International Institute for Sustainable Laboratories®

# Best Practices Guide: Laboratory Resilience

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## Introduction

Resilience has emerged as a key concept in navigating an era of increasing uncertainty. While traditional risk analyses can be more reactive and focused on a particular class or suite of hazard types, resilience emphasizes the need to understand the critical functions of a system and taking steps to ensure continuing operability. Resilience recognizes the existence of ever-evolving and increasingly complex disruptors and the importance of finding a dynamic equilibrium amid new realities. A truly resilient approach requires a willingness to spend more time thinking about low-probability, high-consequence events and allowing for more than one possible future. Scenario planning, informed with lessons learned, is a valuable way to identify key areas of vulnerability and to highlight what has (and hasn't) worked to improve resilience within and across systems.

The concept of resilience was formally introduced in the 1970s within the field of ecology (e.g., Holling, 1973). It has enjoyed a renaissance in recent years, including a broader and more formalized application to the built environment. It differs from some definitions of sustainability as it is focused more on continuity of services and not primarily on minimizing environmental impacts—although the ideal approach would achieve both.

### What Is a Lab?

A laboratory is a facility that provides safe and controlled conditions where scientific research, precise measurements, and/or experiments can be conducted. Labs include a variety of functions and types:

- Scientific discipline: biology, chemistry, physics
- Purpose: teaching, research, analytical
- Physical characteristics: dry lab, wet lab, high-bay
- Process: animal facility, cleanroom, tissue culture lab
- Instrument used: NMR lab, microscope lab
- Hazard level: Biosafety Level (BSL-3), Occupational Exposure Band (OEB)

See the Laboratory Resilience section of this guide for a more detailed discussion.

This guide takes the concepts underlying resilience and applies them in a practical way to labs—exploring both the operational and physical aspects necessary for maintaining continuity. The authors explore these key questions:

- How is resilience defined for labs?
- How might it impact how labs are sited, planned, designed, operated, or even funded?

What are the emerging resilience challenges for labs, and how might we learn from recent events to further optimize for resilience?

The intended audience for this guide includes lab owners, operators, programmers, funders, facility owners, design professionals, researchers, and occupants. The focus is squarely on maintaining continuity of services in an age of uncertainty.

The authors explore how resilience can inform physical and operational decisions, as well as investment criteria and business models.

> Resilience is the capacity of individuals, communities, institutions, businesses, and systems to survive, adapt, and thrive no matter what kinds of chronic stresses and acute shocks they experience.
>
> - The Rockefeller Foundation, 2013

We hope to provide sufficient context to illustrate key concepts while delivering a pithy narrative, with clear graphics to make the topic more accessible. As with any first edition, we've condensed some case studies and topics that deserve more attention. We may refine these in subsequent versions. For this edition, we aim to define lab resilience in sufficient detail to encourage a shift in how these facilities are planned, designed, operated, sited, and potentially funded. The end goal is to infuse resilience throughout the lab sector, minimizing disruption to what is often life-changing research.

The first section of this guide focuses on defining resilience broadly, explaining how it differs from risk, exploring how people approach resilience, and identifying key disruptors for labs. The next section translates that theory into practice, highlighting programmatic and systems-level interventions, with a focus on engineering and architectural aspects. Case studies in the matrix provide examples of these concepts in action.

The last section lists high-level considerations related to the business case for resilience, and offers a facility-based "resilience checklist" that can be used to influence larger planning and investment discussions.

## Defining Resilience

Resilience has emerged as a key concept in a world marked by evolving disruptors and increasing uncertainty. It speaks to the ability to maintain continuity in the face of ongoing shocks and stressors. A transformational approach to resilience includes the ability to thrive in the midst of uncertainty and change, rather than simply adapting.

