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# Reconciling innovation and safety for additive manufacturing in academia

**Dr. Leigh S McCue, George Mason University**

Leigh McCue is a Professor and Chair of George Mason University's Department of Mechanical Engineering.

**Dr. Shaghayegh Bagheri, George Mason University**
**Leanne Wright, George Mason University**
**Kevin Hicks, George Mason University**
**Amrita Ganguly, George Mason University**
**Akriti Bagale, George Mason University**

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## Abstract
Additive manufacturing has quickly expanded and transformed the educational and research landscape, allowing rapid prototyping and local fabrication for researchers, practitioners, and students from a variety of fields. Alongside these advantages, however, the growth of 3D printing technologies has introduced a wide range of health and safety challenges, and safety standards have not kept pace. This has created a challenging regulatory landscape for educators to navigate, as they balance compliance with the need to expand 3D printing capabilities to keep up with advances in research, and/or conduct research in additive manufacturing themselves.

Current fire codes requiring UL listing or field evaluation create significant hurdles for manufacturers and users, and limit flexibility for research applications. Similarly, while UL 2904 GREENGUARD certification provides for testing and assessing particle and chemical emissions of 3D printers, there are no standardized requirements for building ventilation or filtration in rooms supporting additive manufacturing operations, leaving institutions to develop their own approaches. Further complicating matters, modifications of commercial 3D printers in research settings frequently negate compliance with established fire and electrical safety standards.

This paper provides an overview of the health and safety risks associated with additive manufacturing. It provides insight on 3D printing safety policies and practices across U.S. universities, highlighting both common strategies and gaps. Finally, the discussion will examine challenges posed by restrictive fire and electrical standards and propose potential pathways toward balanced, practical solutions that encourage innovation. By doing so, this paper aims to spark dialogue about these issues to ultimately advance a more consistent, evidence-based approach to additive manufacturing safety in academia.


## Introduction
Additive manufacturing is transforming the educational landscape. With inexpensive, user-friendly, 3D printers appearing in elementary school classrooms, maker spaces, and home offices, one would be hard pressed to find a modern engineering program that does not utilize 3D printing in some manner in the curriculum and/or in extracurricular design-build activities. In his 2013 State of the Union address, President Obama touted 3D printing workforce development activities for a manufacturing revolution:

> *"Last year, we created our first manufacturing innovation institute in Youngstown, Ohio. A once-shuttered warehouse is now a state-of-the art lab where new workers are mastering the 3D printing that has the potential to revolutionize the way we make almost everything. There's no reason this can't happen in other towns. So tonight, I'm announcing the launch of three more of these manufacturing hubs, where businesses will partner with the Departments of Defense and Energy to turn regions left behind by globalization into global centers of high-tech jobs. And I ask this Congress to help create a network of fifteen of these hubs and guarantee that the next revolution in manufacturing is Made in America." – Obama, 2013.*[1]

Federal investment in advanced manufacturing more broadly includes the NSF Advanced Manufacturing[2] and Future Manufacturing[3] programs, the Department of Defense's Manufacturing Technology (ManTech) program[4], and the Department of Energy's Advanced Materials and Manufacturing Technologies Office[5]. Academic centers focused on nurturing research, innovation, entrepreneurship, and education in advanced manufacturing are plentiful, for example Virginia Tech's Virginia Tech Made[6], University of Maine's Advanced Manufacturing Center[7], and Marshall's Advanced Manufacturing Center[8] to name a few.

Additive manufacturing, by its nature, attracts tinkerers who embrace rapid technology evolutions. Occupational safety and health best practices, however, are intentionally risk averse, resulting in codes and standards that often lag technological innovation.

**Overview of Health and Safety Risks**

In this section, we summarize known risks associated with airborne emissions and ventilation challenges, electrical safety considerations, chemical safety and burns. This has been studied comprehensively dating back to Stephen Deak's 1999 work[9]. The content is provided here for the sake of comprehensiveness, and to set the stage for subsequent sections discussing fire code requirements, NRTL certification and challenges to academia.

