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ABSTRACT. *Nondestructive testing* is any technique used to inspect the integrity of a manufactured item without diminishing its future usefulness. Magnetic particle inspection is one type of nondestructive testing that uses electromagnetism in the inspection procedure, thus potentially exposing the operator to magnetic fields. During magnetic particle inspection, investigators took peak magnetic field measurements of 8 turbine engine shafts at a turbine engine overhaul and repair center. They recorded 95 peak magnetic field measurements, ranging from < 0.1 to 29.27 mT. The exposure values measured were among the highest reported in the occupational setting. Further work is needed to characterize magnetic field exposures in magnetic particle inspection operations—in particular, by differentiating magnetic field magnitude by current frequency—and to understand exposure as it relates to different types of magnetic particle inspection devices.

KEYWORDS: magnetic fields, magnetic particle inspection, nondestructive testing

Nondestructive testing (NDT) is a technique widely used to examine a machine part without diminishing the part's future usefulness. NDT can be a simple visual inspection or a more complex procedure such as acoustic or x-ray inspection. Virtually every machine part is inspected through NDT, and systems engineered for high pressure, temperature, and speed rely particularly on this type of testing. Industries such as nuclear energy, aeronautics, and marine engineering depend on NDT to prevent failures that may cause the loss of human life as well as great financial loss, by detecting flaws that other inspection techniques cannot identify.[1] Electromagnetic testing is one type of NDT that uses electromagnetism in the inspection process. This is particularly useful in inspection of large parts that cannot be easily inspected otherwise and also for parts that will have to operate under high stress or strain. Therefore, electromagnetic testing has been particularly important in the manufacture of high-speed, high-pressure, rotating equipment such as gas turbine engines.

Because of the high electrical current used in electromagnetic testing to create adequate magnetic fields (MFs) for inspection operations, potential exists for worker exposure to magnetic fields. Maxwell's field equations show that MFs have intensities directly proportional to the electric current used to generate them.[2]

The health effects from MF exposure have not been fully characterized, particularly at the intensities used in certain NDT operations. Table 1 shows reported MF measurements in the occupational environment.[3–7] The general consensus within research and regulatory groups is that findings on the risks of MF exposure are limited and inadequate. The epidemiologic research findings are inconsistent, and biological plausibility has not been proven. However, because of the ubiquitous nature of MF exposure, several regulatory groups have set suggested exposure limits, and the International Agency for Research on Cancer lists extremely low-frequency (ELF) MF exposure as a possible human carcinogen (Group IIB).[8]

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Table 1.—Published Occupational Magnetic Field Exposure Values

Occupation	Peak level (mT)	Source	Frequency	Measurement
Magnetic resonance imaging technician	200–2,000	Karpowicz J, 2006[3]	Static	Static meter
Sewing machine operator	0.0028	Hansen N, 2000[4]	60 Hz	Personal dosimeter
Transmission worker (engineer)	5.4–13.4	Harrington JM, 1997[5]	60 Hz	Calculation
Welder	0.11	Floderus B, 1996[6]	50 Hz	Dosimeter
Railway maintenance worker	0.0259	Wenzel TB, 1997[7]	16 2/3 Hz	Spot

Magnetic Particle Inspection Theory

Magnetic particle inspection (MPI) is a type of NDT that uses magnetic fields to detect defects by magnetizing a part. It involves applying a fluorescent metallic indicator suspension to the part surface and visually inspecting the part under an ultraviolet (UV) lamp (black light). Different types of MPI devices are appropriate per the size and shape of the part being inspected.

In the horizontal wet-bed MPI procedure, a part is magnetized by running an electrical current through a conductor. The current creates an electromagnetic field with an MF intensity vector $\vec{H}$ (A/m) and a magnetic flux $\vec{B}$ (tesla or gauss)[9]:

$$\vec{B} = \mu\mu_0 \vec{H},$$

where μ = permeability of material and μ_o = permeability of free space.

Magnetic lines are created as normal to the direction of the current, and the magnetic flux is proportional to the current applied. If there is a discontinuity in the part, then the flux density is interrupted, which creates a flux leakage. This leakage is a grouping of the lines of magnetism, creating an area of higher magnetism. Because the magnetic flux in a part would normally be uniform, an imperfection essentially creates new localized magnetic poles. The indicator solution is strongly attracted to the flux leakage areas of higher magnetization, causing the indicator medium to gather at a point of discontinuity and creating a pattern on the surface of the part being inspected that is visible under a UV lamp.