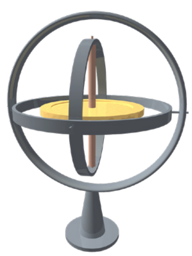


*Figure 1. Like a gyroscope, a laboratory resilience plan aims to support a constant orientation in the midst of a shifting environment. Source: Lucas Vieira, Public domain, via Wikimedia Commons.*

## Envisioning Resilience as a Gyroscope

When thinking of resilience, a gyroscope can offer a useful analogy. Whether we look at the traditional rotating-mass-and-gimbals type that Leon Foucault developed in 1852 to demonstrate the earth's rotation, or the micro-electrical-mechanical types in our phones, gyroscopes have one critical function: providing a constant axial orientation in a shifting environment.

The critical function of a laboratory is carrying on key research, clinical, or other operations. At the micro-level, requirements may include maintaining a certain level of humidity, number of air exchanges, or constant temperature, with the goal of protecting lab users, samples, and/or test subjects (e.g., mice). At a macro-level, resilience may require ongoing access to key supplies, such as particular reagents, testing equipment, and even PPE. Resilience depends on a larger "system of systems," composed of interrelated internal and external drivers. Potential disruptors will impact various levels and intersections.

The recent COVID-19 disruption highlighted both the complexity of these relationships and their related vulnerabilities. This global shock, across all sectors, has provided an opportunity to think about resilience more proactively, more creatively, and, perhaps, with a greater sense of urgency and relevance.

## Starting Where You Are

Ideally, a resilient system reflects all possible future scenarios, incorporates sufficient adaptive capacity, and possesses the flexibility to smoothly transition from one operating state to the next, amid evolving disruptors. However, real-world constraints—financial, economic, temporal, and otherwise—will probably always keep the ideal model in the realm of the theoretical. Nonetheless, having an ideal gives stakeholders something to strive for and allows them to leverage immediate challenges for further learning and capacity-building.

Resilience is not an endpoint but rather a journey toward continual improvement. Extreme events will provoke a predictable chronological order of responses (Figure 2), but steps toward transformation are also possible. This opportunity is often the product of innovation and a keen awareness that returning to past practices (often the focus of the Recovery phases) will not provide a truly resilient "new normal" after the event has passed.

The recent COVID challenge has resulted in several innovations during the response phase. When faced with a shortage of PPE, a process was developed to use ultraviolet light to sterilize

