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UL 3400

**Outline of Investigation for Additive Manufacturing Facility Safety
Management**

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Summary of Topics

This first issue of the Outline of Investigation for Additive Manufacturing Facility Safety Management, UL 3400, applies to additive manufacturing facilities using powder as feedstock material for printing of parts.

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CONTENTS

1 Scope	4
2 Introduction	4
3 Hazard Classification	6
3.1 General	6
3.2 Material hazards	6
3.3 Equipment hazards	7
3.4 Facility hazards	9
4 Units of Measurement	10
5 Normative References	10
6 Glossary	13
7 Design Requirements for the Facility	13
8 Design Requirements for the Equipment	18
8.1 AM machine	18
8.2 Ancillary AM equipment	18
8.3 Safety equipment	19
9 Design Requirements for the Materials	21
9.1 Material storage	21
9.2 Waste disposal	22
9.3 Waste from wet separator	22
10 Process Safety Information (PSI)	23
11 Standard Operating Procedure (SOP)	26
12 Emergency Planning and Response (EPR)	28
13 Process Hazard Analysis (PHA)	29
13.1 General	29
13.2 Quantifying risk	29
13.3 Risk levels	31

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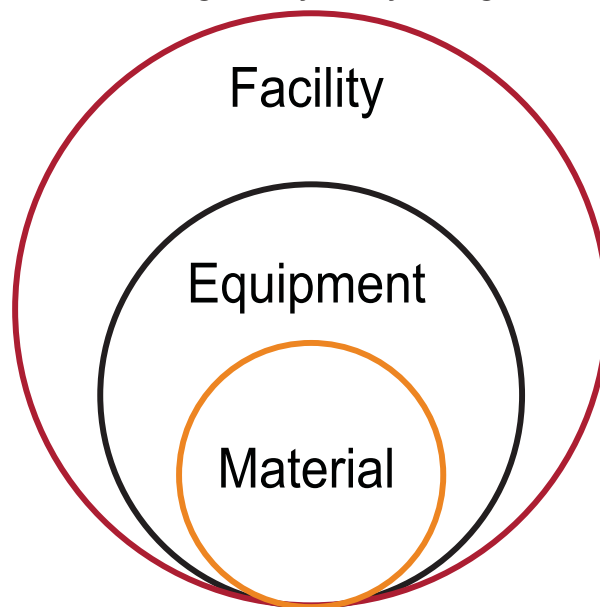
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1 Scope

1.1 This outline covers Additive Manufacturing (AM) facility safety management. It addresses the various hazards associated with material, equipment and facility where parts are manufactured using powder-based additive manufacturing techniques. It covers the potential hazards and risk mitigation measures required for the safe functioning of the facility. These foreseeable hazards include, but are not limited to, fire and explosion, toxic exposure and other workplace hazards. This outline of investigation also includes recommendations for the design, installation and maintenance of additive manufacturing facilities (powder based).

1.2 This outline covers the physical space belonging to the primary AM equipment, ancillary AM equipment and powder storage area unless otherwise specified. In order to fully address the potential hazards, the outline adopts the approach as represented in Figure 1.1.

Figure 1.1
Additive Manufacturing Facility Safety Management Approach



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2 Introduction

2.1 A broad classification of AM Systems based on the initial form of feedstock material (material with which the part is built) is as follows:

a) Powder based AM systems – metals, polymers and ceramics:

- 1) Selective Laser Melting, SLM (metals);
- 2) Electron Beam Melting, EBM (metals);

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- 3) Directed energy deposition (metals):
 - i) Laser Engineered Net Shaping, LENS; and
 - ii) Rapid Plasma Deposition, RPD.
 - 4) Selective Laser Sintering, SLS (polymers);
 - 5) Multi jet fusion technology (polymers); and
 - 6) Binder jetting (ceramics).
- b) Liquid based (vat polymerization) AM systems – Resins, Photopolymers:
- 1) Stereo Lithography Apparatus, SLA (photopolymers);
 - 2) Direct Light Processing, DLP (photopolymers); and
 - 3) Continuous Liquid Interface Production, CLIP (photopolymers).
- c) Solid based AM systems – Wires, Laminates, Pellets:
- 1) Fused Deposition Modeling, FDM (polymers-wire);
 - 2) Electron Beam Wire Feed, EBAM (metals-wire);
 - 3) Laminated Object Manufacturing, LOM (laminates-paper and plastics); and
 - 4) Ultrasonic Consolidation, UC (metals).

2.2 AM facilities that utilize Powder Bed Fusion (PBF) process to create parts make use of metal powders (in Selective Laser Melting, SLM) and polymer powders (in Selective Laser Sintering, SLS) as feedstock material.