Description of the Inspection Process

We observed the MPI process while it was performed by a technician in the quality assurance department of a repair and refurbishment center of a turbine engine manufacturing company. The horizontal wet-bed MPI inspection device used 1,400-A to 5,000-A, 3-phase, fully rectified 60-Hz alternating current. Figure 1 shows a schematic of the MPI operation workspace.

An operator performs a quality control procedure daily to ensure proper function of the MPI device. Afterward, the operator proceeds with the actual inspection process. The general steps involved in the inspection process we observed were:

1. Radial magnetization of the part.
2. Visual inspection of the part's outer surface.
3. Borescope inspection of the part's inner surface.
4. Longitudinal magnetization of the part.
5. Visual inspection of the part's outer surface.
6. Borescope inspection of the part's inner surface.
7. Demagnification of the part.

After the part was magnetized in the radial direction, the operator visually inspected the outer surface of the part, removed it from the MPI device, and transferred it to a neighboring borescope station for visual inspection of the inner surface. The operator then returned the part to the MPI device to be magnetized in the longitudinal direction for outer surface visual inspection, then again moved it back to the borescope station for inspection of the inner surface. Last, the operator moved the part back to the MPI device for demagnetization. The major steps are detailed in the next sections.

Quality Control Procedure

The process began with an examination of the fluorescent metallic indicator suspension to verify proper metallic particle concentration. The indicating medium for this MPI device was a wet slurry, with ferromagnetic particles ranging from 40 to 60 μm in size, suspended in mineral oil.[10] In general, the composition of the particles includes a nickel, chromium, and hydrocarbon blend, de-aromatized by catalytic hydrogenation.[11–13] Concentration was determined by filling a settling tube with 100 mL of the indicator suspension and demagnetizing the suspended particles using the MPI coil. During this step, the operator held the settling tube inside the coil, applied current, and allowed the particles to settle. The operator then determined the concentration of particles in the suspension by reading the graduations on the settling tube.

The technician then inspected 2 small test pieces for quality control: a steel rectangle and a ring. Each was placed on a small solid copper rod, and each was magnetized and visually inspected. The technician magnetized the test pieces to identify a standard number of flaw lines (to ensure proper functioning of the MPI device), then washed the test pieces with a mineral oil to remove the indicator solution and stored.

After the quality control procedure, the actual inspection process begins. During our observation, only turbine shafts were inspected.

Radial Magnetization and Inspection

A complete inspection lasts more than an hour. To begin, the operator used an overhead hoist to move the

