



# Operating Experience Summary

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### Equipment Labeling Error and Inadequate Zero-Energy Check Result in Electrical Arc Flash

# 1

On April 21, 2006, at the Pacific Northwest National Laboratory, an electrical arc flash occurred inside a 480-volt combination motor-starter, resulting in a minor first-degree burn on the left wrist of an electrician. The electrician was repairing a chilled water pump for Life Sciences Building 1 when the arc flash occurred. He was taken to the onsite medical provider for evaluation and was released for work without restrictions. The electrician believed the equipment was de-energized; however, an equipment labeling error resulted in the wrong circuit breaker being locked and tagged out. An ineffective safe-condition check failed to identify that the circuit was still energized. (ORPS Report SC--PNSO-PNNL-PNNLBOPER-2006-0007; final report filed June 26, 2006)

The work activity involved repairing chilled water pump (CHWP) #2 for the 600-ton chiller, which failed to run when activated by the automated facility control system. During diagnostics of the system on April 20, an operator noticed that, in addition to the #2 pump failing to run when activated, CHWP #1 shut down when the circuit breaker for pump #2 was opened manually. The operator wrote a service request to troubleshoot and repair the combination motor-starter for CHWP #2.

On the day of the incident, two electricians, wearing appropriate PPE, closed the disconnect switch for CHWP #2 to verify the source of power. With the cabinet door open, the first electrician performed the safe-condition and safe-to-work checks using a Fluke® T-2 meter, reading line-side voltage through the arc

suppressor (measuring phase to phase and phase to ground). While performing these checks, corrosion was observed on some components, as was some water in the bottom of the cabinet. Figure 1-1 shows the combination motor-starter cabinet for CHWP #2.



Figure 1-1. CHWP #2 cabinet with open door

The first electrician then walked over to the power distribution panel, which provides power to the combination motor-starter, opened the circuit breaker labeled as CHWP #2, and applied his Authorized Worker Lock (AWL). He returned to the combination motor-starter and checked the line side of the disconnect switch through the arc suppressor for absence of power as he had done before. There was no indication of electrical power. The safe-condition and safe-to-work checks on the line side of the disconnect switch were complete. However, investigators would later conclude that inadequate contact between the test meter probe and the phase conductors resulted in a failure to detect the presence of electrical energy.

The electrician opened the disconnect switch and measured for voltage on the load side of the switch; none was observed. Both electricians now believed that the safe-condition and safe-to-work checks were complete. The second electrician then applied his personal AWL to the same circuit breaker at the distribution panel, and they began to troubleshoot the load side of the combination motor-starter.

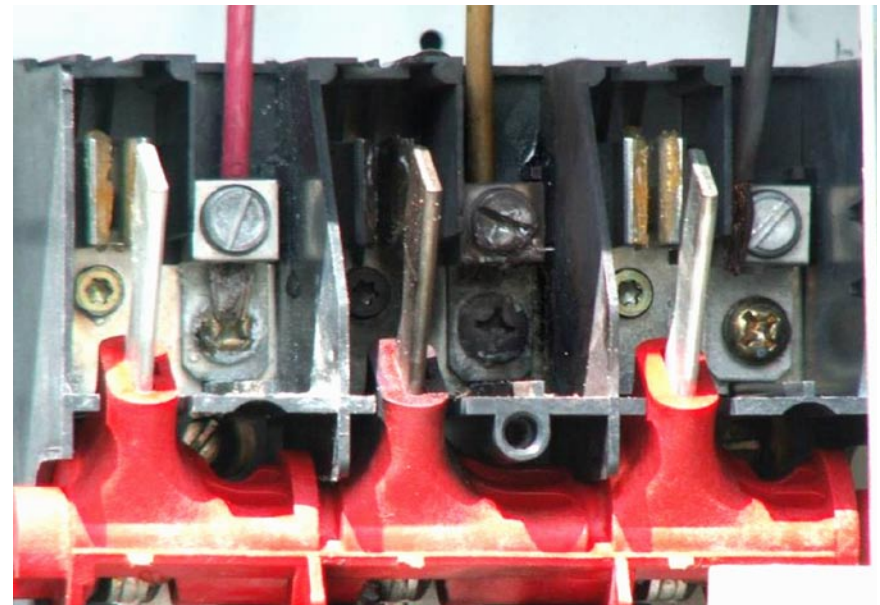
The electricians determined that a control power transformer had failed. They removed a mounting plate holding the transformer and then removed the transformer. The first electrician had to leave, and the second electrician obtained a replacement transformer. While repositioning the mounting plate with the new transformer attached, the line-side C-phase conductor came out of its lug and contacted the B-phase lug resulting in an arc flash. Figure 1-2 shows the burned B-phase lug.