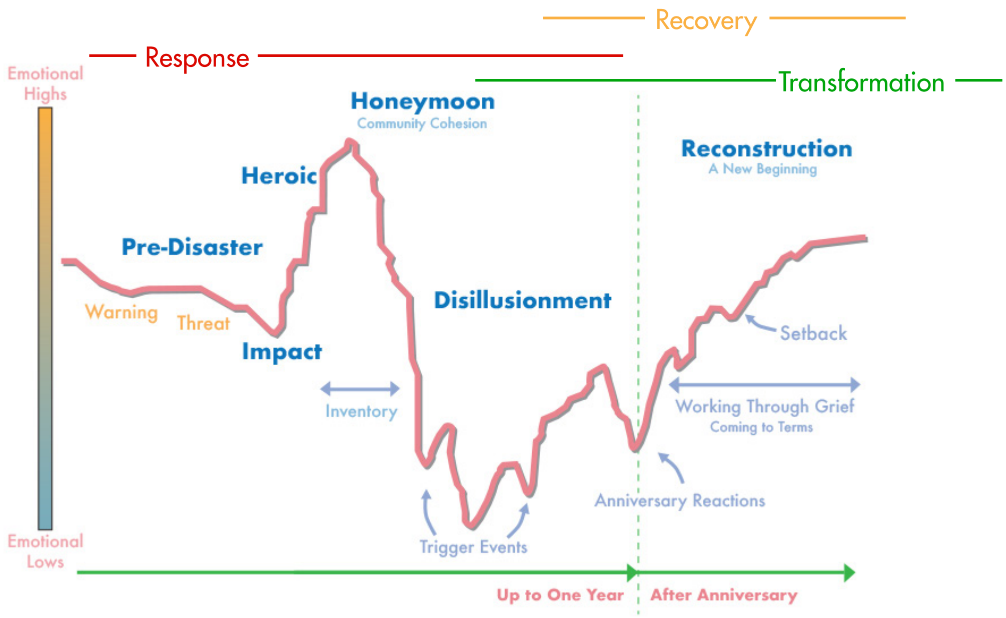



*Figure 2. How people experience extreme events from a behavioral perspective and how that influences whether resilience is approached reactively (immediate response to a particular event, often with a focus on urgent health and safety concerns) or proactively (innovative change that creates a path forward and results in longer-term adaptation). Source: U.S. Dept. of Health & Human Services, Substance Abuse and Mental Health Services Administration*

## Table 1: Typical Areas of Resilience "Focus"

| Time Frame | Activities |
|---|---|
| During the event (Response period) | Immediate health and safety needs<br>Modifying operations to prioritize critical needs<br>Remote working, resilience of staff<br>Meeting immediate needs of client, customer, community |
| After the event (Recovery period) | Sharing and leveraging lessons learned, including innovations<br>Recognizing key areas of failure, opportunities for optimization<br>Developing planning scenarios to test future resilience |
| Transformation (Response, Recovery, and/or Planning period) | Innovating<br>Creating a culture that allows for step change and quick pivots<br>Planning and designing for uncertainty<br>Using resilience to guide longer term strategies and inform near-term decision-making<br>Creating strategies that are implemented before an event, to enhance resilience |

*Table 1. Depending on where you are in your resilience journey, these areas of focus may be at the forefront of your thinking.*

masks for reuse. 3-D printing was used to print much-needed swabs for testing. At an operational level, regulators and vaccine developers developed new knowledge-sharing and review practices that allowed them to work more collaboratively and dramatically shorten times between submission and approvals. All of these represent a willingness to "think outside of the box"—a key element to solving for longer-term resilience amid increasing uncertainty.

Where you are within this journey will necessarily define the types of questions to address. During a crisis, immediate needs are a necessary focus.

The scope will be more tactical and short-term, with an emphasis on urgent health and safety considerations. The Recovery phase will present an opportunity to reflect on lessons learned and to incorporate realizations and innovations in plans for the future. A transformational shift occurs when there is a commitment to planning for the new "abnormal," becoming comfortable with uncertainty, and recognizing that the past will no longer provide a reliable guiding framework.

Realigning around resilience, vs. a more risk-based approach, shifts the focus to the core competencies that must be maintained to ensure continual operation. The concept of operational continuity should apply not only to the lab and its work, but also to the lab's intersection with the larger program of the organization and, in turn, how that entity is supporting the resilience of the larger community. As with COVID, that influence can have global implications.

## Scales of Resilience

The resilience of labs can be framed from different levels and across various hazards. The goal of this guide is to introduce key concepts in framing that approach, accompanied by concrete examples. We want to describe what successful resilience looks like in research organizations, lab operations, and laboratory facility designs. Time is also a consideration, as life expectancies of a lab vary depending on type and associated use (e.g., academic research facility vs. a private pharmaceutical operation).