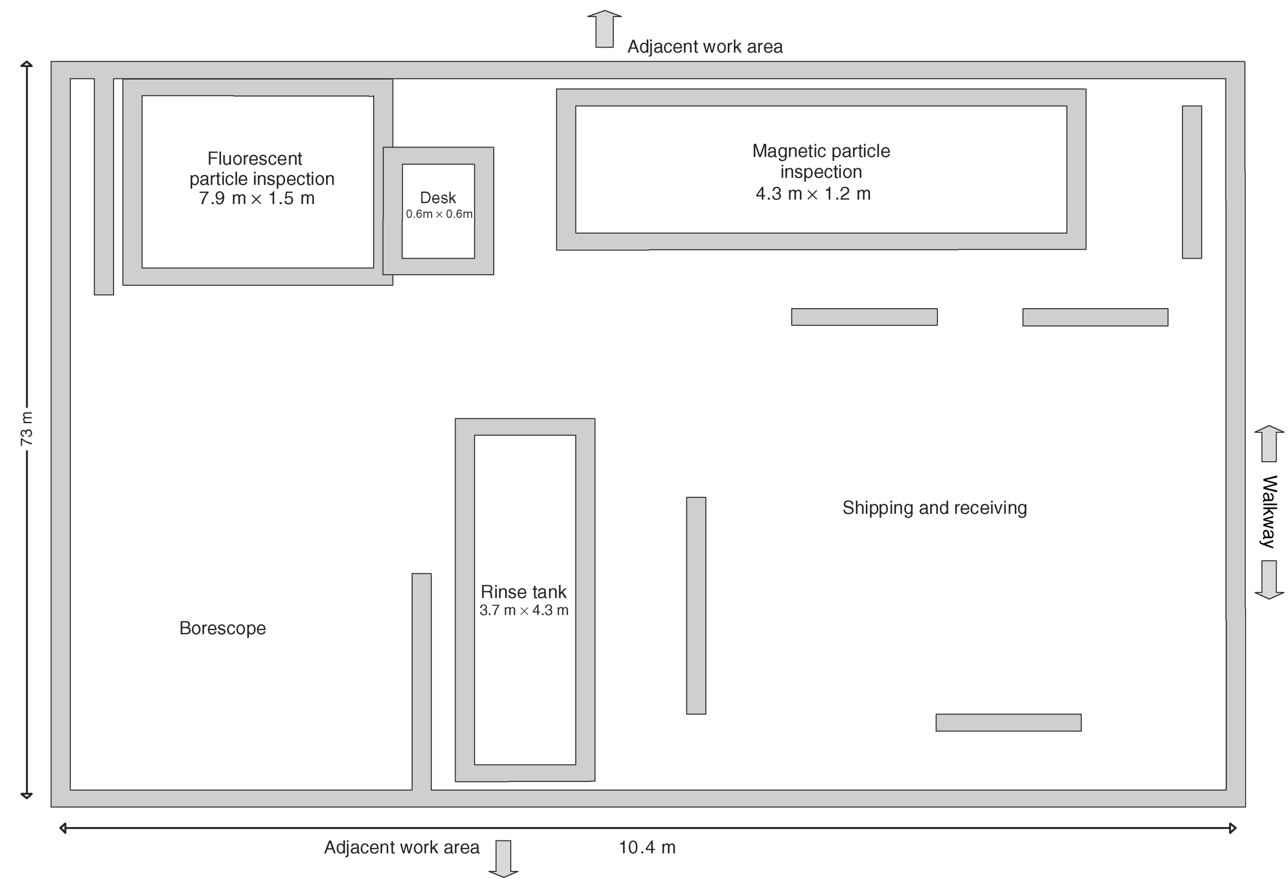

Fig. 1. Schematic of workplace.

part from its shipping container and loaded the part on the MPI bed, then coated the part on all surfaces with the indicator solution via a low-flow nozzle. Radial magnetization involves placing a conducting bar through the part and placing the bar between 2 copper plates, which passes current through a conducting rod to magnetize the part. The MF produced is circular relative to the axis of the part. The radial magnetization step is called a *head shot*. The technician selects the current on the back control panel above the part. To adjust the current, the technician must lean over the part at a 45° angle with his or her head and chest directly above the part. The technician then stands upright to magnetize the part by activating a knee bar approximately 1 m off the ground.

The technician brings down a large curtain to make a dark enclosure around the MPI device, the part, and the technician, who then illuminates the part under the handheld UV lamp and continues to coat the part with indicator solution using the low-flow nozzle. The technician repeatedly activates the current while leaning in toward the part to look for fluorescent flaw indications (with approximately 15 cm between operator's head and the part). This process continues down the length of the part, with the technician rotating the part to examine all sides. When the external inspection is complete, the operator uses a hoist to move the part to a neighboring borescope station for internal inspection and then returns the part to the MPI bed for longitudinal magnetization. Parts are magnetized both radially and longitudinally to ensure that any discontinuities can be seen in either direction.

Longitudinal Magnetization and Inspection

The second magnetization creates magnetic field lines running along the longitudinal axis of the part. An example of longitudinal magnetization is the solenoid method, commonly referred to as a *coil shot*.[14] A *solenoid* is a series of circular wire rings fixed on a metal coil. The technician moves the solenoid laterally along the part, creating an MF that is proportional to the current in the wires, the number of turns in the current-carrying wire, and the distance from the coil.[9] The technician moves with the coil down the length of the part in approximately 0.20-m intervals, coating the part with the indicator suspension and inspecting the part with a handheld UV lamp. When external inspection is complete, the technician moves the part to the borescope station for internal inspection and then back to the MPI bed for demagnetization.

Demagnetization

After the inspection process is complete, the part is demagnetized. The technician uses alternating current (60 Hz) of decreasing magnitude to bring the magnetization state of the part to 0.[1]

METHODS

Magnetic Field Meter

We made quantitative MF measurements using a Holaday Low Frequency HI-3550 magnetic field monitor (Holaday Industries Inc, Eden Prairie, MN). This personal MF monitor performs 3-axis detection regardless of the orientation of the monitor in relation to the field. Both an instantaneous and a time-integrated measurement setting with peak hold values are also displayed. The device can measure MFs created by static direct current (DC) or low-frequency alternating current (AC) in the range of 0 to 1 kHz. The measurement range is from 0.1 mT to 0.3 T, with an accuracy of ± 10%; measurement updates are displayed every 3 seconds.