2.3 A variety of metals and alloys including aluminum, cobalt, nickel, stainless steel and titanium are used in SLM process. The building process generally takes place in an inert atmosphere using gases such as nitrogen, argon etc. Nitrogen is typically used for stainless steel, nickel alloys and cobalt chrome. Argon is used when fabricating parts using aluminum and titanium powders. The additive manufacturing system, raw powder, filter system, and ancillary AM equipment (e.g. wet separator vacuum) all pose safety and environmental hazards which shall be covered by this outline.

2.4 SLS process employs various polymer powders such as Polyamide 12 (Nylon12), Polyamide 11, Polyamide 12 with Aluminum/Carbon fiber/Glass bead, Polyether Ether Ketone (PEEK), Thermoplastic Poly Urethane (TPU), Thermoplastic Elastomer (TPE), Polycarbonate, PEBA, etc. to produce plastic parts.

2.5 Binder Jet Process uses a number of ceramic powders (in addition to metal powders) for printing of parts. Commonly used ceramic materials include but are not limited to: aluminum oxide, calcium sulfate, silica, ceramic sand, gypsum and glass.

3 Hazard Classification

3.1 General

3.1.1 The list of hazards included in this section are currently identified and addressed by this outline. The list is not exhaustive and the risks shall depend upon the specific nature of each material and type of AM equipment used within an individual facility.

3.2 Material hazards

3.2.1 Deflagration and Detonation Hazards: The combustion hazard of a potential powder dust cloud under the right conditions. It can be a deflagration (combustion zone propagating at less than the speed of sound) or a detonation (the flame front travelling at greater than the speed of sound). Dust cloud ignition may be caused by many factors such as presence of explosible concentrations of dust and oxidizers, ignition sources such as sparks, arc discharges, hot surfaces, friction, etc.

3.2.2 Exposure Hazards – Single and Systemic (Metal powders): Accidental exposures (spills and falls) or long term industrial exposure that may cause dermatitis, skin ulcers, perforation of the nasal septum, as well as cancers of the lungs, nasal cavity and paranasal sinuses.

3.2.3 Exposure Hazards – Single and Systemic (Polymer powders): Polymer powders upon burning produce many noxious and toxic fumes. These thermal decomposition products include carbon dioxide, carbon monoxide, and aldehydes.

3.2.4 Flammability Hazards: Hazard of catching fire or release of highly flammable gases when powders come in contact with water, oxidizers, alkalis or other incompatible materials.

3.2.5 Health Hazards: Effects of overexposure to metal powders may include lung effects (irritation, fibrosis, asthma), cardiovascular effects (cardiomyopathy), liver and kidney congestion. Systemic effects from ingestion of nickel salts include capillary damage, kidney damage, myocardial weakness and central nervous system depression.

3.2.6 Ingestion Hazards: Ingestion may cause gastrointestinal irritation with nausea, vomiting and diarrhea.

3.2.7 Inhalation Hazards (Metal Powders): Repeated inhalation may cause allergic respiratory reaction (asthma). Chronic inhalation of metal powders can result in mottling of the lungs, a condition referred to as siderosis.

3.2.8 Reactivity Hazards (Metal powders): When they come in contact with incompatible materials, metal powders can cause hazardous decomposition products. For example, metals such as maraging steels upon contact with mineral acids cause the release of hydrogen gas and may form explosive compounds with air; or aluminum powders may react with water causing the formation of hydrogen.

3.2.9 Decomposition Hazards (Ceramic powders): When burning or at high temperatures, ceramic powders release hazardous decomposition products such as oxides of sulphur and calcium, carbon dioxide and carbon monoxide.

3.2.10 Toxicity Hazards: Exposure to metal dusts and oxides may cause metal fume fever. Many of the metals such as cobalt and nickel are considered possibly carcinogenic to humans.

3.2.11 Chemical Hazards: A risk of damage to the respiratory tract and lungs exists when handling metal powders and filter dusts. It may cause damage to the eyes if metal powder or dust gets into the eyes. Many metal powders and dusts are suspected of being carcinogenic to humans.

3.2.12 Indoor Pollution Hazards (Ceramic powders): Quartz particles of size less than 1 micron stay airborne for extended periods of time, sometimes for several days. These particles are small enough to penetrate and clog the air pockets in lungs and cause silicosis resulting in shortness of breath, cough, bluish skin and fever.

3.3 Equipment hazards

3.3.1 Electrical Energy Hazards: Dangerous voltages of electrical circuits and stored electric charges from electronic components pose life threatening hazards such as serious burns and electrocution.

3.3.2 Electromagnetic Hazards: High frequency devices can interfere with some of the AM machines and result in erratic machine behavior which poses a threat to operating personnel.