*Airborne Emissions and Ventilation Challenges*

Additive manufacturing processes, particularly material extrusion–based 3D printing, are known to emit volatile organic compounds (VOCs) and ultrafine particles (UFPs) during operation. The magnitude and composition of these emissions are variable and difficult to predict. Differences in print media, extrusion temperatures, printer design, and project run times significantly influence both the type and quantity of airborne contaminants released. Even when printing using similar material types, emission profiles can vary substantially between manufacturers due to differences in filament formulations[10]. These variations complicate efforts to establish uniform exposure controls.

Prior studies have shown that emission levels can increase substantially under certain operating conditions. For instance, Stefaniak et al. (2021) demonstrated that elevated printing temperatures significantly increase ultrafine particle emissions[11], while Azimi et al. (2016) reported that both ultrafine particle and VOC emissions vary widely depending on filament type[12]. Consistent with these findings, workplace evaluations such as those provided in Stefaniak et al. (2019) confirm that real-world exposures occur, but can be effectively reduced through engineering controls such as ventilated enclosures[13].

At present, no long-term epidemiological studies exist evaluating chronic exposure to airborne emissions from additive manufacturing[14,15] and there are no established occupational exposure limits specific to 3D printing–generated particulates or vapors. As a result, there is no known safe level of exposure to airborne print materials.

Compounding this challenge is the absence of formal regulatory standards governing acceptable airborne particulate concentrations or VOC levels specific to additive manufacturing operations. In the absence of enforceable exposure limits, institutions of higher education have been required to develop their own guidance based on precautionary principles, available emissions research, and general industrial ventilation standards. Local exhaust ventilation, filtered enclosures, or a combination of both are typically implemented to control these hazards. Fully enclosed printers equipped with high-efficiency particulate air (HEPA) and activated carbon filtration systems are frequently used to reduce emissions at the source, particularly in spaces where direct exhaust to the outdoors is not feasible. These approaches and standards are largely based on non-regulatory and 3D printer non-specific guidelines published by ANSI/ASHRAE[16], NIOSH/CDC[17], and OSHA[18].

Several third-party filtration certifications are available on the market, including GREENGUARD certification, which evaluates chemical emissions from products used in indoor environments against the UL 2904 3D printing emissions standards[19]. While such certifications may provide some assurance regarding lower-emission materials or filtration effectiveness, they are not specific regulatory requirements and do not replace the need for engineering controls or institutional review and oversight.

A review of ventilation requirements adopted across U.S. universities reveals a wide range of approaches and criteria. Many institutions distinguish between lower-emission filaments, such as polylactic acid (PLA), and higher-emission materials, including acrylonitrile butadiene styrene (ABS), nylon, and composite filaments. Lower-emission materials are commonly permitted in spaces providing a minimum of four air changes per hour, while higher-emission materials often require six or more air changes per hour with single-pass (non-recirculated) exhaust air. Additionally, many universities require environmental health and safety (EHS) review of printer installations, filament types, and anticipated material volumes to ensure that ventilation systems are adequate to protect occupant health.

*Electrical Safety Considerations*

There have been documented incidences of fires caused by 3D printers. EFI Global[20] provides a commentary paper summarizing fire hazards inclusive of example cases; an additional example case was covered by the BBC[21]. Recently, Bambu issued a recall on their A1 printers to mitigate a potential fire risk[22], with trade publication coverage expanding upon the issue[23,24,25]. That is to say, concern about fire risk for 3D printers is not unfounded, though it is unclear how high this risk is by comparison to other common consumer electrical devices.

The electrical and fire safety of 3D printing equipment in research and educational environments is primarily governed by the National Fire Protection Association (NFPA) codes, including NFPA 70 the National Electrical Code (NEC) [26,27] and NFPA 72 the National Fire Alarm and Signaling Code[28]. NFPA 70 establishes minimum requirements for safe electrical design, installation, and operation of equipment to reduce the risk of fire and electrical shock. For 3D printers, this includes requirements related to power supplies, wiring integrity, grounding, overcurrent protection, and the use of listed electrical components. NFPA 72 addresses fire detection, alarm, and signaling systems, including requirements for smoke detection, alarm notification, and system integration within buildings. While NFPA 72 does not regulate 3D printers directly, its requirements influence how 3D printing spaces are designed and monitored.