Background MF Measurements

We took background MF measurements at locations removed from the targeted MF source, including the facility parking lot and the main lobby of the facility. We also took background MF measurements in the MPI work area, both before and after we observed the MPI inspection process.

Quality Control Procedure Measurements

During the quality control procedure, we recorded peak MF levels during the determination of the indicator solution particle concentration. Peak MF levels were recorded during the magnification and the demagnification of the 2 metal test pieces. For the ring test piece, we set the magnification at 3

Table 2.—Peak Magnetic Field (MF) Levels During Quality Control Procedure

					Sensor distance (m)		
Day	Part	Type of magnetization	Current (amps)	Peak MF (mT)	From plate	From part	From coil
1	Indicator solution	Demagnetization	NA	0.19	1.18	NA	NA
	Ring test piece	Head shot	1,400	1.46	0.35	NA	NA
		Head shot	2,500	1.75	0.35	NA	NA
		Head shot	3,400	3.53	0.35	NA	NA
		Head shot	5,000	4.43	0.35	NA	NA
		Demagnetization	NA	3.4	0.35	NA	NA
	Rectangle test piece	Head shot	2,000	$<$ 0.1	0.18	NA	NA
		Demagnetization	NA	1.41	0.18	NA	NA
2	Indicator solution	Demagnetization	NA	8.48	0.58	NA	NA
	Ring test piece	Head shot	1,400	0.26	0.41	NA	NA
		Head shot	2,500	$<$ 0.1	0.41	NA	NA
		Head shot	3,400	2.31	0.41	NA	NA
		Demagnetization	NA	4.11	0.41	NA	NA
	Rectangle test piece	Head shot	2,000	0.82	1.48	0.22	NA
		Demagnetization	NA	1.34	1.48	0.22	NA
3	Indicator solution	Demagnetization	NA	0.52	1.13	NA	NA
	Ring test piece	Head shot	1,400	$<$ 0.1	0.41	0.22	NA
		Head shot	2,500	1.4	0.41	0.22	NA
		Head shot	3,400	1.73	0.41	0.22	NA
		Demagnetization	NA	1.24	0.41	0.22	NA
	Rectangle test piece	Head shot	2,000	0.62	0.18	0.28	NA
		Demagnetization	NA	0.7	0.18	0.28	NA
4	Indicator solution	Demagnetization	NA	3.31	0.41	NA	NA
	Ring test piece	Head shot	1,400	0.86	0.41	0.22	NA
		Head shot	2,500	1.05	0.41	0.22	NA
		Head shot	3,400	1.53	0.41	0.22	NA
		Demagnetization	NA	7.28	0.41	0.22	NA
	Rectangle test piece	Head shot	2,000	0.4	0.28	0.28	0.36
		Demagnetization	NA	2.68	0.28	0.28	0.36
5	Indicator solution	Demagnetization	NA	3.99	0.41	NA	0.40
	Ring test piece	Head shot	1,400	0.73	0.41	0.22	NA
		Head shot	2,500	1.16	0.41	0.22	NA
		Head shot	3,400	1.6	0.41	0.22	NA
		Demagnetization	NA	1.63	0.41	0.22	NA
	Rectangle test piece	Head shot	2,000	0.66	0.28	0.28	0.36
		Demagnetization	NA	0.69	0.28	0.28	0.36

Note. NA = not applicable (not recorded).