3.3.3 Entrapment Hazards: Body or limbs such as hands and legs may get trapped inside a machine enclosure or between moving parts.

3.3.4 Fire and Explosion Hazards: There are explosion hazards from reactive metal-air mixtures. Accidental swirling up of metal powder residues, process-related soot and filter residues in an atmosphere containing oxygen may produce an explosive atmosphere.

3.3.5 General Operational Hazards:

- a) Risk to life from non-functioning and/or malfunctioning safety equipment;
- b) Injuries from slipping on metal dusts; and
- c) Injuries from falling or tripping.

3.3.6 Hazards caused by non-ergonomic equipment:

- a) Operator's position and location of controls;
- b) Difficulty of access for settings, adjustments, powder filling and removal, cleaning; and
- c) Unsafe zone for operation and maintenance of AM equipment.

3.3.7 Hazards from Hot Surfaces: Hot surfaces such as build plate, re-coater blade, electric motors and heater coils have the potential to cause serious burn injuries.

3.3.8 Inert Gas Hazard:

- a) Oxygen depletion;
- b) Inert gas asphyxiation; and
- c) Suffocation from leakage of toxic gases.

3.3.9 Irradiation Hazards: There is a danger of injury from laser radiation and electron beams. When directly looked upon by the naked eye, laser radiation can destroy the retina. Laser radiation (direct or scattered) is dangerous to the skin and can cause burns. It can also cause fires and explosions.

3.3.10 Mechanical Hazards:

- a) Moving parts of the machine;
- b) Sharp edges and corners;
- c) Heavy building platform and build plate;
- d) Broken optical components; and
- e) Pinch point injuries.

3.3.11 Noise Hazards: There can be noise and vibrations from external sources.

3.3.12 Pneumatic Equipment Related Hazards:

- a) Leaks;
- b) Bursting of hoses; and
- c) Whiplashing of unsecured compressed air hoses under pressure.

3.3.13 Compressed Gas Systems: This refers to accidental releases such as compressed air outflows.

3.3.14 Thermal Hazards: This refers to the risk of injury from hot surfaces such as build platform.

3.4 Facility hazards

3.4.1 Air quality hazards:

- a) Inadequate oxygen content in breathing air; and
- b) Suspended particles and contaminants.

3.4.2 Emergency evacuation related hazards:

- a) Insufficient number of emergency exits;
- b) Improper location of emergency exits;
- c) Inaccessibility of egress points; and
- d) Lack of emergency evacuation readiness.

3.4.3 Inadequate first aid measures for:

- a) Burns from powder and dust fires;
- b) Accidental exposure to eyes;
- c) Accidental exposure to body; and
- d) Poisoning from inhalation of inert gases and toxic fumes.

3.4.4 Explosive atmospheres hazards:

- a) Presence of spontaneously inflammable fine metal powder dispersed in air; and
- b) Hazardous ancillary AM equipment.

3.4.5 Fire hazards:

- a) Lack of proper firefighting systems;
- b) Incompatible portable firefighting media;
- c) Incompatible fixed suppression system media;
- d) Insufficient fire rating of facility construction; and
- e) Lack of fire safety training for personnel.

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3.4.6 Non-optimal ambient conditions:

- a) Temperature; and
- b) Humidity levels.

3.4.7 Static electricity hazards:

- a) Generation, accumulation and discharge of static charges;
- b) Dry non-humid ambient conditions;
- c) Insulated surfaces; and
- d) Lack of conductive paths.

4 Units of Measurement

4.1 Values stated without parentheses are the requirement. Values in parentheses are explanatory or approximate information.

4.2 Metric units shall be used throughout this outline unless otherwise mentioned. Imperial equivalents will be used additionally wherever deemed necessary.

5 Normative References

5.1 AM facilities covered by this outline shall comply with the reference standards noted in this section as appropriate for the country where the facility is to be installed. When the facility is intended for use in more than one country, it shall comply with the standards for all countries where it is intended to be installed.

5.2 Any undated reference to a code or standard appearing in the requirements of this outline shall be interpreted as referring to the latest edition of that code or standard.

5.3 Portions of these referenced standards as identified in this outline are essential for compliance. The codes and standards that have been adopted by a jurisdiction control the requirements for Additive Manufacturing equipment placement, facility design and safety requirements. Examples of these codes are listed below.

ASTM Standards

ASTM C33

Standard Specification for Concrete Aggregates

ASTM F2413-11

Standard Specification for Performance Requirements for Protective (Safety) Toe Cap Footwear

EN Standards

EN 143

Respiratory Protective Devices – Particle Filters – Requirements, Testing, Marking

EN 166

Personal Eye-Protection – Specifications

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