Nationally Recognized Testing Laboratories (NRTLs), such as Underwriters Laboratories (UL), evaluate the electrical and fire safety of commercial 3D printers[29]. NRTL listing or certification indicates that a device has been tested against consensus safety standards for electrical integrity, thermal performance, and fire resistance. Many fire codes and institutional policies require electrical equipment used in occupied buildings to be listed or certified by a NRTL.

*Chemical Safety and Burn Hazards*

In addition to airborne and electrical risks, additive manufacturing processes present chemical exposure and thermal burn hazards that must be carefully managed. Many filaments, resins, adhesives, and post-processing chemicals used in 3D printing can pose skin, eye, and respiratory irritation risks, particularly when handled without appropriate personal protective equipment (PPE). Safety Data Sheets (SDS) for all materials should be reviewed to understand hazards such as toxicity, sensitization potential, and safe handling procedures. Furthermore, material extrusion printers operate at high temperatures, with nozzle temperatures often exceeding 200 °C and heated build plates at elevated temperatures, creating a recognized risk of thermal injury. These components present a significant risk of contact burns during operation and shortly after use. Additional burn hazards may arise during part removal or when handling recently printed objects that have not yet cooled. To mitigate these risks, users should receive proper training, utilize heat-resistant tools where appropriate, and ensure that guarding or clear labeling is in place to prevent accidental contact with hot surfaces.

**NRTL Certification**

For manufacturers of 3D printers, obtaining a NRTL certification can be challenging due to rapid design iterations, customization, and the research-driven nature of many devices. Certification processes are time- and resource-intensive, posing a significant hurdle particularly for smaller or open-source vendors.

In research environments, compliance with NFPA 70 and 72 and maintaining the integrity of a NRTL certification can be extremely challenging when printers are modified for experimental purposes. Alterations to electrical components, heating elements, firmware, or safety interlocks may invalidate assumptions underlying code compliance and increase fire risk.

As a result, universities must develop alternative compliance pathways for uncertified or modified printers. These may include engineering reviews, fire risk assessments, operational restrictions, enhanced supervision, or the use of secondary containment and fire detection. While these approaches allow continued innovation, they can be complicated and costly. They also underscore the tension between existing certification frameworks and the evolving realities of additive manufacturing in research environments.

The International Fire Code for 2021 and 2024 require UL 2011, 60950-1 or 62368-1 certification of non-industrial 3D printers, UL 2011 certification or field evaluation by an approved agency for industrial 3D printers, or, where approved by the fire code official, may satisfy a performance-based design alternative[30,31]. Our interpretation of the field evaluation requirement is that an approved agency must be a NRTL. Numerous states have adopted the 2021 International Fire Code[32], thereby extending this UL certification requirement to all 3D printers in state owned buildings (e.g. public schools, colleges, and universities). However, few 3D printers are UL certified; a list of those certified via UL Solutions can be found utilizing their Product iQ tool[33]; though products may be certified via other NRTLs to the UL standard. The UL certification requirement, seeking to mitigate hazards, thereby introduces a significant limitation on the variety and capabilities of 3D printers that educational institutions in IFC-adopting states can utilize. UL noted the "dual challenges of keeping pace in the swiftly moving additive manufacturing marketplace, and identifying the applicable safety standards and other regulations for 3D printing equipment…"[34] as they addressed the additive manufacturing industry in 2015. Specific to particle and chemical emissions, UL released GREENGUARD certification for non-industrial 3D printers, UL 2904 in 2019[35].

**Current State of the Art**

Amongst consumer grade 3D printers, defined as printers under $2,500, often used in teaching and research laboratories, market share is dominated by Bambu Lab and Creality 3D who together account for 73% of sales[36,37]. To the best of the authors' knowledge, at the time of this writing, no Bambu Lab printer has UL 2011, UL 60950-1 or UL 62368-1 certification which would satisfy International Fire Code, though some Bambu-branded filaments carry UL 94-2023V-0 flame retardancy[38,39] and Bambu now offers a model with UL 2904 GREENGUARD certification for indoor air quality when using Bambu PLA Basic or PETG HF filament[40]. Creality 3D has UL certification for their power supplies[41], but based on information available to the authors at the time of this writing, it does not appear the printers at this price point are UL certified.