Table 3.—Peak Magnetic Field (MF) Levels During Inspection Procedure

Day	Part	Type of magnetization	Current (amps)	Peak MF (mT)	Sensor distance (m)		
					From plate	From part	From coil
1	1	Head shot	4,500	3.74	0.44	0.12	NA
		Head shot	4,500	3.65	0.44	0.12	NA
		Coil shot	2,031	19.19	1.28	0.12	1.60
		Coil shot	2,031	11.44	1.82	0.12	1.82
		Demagnetization	NA	4.7	1.50	0.12	1.82
		Coil shot	2,031	25.03	0.85	0.12	NA
1	2	Head shot	2,000	1.5	0.05	0.18	NA
		Head shot	4,500	2.86	0.05	0.18	NA
		Coil shot	3,000	13.16	0.36	NA	NA
		Coil shot	3,000	10.35	0.48	NA	0.40
		Coil shot	3,000	13.5	0.47	NA	0.18
		Head shot	3,000	4.05	0.58	0.16	NA
		Demagnetization	NA	2.87	0.58	0.16	NA
2	3	Head shot	2,000	0.45	1.15	0.16	NA
		Head shot	2,000	1.73	1.15	0.16	NA
		Head shot	5,000	3.02	1.15	0.16	NA
		Coil shot	2,031	13.61	0.98	0.15	0.14
		Coil shot	2,031	18.36	1.84	0.13	0.13
		Coil shot	2,031	14.74	2.41	0.14	0.17
		Head shot	NA	2.82	1.06	0.16	NA
		Demagnetization	NA	4.95	1.06	0.16	NA
2	4	Head shot	2,000	1.98	1.15	0.16	NA
		Head shot	2,000	2	1.15	0.16	NA
		Head shot	5,000	4.79	1.15	0.16	NA
		Coil shot	2,031	0.91	2.18	0.16	NA
		Coil shot	2,031	5.01	2.54	0.16	0.1
		Coil shot	2,031	12.49	2.54	0.16	NA
		Head shot	NA	2.79	1.06	0.16	NA
		Demagnetization	NA	4.22	1.06	0.16	NA
		Head shot	NA	6.08	1.06	0.16	NA
		Demagnetization	NA	3.81	1.06	0.16	NA
		Demagnetization	NA	0.52	1.13	NA	NA
3	5	Head shot	2,000	1.78	1.15	0.16	NA
		Head shot	5,000	5.35	1.15	0.16	NA
		Coil shot	2,031	5.36	1.23	0.16	0.42
		Head shot	NA	3.61	1.23	0.16	0.42
		Demagnetization	NA	6.16	1.23	0.16	0.42
3	6	Head shot	2,000	0.16	1.15	0.16	NA
		Head shot	5,000	5.98	1.15	0.16	NA
		Coil shot	2,031	2.62	1.23	0.16	0.42
		Head shot	NA	1.11	1.23	0.16	0.42
		Demagnetization	NA	5.49	1.23	0.16	0.42
4	7	Head shot	4,500	2.8	0.44	0.12	NA
		Coil shot	2,031	3.12	0.84	NA	0.11
		Coil shot	2,031	25.03	0.88	NA	0.09
		Coil shot	2,031	12.16	1.83	NA	0.28
		Coil shot	2,031	12.74	2.41	NA	0.28
		Coil shot	2,031	4.44	2.73	NA	0.28
		Demagnetization	NA	3.92	0.85	NA	NA
		Demagnetization	NA	3.91	0.85	NA	NA
5	8	Head shot	4,500	3.17	0.44	0.11	NA
		Head shot	4,500	3.05	0.44	0.11	NA
		Coil shot	3,400	27.32	0.45	0.11	0.11
		Coil shot	3,400	16.93	0.99	0.11	0.11
		Coil shot	3,400	29.27	1.47	0.11	0.11
		Coil shot	3,400	27.51	2.09	0.11	0.11
		Head shot	NA	0.55	1.18	0.11	0.11
		Demagnetization	NA	2.98	1.18	0.11	0.11
		Demagnetization	NA	3.06	1.18	0.11	0.11

Note. NA = not applicable (not recorded).

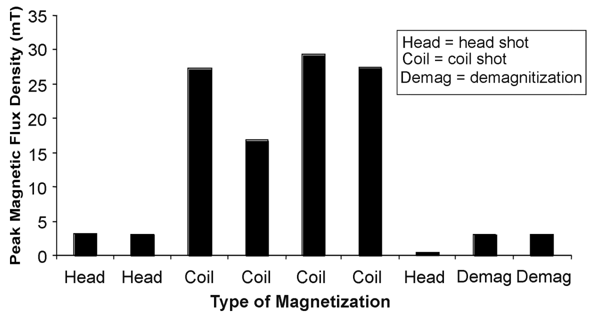

Fig. 2. Successive magnetic field measurements during inspection process of one turbine shaft.

different levels of increasing current; the rectangular test piece was tested at one current setting. We recorded the peak MF levels for each current setting used for the test pieces.

