reminisce nostalgically on NDT through the years, the Mare Island NDT exhibit also serves the purpose of educating future generations. The exhibit is likely to prove an interesting addition for school groups touring the island. Kerr hopes that students who are interested in the history of the Navy will also stop in and see the NDT exhibit.

Despite the opening of the exhibit, the Bay Area has seen a decrease in NDT education in recent years. Contra Costa College, which donated a large number of the items in the collection, once offered an NDT associate’s degree program under the direction of Fred Lockwood. Today, the program has been abandoned, and according to Kerr, there is currently no dedicated NDT degree program anywhere in Northern California, due in part to state budgeting. However, Kerr does see hope for the future, as funding increases and interest is renewed. For his part, Kerr volunteers his time teaching math and science to elementary school students, offering hands-on NDT demonstrations. He explained, “Kids that age are open books, and we should start working with them earlier to increase their self-confidence about science and life in general.”

He and others in the Golden Gate Section also provide facility daytrips as a way to get high school and college students exposed to NDT. For college students and older adults, classes like the Level I and Level II UT courses offered by Mark Reese at American River College in Sacramento continue to gain in popularity.

The Mare Island NDT exhibit is for certain a labor of love, with every single item in the collection having been donated and maintained by a volunteer effort. Although it showcases NDT equipment used around the country and even around the world, so far the majority of items on display have come from the San Francisco Bay Area. It demonstrates how NDT has evolved, in the Navy and industry in general.

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REFERENCES


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David J. Vigne  
Vice President

dave.vigne@nicinc.com  
Cell (239) 340-2229
From jet engines to bulletproof vests and fuel injectors, Norman Link is a self-described mad scientist whose work takes him all over. Here we learn a little more about dynamic flash X-ray and the senior technical consultant with his finger on the power button.

Q: How did you become involved with nondestructive testing?
A: I’ve been doing digital imaging since the early 1980s. I did cancer research for a number of years. My graduate work was with the NIH [National Institutes of Health] doing early detection of cancer for third-world countries, and then I got involved in some startups in high technology, and finally started doing consulting work. It was all image analysis.

Q: Where did you go to school?
A: I did a bachelor’s and a master’s in electrical engineering at UC [University of California] Berkeley, a Ph.D. at Carnegie Mellon. I then went to medical school at UC San Francisco and then back to Berkeley for an MBA. So, there was no straight line in there.

Q: How did you end up at your current job?
A: My father was a physics professor. He was hired to help with the early years of the company, where around age 12, I went and swept up pulsed power oil. In 1998 I saw the building was asking someone to come in for a three-week job and I’ve been there ever since.

Q: What do you do?
A: There are a number of people who need to be able to see things with flash X-ray. In other words, see through something, usually that is moving very quickly. One example is when we went into Afghanistan; I got a call asking me to look at bulletproof vests because they were failing when a certain type of ammunition was hitting it. We made some ballistic gel blocks, put the vest around the ballistic gel and shot flash X-rays as the bullet went through the bulletproof vest.

Another example is when you fly in an airplane, there is a surprisingly large chance that the airplane will hit a bird. There’s something called the 20/20 rule where, if the engine starts to fail, then you should have 20 percent power for 20 minutes. You should be able to land on one engine after that. So, how does a jet engine fail once a bird hits it? The only way to do that would be with flash X-ray.

There are also examples of how mechanically things happen in a dynamic fashion, as opposed to looking for a flaw or crack. I’ve looked at airframes under stress and things like that. On the more mundane side, how do you make a very efficient fuel injector? You squirt different fluids at each other. They mix at the impact point, and then, depending on how well they mix, you can get a better burn of fuel. We can X-ray that fuel as it mixes, and integrate the exact amount of volume of each of the components of the fuel and how they intermix together using flash X-ray.

Q: Do you do onsite work?
A: Projects are a mix of both out-of-house and in-house. With the flash X-ray, there are maybe a thousand installations around the world, so we do go out a lot. A lot of times when I am at home they will ask, “Is it possible to do so and so,” and send me a component. For example, “Look at the tip of this bullet and see if it’s armed,” because there are some bullets that get armed in flight. Bulletproof vests are another example of in-house testing.
Q: What are some of the more challenging aspects of the projects you’ve encountered?

A: In the flash X-ray world, the problem is getting the X-ray to flash at the time that you wanted it. You get one burst of X-rays and you’ve got to do the best you can with whatever dose you are given. The other problem is you could be working with something that is very expensive. Firing an object through a jet engine that suddenly fails, that’s an expensive shot, and you can’t miss it.

Q: Do you see new trends coming out?

A: When I first started we had three film darkrooms in my building. We now have zero. At the time I was brought in, they said, “We’re starting to have problems with obtaining film.” This was the late 1990s, early 2000s. Film was starting to go away. It was getting very expensive keeping each of the darkrooms up and running. Now, our biggest problem is that a person might say CR [computed radiography] is a direct replacement for film, but it’s not true. You have to change the way you look at things. They don’t plug in directly as analysis is concerned. You can change a lookup table on a digital image so it looks like a film image, but then you’re not seeing all the data that’s actually there. Digital is a double-edged sword. That’s not to say that film is better or that CR is better. It’s a different tool and you’ve got to train your people to understand that.

Q: What do you like best about your job?

A: I never do the same thing twice. People, for example, say, “I want to take X-rays underwater.” Of course, taking X-rays through water is not a really easy thing to do, but it’s quite possible, and it’s an incredibly interesting technological question.

Q: Are you doing different kinds of work every day?

A: My projects range from a few weeks to a year, and I’m usually doing a couple of them at the same time. We spend time every year teaching classes because you’ve got to educate people. We just had a class where we had 25 people from various walks of life. This particular case was a flash X-ray class. Just because you can make a flash X-ray pulse doesn’t mean you got the image. So the question is how do you get the image? You’ve got to have a picture at the end that shows what the customer wants to see. The money shot.

Q: Are you a member of any committees or technical societies?

A: I’m with ASTM Committee E07 on Nondestructive Testing. ASTM is the one they send me to a few times a year. That’s really the big one for me. I’ve often given papers and talks in other places. I worked, for instance, with the DWG [Defense Work Group] on methods.

Norman Link can be contacted at norman.link@I-3.com.