An investigation team was formed to identify causal factors. They determined that the labeling error dated from the time of system construction in the summer of 2000. The labeling on the 25-amp circuit breakers at the distribution panel for the two chilled water pumps was reversed. They also determined that

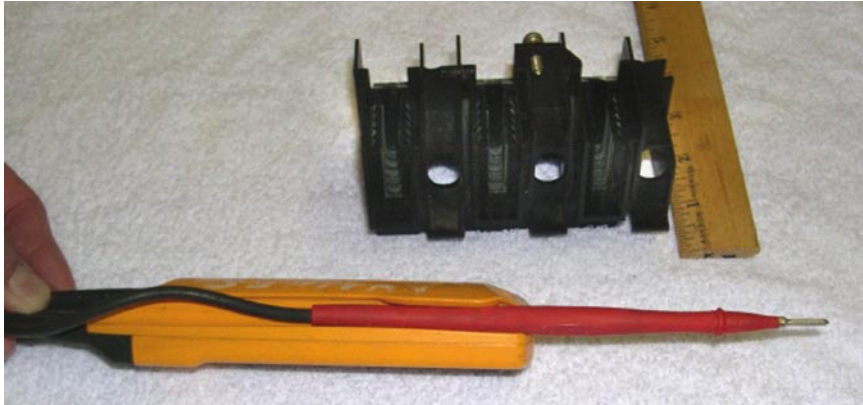
the design of the arc suppressor on the line-side disconnects restricted access and visibility of the phase lugs during zero-energy checks.

Investigators believe one of the following three credible failure modes resulted in the voltmeter test probe not making contact with the line-side phase lug.

1. Use of the probe holder on the meter while positioning the test probe could have resulted in failure of the probe to contact the phase lug. If the probe was not positioned in the meter probe holder correctly, or if it slid back in the holder, the probe might not have reached far enough through the arc suppressor to make contact with the phase lug. (Figure 1-3 shows the meter and test probe.)



**Figure 1-2. Closeup of the burned B-phase lug (center)**



**Figure 1-3. Fluke T-2 meter with test probe in holder (arc suppressor shown above)**

## GUIDANCE

- DOE Order 5480.19, *Conduct of Operations Requirements for DOE Facilities*, chapter XVIII, “Equipment and Piping Labeling,” states that equipment labeling should help ensure that facility personnel are able to positively identify equipment they operate.
- OSHA Standard for General Industry, 29 CFR 1910, Subpart S - *Electrical* and OSHA Standard for Construction, 29 CFR 1926 Subpart K - *Electrical*, 1926.403(h), “General Requirements” state that “Each disconnecting means required by this subpart for motors and appliances shall be legibly marked to indicate its purpose, unless located and arranged so the purpose is evident. Each service, feeder, and branch circuit, at its disconnecting means or overcurrent device, shall be legibly marked to indicate its purpose, unless located and arranged so the purpose is evident. These markings shall be of sufficient durability to withstand the environment involved.”

2. The electricians could have mistaken contact with the arc suppressor as being contact with the phase lug without any distinct indication on the meter.
3. Corrosion on the phase lugs could have prevented adequate contact between the meter probe and the lug.

The investigation team identified the following contributing causes.