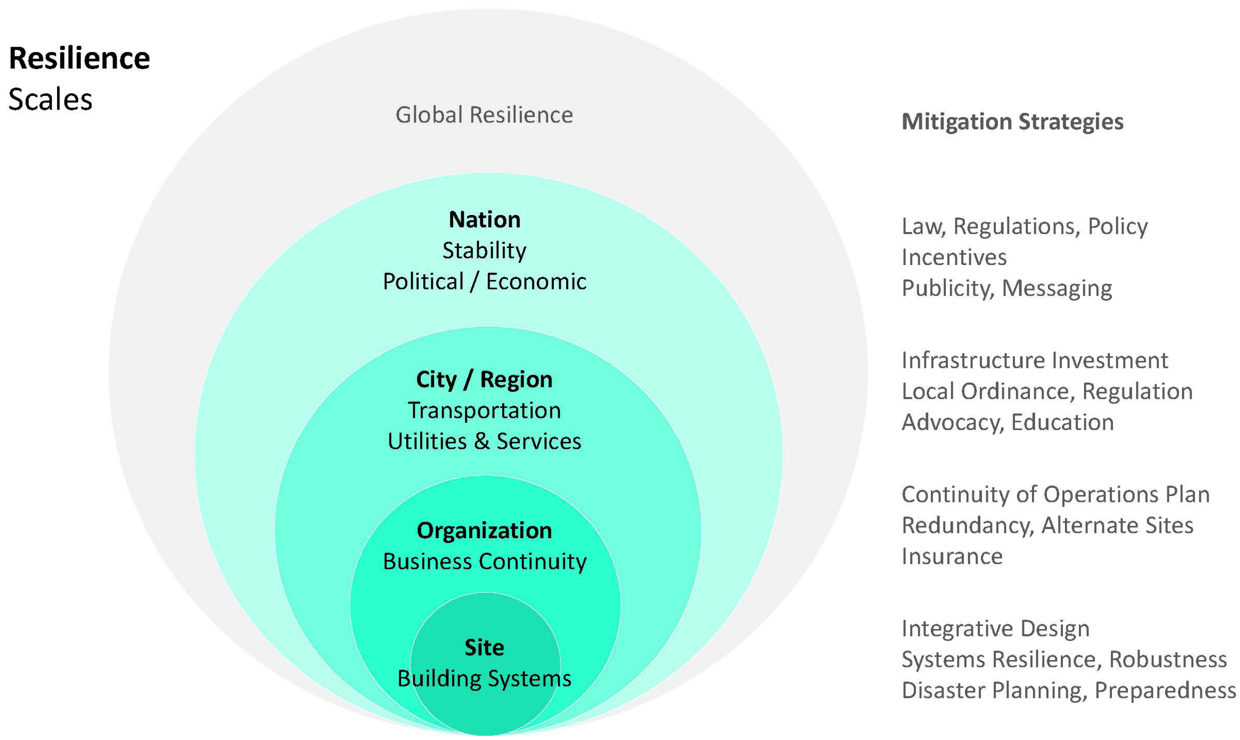



*Figure 3. Scales of resilience, from local to global. Source: Perkins&Will*

## Anticipating Change

Humans have a difficult time anticipating major events or living within prolonged periods of uncertainty. People generally expect the past to be a reliable analogue for present and future conditions. We tend to be reluctant to consider other possible futures, and we thereby develop blind spots around significant areas of vulnerability.

COVID is one such example. For many of us, COVID started out as a seemingly isolated event in Asia, but it grew into a global pandemic in a matter of months. The extent and intensity of the disruption has been sobering; it has stress-tested our social, economic, and political systems. In short, the pandemic delivered an extreme shock to our world.

Was COVID predictable? Some people describe it as a "Black Swan Event," that is, a very low-probability event that cannot be mathematically predicted but which has dire consequences (Taleb, 2007). A Black Swan represents the extreme tail-end member in a distribution of events. More recently, the term "Green Swan" has been introduced to indicate the unpredictable and potentially catastrophic impacts that climate change and other significant environmental perturbations could play in undermining economies (Elikington, 2019).

The counterpart to the Black and Green Swans is the Gray Rhino. The Gray Rhino is described as a known risk that people choose not to act on despite its potential for harm (Wucker, 2017). In some ways, it is analogous to the proverbial elephant in the room.