Inspection Procedure Measurements

We collected peak MF measurements in the turbine engine shaft inspection and repair center of the facility over 2 sessions of 3 consecutive days each. During that period, MPI was used to measure 1 to 2 turbine shafts each day, resulting in 8 shafts inspected; 4 types of shafts were inspected. The shafts ranged in length from 0.82 to 2.8 m, with inner radii ranging from 0.08 to 0.24 m.

We placed the MF meter approximately 0.29 m above the MPI bench surface during the inspection procedure. Peak MF levels were recorded during each radial and longitudinal magnetization and during demagnetization. We placed the meter 0.15 m from the front of the machine face, secured in position on a ring stand at a 45° angle toward the part being inspected. The MF meter was moved laterally along the machine bench to keep the device approximately in front of the technician. The meter was always positioned as close as possible to the operator without interfering with the work. Often, the chest of the operator would actually touch the meter. We measured and recorded MF meter locations in relation to the part, coil, and operator.

Following work orders and standard operating procedures, the parts were magnetized with prescribed levels of current, and peak MF levels were recorded at each current setting. For radial magnification, the meter was positioned in one location only. During longitudinal magnetization, the coil was moved along the part with the technician, and the MF meter was moved with the technician, accordingly. At each location, a peak MF level was recorded.

Demagnetization

During demagnetization of a longitudinally magnetized part, we recorded the peak MF level for each demagnetization; the part occasionally remained magnetized, and subsequent demagnetizations were necessary. Sometimes the operator would deliver a head shot before demagnetization; when this step occurred, we recorded the peak MF level and position of the meter.

RESULTS

Background MF Measurements

Background MF levels outside the facility were on average < 0.1 mT (the instrument's lower limit of detection) and never exceeded 0.13 mT. Median background MF level in the MPI work for each of the 3 days was < 0.1 mT.

Quality Control Procedure Measurements

Table 2 shows the peak MF levels recorded during the quality control procedure. The radial magnetization peak MF levels ranged from < 0.1 to 4.43 mT, with a median value of 1.05 mT. The demagnetization peak MF levels ranged from 0.19 to 8.48 mT, with a median value of 1.63 mT.

Inspection Procedure Measurements

Table 3 shows the levels recorded during the actual inspection procedures. The peak MF levels during radial magnetization (head shot) ranged from 0.16 to 6.08 mT, with a median value of 2.84 mT. The peak MF levels during longitudinal magnetization (coil shot) ranged from 0.91 to 29.27 mT, with a median value of 13.16 mT. The peak MF levels during demagnetization ranged from 0.52 to 6.16 mT, with a median value of 3.92 mT. Figure 2 shows the exposure measurements recorded at the various stages of an inspection procedure for one shaft.

Table 4.—Recommended Occupational Exposure Guidelines for 60-Hz Magnetic Field

Association	Type of limit	Year	Magnetic field (mT)
IEEE	Maximum permissible exposures (head/torso)	2002	2.71
	Maximum permissible exposures (arms/legs)	2002	63.2
ICNIRP	Reference level	1998	0.42
ACGIH	Threshold limit value (whole-body)	2007	1
	Threshold limit value (arms/legs)	2007	5
	Threshold limit value (hands/feet)	2007	10

Note. ACGIH = American Conference of Governmental Industrial Hygienists; IEEE = Institute of Electrical and Electronics Engineer; ICNIRP = International Commission on Non-Ionizing Radiation Protection.

COMMENT

For occupational MF levels, MPI produces one of the highest magnetic flux densities recorded in the literature—higher than the exposures to which welders, electrical utility workers, and railway employees generally are exposed (see Table 1). The only occupational MF levels that exceed those produced by MPI are from magnetic resonance imaging operations.

The background MF levels measured were negligible, near the meter's limit of detection. The proximity of the operator to the inspected part puts them in close proximity to the generated MF. During inspection, the operator places his or her hands on the part and leans in closely with the handheld UV lamp, placing the torso and head close to the part being inspected. Exposures are presumably the highest during this time of close inspection because of the worker's proximity. In this study, we took measurements to approximate the exposure at the operator's head, torso, and hands.