Searching UL Solutions Product iQ for the keyword "3d printer"[42] includes certified printer models by HP Printing and Computing Solutions, Young Optics, Digital Metal, MakerBot Industries, LLC, Formlabs Inc, Osstem Implant Co., Ltd. Many of these printers are industrial, metal or composite, or otherwise specialized. The authors are aware of other makes/models of 3D printers which are certified by other NRTLs to UL standards, for example the Stratasys F900 which advertises TUB listing[43] and multiple models of Ultimaker printer which have DEKRA[44] or eurofins[45,46] certification. Returning to emissions, rather than fire and electrical criteria, Stratasys also reports GREENGUARD certification for multiple models of their printers[47]. That is to say, while there are printers that have received the UL certification required by the International Fire Code of 2021, restricting usage to only those which have certification is a significant restriction on academics, potentially driving purchasers to printers designed for commercial utilization rather than lower cost consumer grade models, printers launched by companies entering the market, or niche printers aligned to research needs of specific projects.

**Challenges to Academia**

It is the opinion of the authors that the existing conflict between International Fire Code requirement for UL certification with the relative scarcity of options of compliant printers puts schools, colleges, Universities, and researchers in a challenging situation. While some may choose to follow common sense guidelines and best practice documents, such as that published by the Snapmaker Team[48], for those seeking to rigorously comply with fire code, e.g. a restriction that presumably applies to every state institution (public schools, colleges, Universities, etc…) in those states which have adopted the International Fire Code of 2021 or 2024, options become independent in situ certification or restricting purchases to the few makes and models which are "listed and labeled in accordance with UL 2011, UL 60950-1 or UL 62368-1."[30] These options are prohibitive and/or costly.

Furthermore, the implications for student-designed printers, modified commercial systems, or fundamental research remain unclear, particularly where research objectives require altering hardware, firmware, materials systems, or safety interlocks in ways that invalidate existing UL certification. Indeed, commercially available printers that may be suitable in stock form are frequently modified to better support education, experimentation, or research and development, placing otherwise compliant devices outside the scope of their original listing. The frank reality is that many public schools, colleges, and universities inevitably operate equipment that does not clearly comply with fire-code requirements.

Compounding this challenge, enforcement and interpretation are typically left to local Authorities Having Jurisdiction (AHJs), resulting in inconsistent application across institutions. In practice, many universities and colleges therefore rely on internal safety reviews, engineering controls, and administrative procedures to manage risk where clear, affordable, and widely available code-compliant equipment is lacking, underscoring the gap between regulatory intent and practical implementation in educational and research environments.

**Future Work**

The project team has efforts underway to survey the current state of higher education environmental health and safety office requirements and/or standards for ventilation and electrical safety. In parallel the team has launched a user-survey to better understand elementary, middle, and high school, college, and university compliance with international fire code requirements.

**Conclusions**

In the decade since the 2015 UL 3D Printing & Additive Manufacturing Equipment Guideline[34] was released, the market for these devices has grown significantly, and continues to grow, with new technology introduction outpacing regulation. For legacy 3D printers manufactured by companies no longer in operation, devices prototyped as part of student design projects, or devices and materials modified for research activities, UL certification is impractical, if not impossible. This challenge is compounded in academic research and development, where modifications to printing processes, materials, or hardware are often essential and can complicate or invalidate any existing certification. In short, the International Fire Code requirements placed upon both industrial and non-industrial 3D printers are inconsistent with the state of the market of 3D printers. These requirements become cumbersome at best, and prohibitive at worst to education and research in academic settings, whereas there is a clear need and priority for education in 3D printing for the future workforce. Furthermore, considering 3D printing safety more broadly, fire code requirements may pose a distraction from concerns related to chemical emissions from 3D printing processes, which anecdotally it appears manufacturers are more eager to address via UL GREENGUARD certification.

More broadly, one might view 3D printing as a proxy of a larger advanced manufacturing boom being driven by increased emphasis on onshoring United States manufacturing. As such, it is our hope that this manuscript sparks discussion on reconciling innovation and safety in 3D printing and advanced manufacturing technologies in academic settings.

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