- Procedures for verification of safe-condition and safe-to-work checks are less than adequate. Qualified and experienced workers performed the checks in accordance with established requirements that are consistent with industry practice.
  - The existing lockout/tagout (LOTO) procedure allows the same worker to simultaneously perform the safe-condition and safe-to-work checks.
  - The LOTO and electrical safety procedures do not anticipate the safe-condition and safe-to-work check failure scenarios identified by the investigators.
  - The LOTO and electrical safety procedures rely on the skill of the electrical worker to perform safe-condition and safe-to-work checks and do not provide specific guidance on the proper way to check three-phase electrical systems.
- The CHWP configuration information was not identified or acted on as part of the planning or the troubleshooting and repair of CHWP #2. The system configuration discrepancy with CHWP #1 and CHWP #2 was noted and logged by the operator on April 20, 2006. However, the possibility of reversed breaker labeling was never identified as an explanation of the conditions noted by the operator.
  - The decision to troubleshoot and repair relied heavily on the premise that the issue was likely a problem with the automated control system.



- The work evolution identified failed control components, further supporting the control issue theory.
- Operations and maintenance staff often consider the automated control system to be responsible for operational issues that are not readily apparent.

Recommendations included revising the following procedures:

- Engineering and operations procedures that address new or modified electrical systems need to include verification of correct component labeling and confirmation that the labeled isolation point correctly isolates the identified component; and
- Electrical safety and LOTO procedures and personnel training, which need to include verifying electrically de-energized conditions by 1) observing the test meter probe as it contacts the component to be tested; and 2) observing test meter indications falling when the component is de-energized.

*This event underscores the importance of properly commissioning new or modified systems to ensure that components are correctly labeled. This is extremely important with electrical systems in order to guarantee proper isolation of hazardous energy. Commissioning procedures need to include verification of proper labeling, and system acceptance testing needs to confirm that components are energized and de-energized from the correct electrical sources as designed. In addition, operational awareness of component/system response is important when diagnosing system or equipment problems. Workers need to maintain a questioning attitude when unexpected conditions are observed.*

**KEYWORDS:** *Electrical safety, arc flash, burn, lockout/tagout, equipment labeling, zero-energy check*

**ISM CORE FUNCTIONS:** *Analyze the Hazards, Develop and Implement Hazard Controls, Perform Work within Controls*

## **MISSED OPPORTUNITIES TO PREVENT EVENTS**

- The commissioning process for the chilled water system failed to identify the labeling error. Procedures did not require verification of labeling, and system testing failed to identify the problem.
- Operators failed to recognize the labeling problem when equipment did not respond as expected and contrary to normal system configuration. They assumed a control system problem.
- Zero-energy checks failed to identify the energized circuits. This was the most important, and final, opportunity to identify the labeling error and protect workers from exposure to hazardous energy. In addition, the safe-condition and safe-to-work checks were not performed independently, which was another missed opportunity.



## Failure to Follow Procedures Results in Potential Overexposure During Radiography

# 2

On June 6, 2006, at a non-DOE facility in Louisiana, two radiographers received an effective radiation dose in excess of the Nuclear Regulatory Commission (NRC) annual occupational limit of 5 rem. The radiographers were handling a radiographic device (camera) and believed that the 41-curie, iridium-192 (Ir-192) source was properly stowed in the shielded position when it was not. Neither radiographer had a radiation survey instrument with them that would have warned them of the exposed source. (NRC Event Report 42619; WSRC Lessons Learned 2006-LL-0039)

A radiographer and his assistant were using the camera to perform multiple radiography exposures. After the 19<sup>th</sup> exposure, they noticed that the source assembly appeared to have slightly more resistance when exposing and returning the source to the shielded position. They performed the final exposure and again noticed resistance as the crank handle was rotated to the shielded position and the lock plunger came up to the locked position. The radiographers did not perform any radiation surveys to verify safe conditions, as required. After experiencing some difficulty disconnecting the source tube from the control assembly, the radiographer and assistant carried the radiographic equipment to their truck and drove to their shop. After eating lunch, the radiographers unloaded the camera and realized that the source pigtail (Figure 2-1) was not in the camera.



**Figure 2-1. Typical radioactive source pigtail**

The calculated worst-case dose was 13 rem for the radiographer and 14.5 rem for the assistant. Analysis of the radiographers' thermoluminescent dosimeters (TLDs) revealed a monthly dose of 1.1 rem and 2.2 rem, respectively. The radiographers' employer is performing cytogenetic analysis on blood samples taken from both of the radiographers.