The MF meter used was a broadband device, measuring magnetic flux density in the range of 0–1 kHz. In the magnetization step, the MPI device used 3-phase fully rectified alternating current, which results in direct current, plus some 180-Hz ripple effects caused by incomplete rectification. Therefore, in the magnetization step, the meter responded to both the DC effect and the 180-Hz ripple effect. An ideal exposure assessment of MPI would divide the ELF and static MF magnitudes during the magnetization step. Until the AC and DC contributions to these MF measurements can be differentiated, direct comparison of these data to exposure limit guidelines is inappropriate. (For reference, the static MF threshold limit value [TLV] for whole-body exposure is 60 mT 8-hour, time-weighted average [TWA] with a ceiling value of 2 T; the static MF TLV for limbs is 600 mT 8-hour TWA with a ceiling value of 5 T.)[15]

Because the demagnetization procedure uses 60-Hz AC, we may directly compare the MF measurements to the TLV ceiling values and other recommended exposure limits (Table 4). The peak MF measurements from demagnetization ranged from 0.19 to 8.48 mT, with a median of 3.31 mT. Reviewing the demagnetization data in Tables 2 and 3 reveals that nearly every measurement exceeds the subradiofrequency magnetic fields TLV ceiling value for whole-body exposure of 1 mT, and several measurements exceeded the ceiling value for arms/legs of 5 mT.[15]

Conclusions

The MF measurements for the magnetization step are generally high relative to other occupational exposures, but they cannot be directly compared to the TLV until the characterization of frequencies is known. The MPI device uses 60-Hz AC during the demagnetization step, so the MF measurements are directly comparable to the TLV; most of these measurements exceed the TLV ceiling values of 1 mT for whole-body exposure, and many of the measurements exceed the ceiling value of 5 mT for limb exposure.

The MF measurements were made during the inspection of only 1 type of part (turbine shafts) and using only the MPI device type (horizontal wet bed) for that part; therefore, we did not examine the variability between part type or shape and other MPI device types. Because of the high MF levels observed in this study and because of the limitations of this preliminary characterization, further investigation of MF exposure in MPI operations is warranted.

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References

1. Udpa SS, Moore PO. *Nondestructive Testing Handbook: Electromagnetic Testing*. 3rd ed. Columbus, OH: American Society for Nondestructive Testing; 2004.
2. Menzel DH. *Fundamental Formulas of Physics*. Vol. 1. New York, NY: Dover Publications; 1960.
3. Karpowicz J. Health risk assessment of occupational exposure to a magnetic field from magnetic resonance imaging devices. *Int J Occup Safety Ergo*. 2006;2:155–167.
4. Hansen N, Sobel E, Davanipour Z, et al. EMF Exposure assessment in the Finnish garment industry: evaluation of proposed EMF exposure metrics. *Bioelectromagnetics*. 2000;21:57–67.
5. Harrington JM, McBride DI, Sorahan T, et al. Occupational exposure to magnetic fields in relation to mortality from brain cancer among electricity generation and transmission workers. *Occup Environ Med*. 1997;54:7–13.
6. Floderus B, Persson T, Stenlund C. Magnetic-field exposures in the workplace: reference distribution and exposures in occupational groups. *Int J Occup Environ Health*. 1996;3:226–238.
7. Wenzel TB. Estimating magnetic field exposures of rail maintenance workers. *Am Ind Hyg Assoc J*. 1997;58:667–671.
8. World Health Organization (WHO). *Static and Extremely Low Frequency (ELF) Electric and Magnetic Fields: IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*. Lyon, France: International Agency for Research on Cancer; 2002:1–8.
9. Lovejoy D. *Magnetic Particle Inspection*. London, England: Chapman & Hall; 1993.
10. Betz CE. *Principles of Magnetic Particle Testing*. Chicago, IL: Magnaflux; 1967.
11. NOVAMET Specialty Products Corporation. *Material Safety Data Sheet: NOVAMET Stainless Steel Flake Type SSC*. Wyckoff, NJ: NOVAMET; 2005.
12. Ely Chemical Company. *Safety Data Sheet: MPI Diluent (HF)*. Cambridgeshire, England: Ely Chemical Company; 2003.
13. Magnaflux. *Material Safety Data Sheet: Oil-Based Carrier for MPI Carrier II*. Glenview, IL: Magnaflux; 2004.
14. Navy Department, Bureau of Aeronautics, Inspection Division. *NavAer 00-15PC-503: Aeronautical Technical Inspection Manual: Magnetic Particle Inspection, Volume 3, Section 4*. Washington, DC: US Government Printing Office; 1947.
15. American Conference of Governmental Industrial Hygienists (ACGIH). *Threshold Limit Values and Biological Exposure Indices*. Cincinnati, OH: ACGIH; 2007.