Investigators determined that neither the radiographer nor the assistant used a radiation survey instrument to determine the source position, nor did they turn on their required alarming rate meters. The direct reading dosimeters for both of the workers were determined to be off-scale. The State of Louisiana is conducting a reactive inspection to review the employer's analysis and determine the root cause of the event.

Radiography equipment typically uses 30- to 100-curie Ir-192 or cobalt-60 sources. The source is contained in a small metal capsule at the end of a short flexible cable (pigtail). The other end of the pigtail is attached to a long cable that is cranked out by the radiographer to ensure a safe distance is maintained from the source. The source is positioned near one side of the object being radiographed while the film is placed on the other side and exposed for only a few seconds.

A review of the NRC event notification database showed 18 reported events involving radiography so far in 2006 (Figure 2-2). Almost half of these events resulted in personnel exposures, followed closely by events involving radiographic equipment malfunctions.

Common causes of personnel exposures include the following:

- Believing the source was safely retracted without verification;
- Approaching the camera without survey meter and with an unshielded source; and
- Picking up a guide tube while it contained the source.

Typical equipment malfunctions include the following:

- Crank cable housing came loose while moving the device;
- Source stuck in extended position and failed to retract;
- Disconnected source pigtail; and
- Crimped source tube.

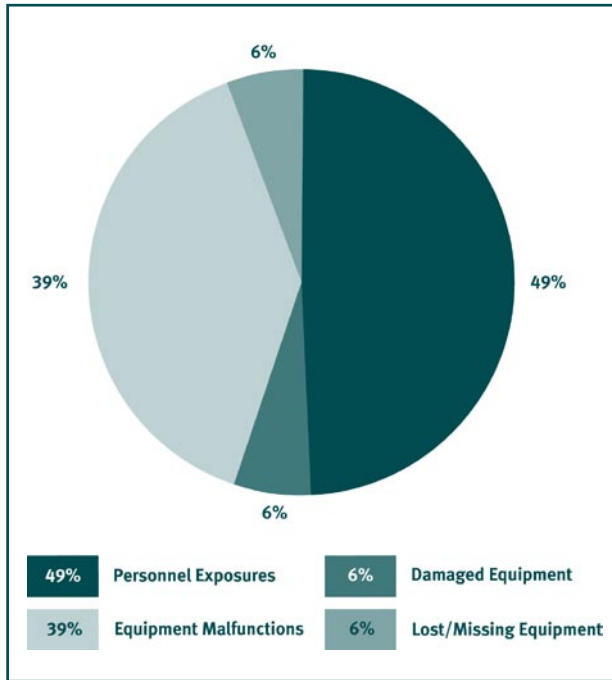


Figure 2-2. NRC-reported radiography events (2006)

Accidents involving the use of radiographic equipment can result in extremely high radiation exposures. For example, on March 3, 2006, at a fixed radiography facility in Rhode Island, a radiographer trainee picked up a guide tube containing a 93-curie Ir-192 source.

The Rhode Island Department of Health Radiation Control estimated the dose at 8 rem whole body and 18,000 rem to the hand. The trainee was taken to an emergency room.

(NRC Event Report 42384)

In March of 1999, the NRC issued Information Notice 99-04, *Unplanned Radiation Exposures to Radiographers, Resulting from Failures to Follow Proper Radiation Safety Procedures*. The information notice was a reminder to the nuclear industry of the risks of unplanned high radiation exposures from radiographic equipment and the need to follow radiation safety procedures. The notice was prompted by a series of incidents that resulted in unplanned radiation exposures. ([NRC Information Notice 99-04](#))

Radiography events at DOE facilities are few in number and result primarily when personnel violate the radiography exclusion areas. These violations resulted from failure to properly post the areas, failure to notify personnel of radiographic operations, failure to activate warning lights, and failure to obey postings. Title 10 of the Code of Federal Regulations, Part 835, *Occupational Radiation Protection*, specifies regulatory requirements for personnel protection such as sealed source control, posting and labeling, training, and entry control.

*These events highlight the importance of strict adherence to radiological safety procedures. Many industry overexposures occur because personnel fail to use radiation survey instruments or wear alarming dosimeters when approaching the equipment. Paragraph 34.49, Radiation Surveys, of 10 CFR 34 requires that radiographers conduct a survey of the radiographic exposure device and the guide tube after each exposure when approaching the device or the guide tube. The survey must determine that the sealed source has returned to its shielded position before exchanging films, repositioning the*



## **GUIDANCE FOR RADIATION GENERATING DEVICES**

DOE-STD-1098-99, *Radiological Control*, section 365, “Radiation Generating Devices,” provides control requirements for radiographic devices and identifies provisions for applicable types of radiation-generating devices that should be included in site-specific procedures.

10 CFR 34, *Licenses for Radiography and Radiation Safety Requirements for Radiographic Operations*, provides requirements for onsite operation with devices containing sealed sources for radiographic use.

ANSI N43.3, *American National Standard for General Radiation Safety-Installations Using Non-Medical X-Ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV*, establishes acceptable guidelines for onsite operations with devices other than sealed sources for radiographic use.

DOE G 441.1-5, *Radiation-Generating Devices Guide*, provides an acceptable methodology for establishing and operating a control program for radiation-generating devices.

DOE G 441.1-13, *Sealed Radioactive Source Accountability and Control Guide*, provides an acceptable methodology for establishing and operating a sealed radioactive source accountability and control program.

*exposure head, or dismantling the equipment. Facility managers should ensure that workers understand their responsibility for procedure compliance.*

**KEYWORDS:** *Radiation exposures, radiography, stop work, radiation control procedures, radiation generating device, camera, source*

**ISM CORE FUNCTIONS:** *Analyze the Hazards, Develop and Implement Hazard Controls, Perform Work within Controls*



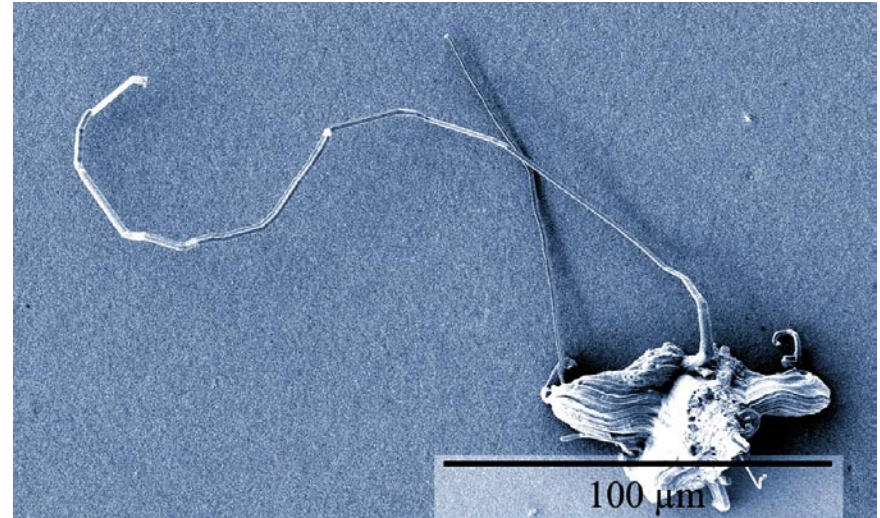
## What Are Metal Whiskers and Why Are They Important?

# 3

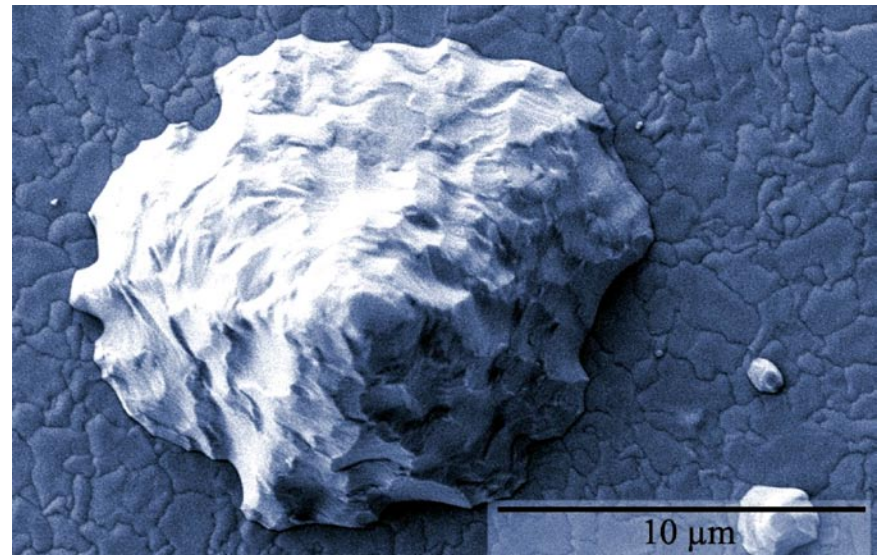
Metal whiskers are column-shaped filaments of soft metals such as tin, zinc, gold, cadmium, and antimony that spontaneously grow outward from a galvanized or electroplated surface and can cause electrical short circuits or electronic component damage. Electrical damage caused by metal whiskers can be particularly difficult to diagnose because the whiskers may vaporize or disintegrate, leaving no trace behind.

Western Electric and Bell Laboratories first documented the existence of metal whiskers in the late 1940s when investigating failures on channel filters in telephone transmission lines. They found that alloying the metal with lead prevented whiskering, and research on the phenomenon of metal whiskers discontinued. However, in response to campaigning from environmental groups to stop using lead, two regulations — the Waste Electrical and Electronic Equipment (WEEE) and Reduction of Hazardous Substances (RoHS) — have compelled European and U.S. electronics manufacturers to produce lead-free components and protective coatings. This has, in turn, resulted in increased incidences of electrical failures when metal whiskers cause short circuits.

Figure 3-1 is a scanning electron micrograph of a whisker growing from a tin-copper alloy surface. Figure 3-2 shows a less-hazardous “hillock” developing from a pure tin surface. These electrically conductive growths can reach several millimeters in length; infrequently, whiskers as long as 10 mm have been reported. The most serious hazard posed by metal whiskers is a metal vapor arc, in which the whisker vaporizes into a cluster of



**Figure 3-1. Metal whisker on a tin-copper surface**



**Figure 3-2. A hillock growing from an electroplated tin surface**

extremely conductive metal ions capable of carrying hundreds of amperes of current. Figure 3-3 illustrates the damage that can occur from such an arc.

Metal whiskers can also cause voltage to jump across electrical circuitry and cause short circuits. Examples of actual failures caused by metal whiskers include the following:

- electrical short circuits that caused nuclear power reactor shutdowns, most notably the April 17, 2005, reactor scram at the Millstone Nuclear Generating Station (NRC Information Notice [2005-25](#));
- whiskers breaking free from their surfaces, entering ventilation systems, and causing damage to electronic and computer equipment;
- product recalls of cardiac pacemakers;
- global-positioning system failures affecting satellite operations; and
- missile failures.

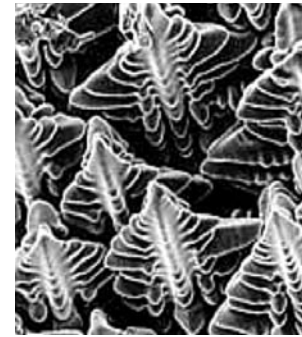


**Figure 3-3. Damage from metal vapor arc**

The National Aeronautics and Space Administration (NASA) has been researching the phenomenon of metal whiskering and has developed a [website](#) that includes photographic and video images, a history of documented failures, and technical papers. The University of Maryland's Computer-Aided Life Cycle Engineering staff has also done research in this

area. The researchers' website includes an [alert](#) page on tin whiskers as well as information on [lead-free](#) solder and assemblies.

Metal whiskers differ from the more commonly known dendrites (from the Greek word for "tree"), not only by their shape and orientation, as shown in Figure 3-4, but also by the mechanism that forms them.



**Figure 3-4. Dendrites**

Dendrites form in damp environments when metal ions dissolve and are then redistributed in the presence of an electromagnetic field. Although the precise mechanism for metal whisker formation remains unknown, it is known that whisker formation requires neither metal dissolution nor the presence of an electromagnetic field.

One theory that has been proposed, but not proven, is that whiskers form in response to the compressive stresses that develop during the electroplating process. Another theory suggests that mechanical stresses produce an environment favorable to whisker formation.

Several groups have been formed to investigate why whiskers form and seek resolution. For example, in 2005, researchers from the National Institute of Standards and Technology (NIST) teamed with the International Electronics Manufacturing Initiative (iNEMI) to examine metal growth formation and grain boundary structure in tin-copper alloy. They found a correlation between grain structure and whisker or hillock formation. When grain boundaries formed into columns, copper impurities held the columnar boundaries in position, resulting in the formation of tin whiskers. If the grain boundaries moved laterally, hillocks were formed. Neither formation occurred on tin-lead alloy.



The NIST/iNEMI researchers are working to devise ways to eliminate mechanical stresses and prevent columnar grain boundary structures. One method being explored involves using an alternating current-on/current-off electroplating process instead of the traditional continuous-current method. The new method may disrupt the formation of columnar boundaries. More information on this research is available at the [EurekAlert!](#) website.

In March 2006, the Joint Electron Device Engineering Council (JEDEC) Solid-State Engineering Association worked with IPC–Association Connecting Electronics Industries to examine current theories on tin whisker formation and provide guidelines for their mitigation. The guideline publication is available on the [Web](#).

In brief, the publication notes that, in general, matte tin finishes are less likely to develop whiskers than are bright finishes. Mitigation strategies involve reducing the compression stress or preventing the grain structure from forming a columnar arrangement through, for example, annealing the metal.

*Metal whiskers have the potential to cause severe damage to equipment, an electrical short-circuit, or a metal vapor arc. It is important for facility managers to know how metal whiskers can form, examine potential surfaces, and take steps to mitigate any potential whisker problems, particularly in high-reliability applications.*

**KEYWORDS:** *Tin, zinc, short circuit, whisker, high-reliability applications, dendrite*

**ISM CORE FUNCTIONS:** *Analyze the Hazards; Develop and Implement Hazard Controls*



# OPERATING EXPERIENCE SUMMARY

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# OPERATING EXPERIENCE SUMMARY

## Commonly Used Acronyms and Initialisms

Agencies/Organizations	
ACGIH	American Conference of Governmental Industrial Hygienists
ANSI	American National Standards Institute
CPSC	Consumer Product Safety Commission
DOE	Department of Energy
DOT	Department of Transportation
EPA	Environmental Protection Agency
INPO	Institute for Nuclear Power Operations
NIOSH	National Institute for Occupational Safety and Health
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
OSHA	Occupational Safety and Health Administration
SELLS	Society for Effective Lessons Learned

Units of Measure	
AC	alternating current
DC	direct current
mg	milligram (1/1000th of a gram)
kg	kilogram (1000 grams)
psi (a)(d)(g)	pounds per square inch (absolute) (differential) (gauge)
RAD	Radiation Absorbed Dose
REM	Roentgen Equivalent Man
TWA	Time Weighted Average
v/kv	volt/kilovolt

Job Titles/Positions	
RCT	Radiological Control Technician

Authorization Basis/Documents	
JHA	Job Hazards Analysis
JSA	Job Safety Analysis
NOV	Notice of Violation
SAR	Safety Analysis Report
TSR	Technical Safety Requirement
USQ	Unreviewed Safety Question

Regulations/Acts	
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
D&D	Decontamination and Decommissioning
DD&D	Decontamination, Decommissioning, and Dismantlement
RCRA	Resource Conservation and Recovery Act
TSCA	Toxic Substances Control Act

Miscellaneous	
ALARA	As low as reasonably achievable
HEPA	High Efficiency Particulate Air
HVAC	Heating, Ventilation, and Air Conditioning
ISM	Integrated Safety Management
MSDS	Material Safety Data Sheet
ORPS	Occurrence Reporting and Processing System
PPE	Personal Protective Equipment
QA/QC	Quality Assurance/Quality Control
SME	Subject Matter Expert