Subject matter experts warned early on that SARS-CoV-2 could spark a major pandemic (e.g., National Geographic, 2020; BioMedWire, 2020). In retrospect, the COVID-19 crisis was not a Black Swan, but rather a Gray Rhino. Experts had

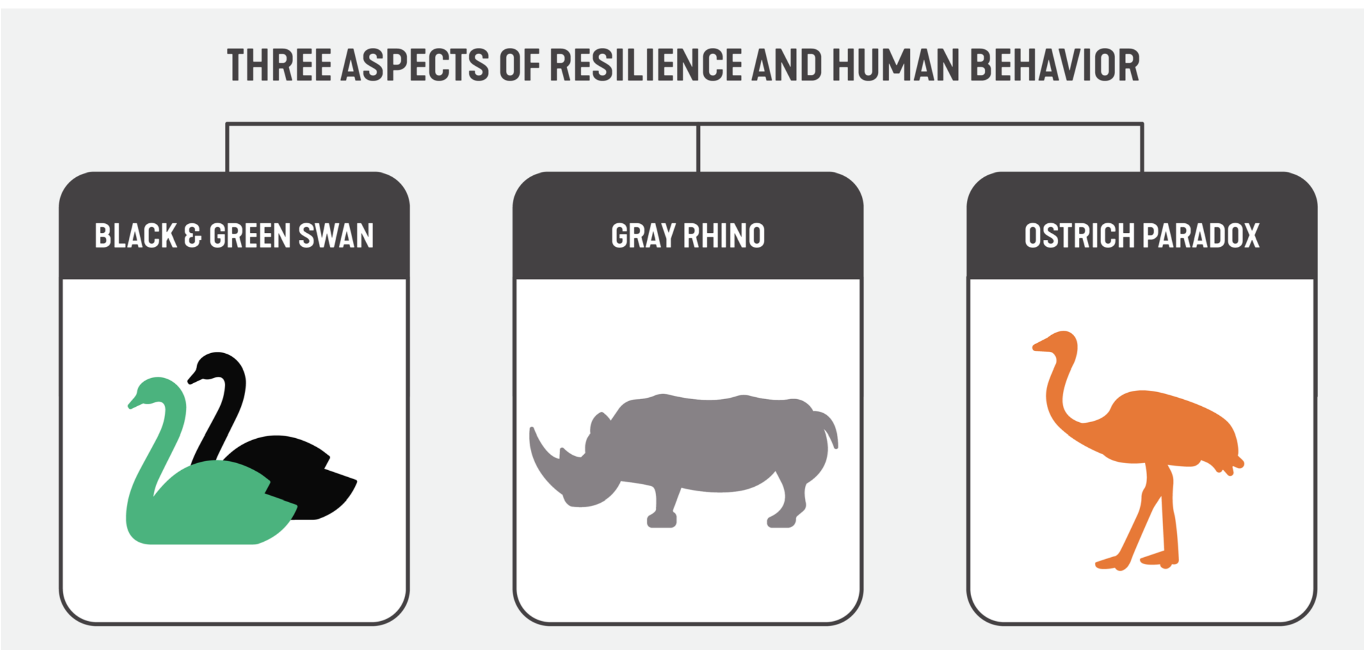



*Figure 4. Three aspects of resilience and human behavior. Source: SmithGroup.*

predicted such a virus for years; it was a known eventuality. But people chose not to prioritize it in their daily decision-making. In fact, it could be argued that the vast majority of all resilience challenges stem from Gray Rhinos and not Black Swans.

People are often reluctant to plan for low-probability events, despite how consequential the potential outcomes might be. In 1981, an epidemiologist, Geoffrey Rose, identified this tendency as the "paradox of preparation": the general feeling that there is a sense of futility and "wasted time" in preparing for low-probability events (Rose, 1981). Given the plethora of past and current disruptions—and the fact that disruptions related to climate change are becoming more frequent and intense, it seems illogical that these types of events fail to figure more prominently in current planning efforts. Why is it that we, as humans, have such trouble anticipating and planning for the eventuality of major disruptors?

To explore the paradox in more detail, Robert Meyer and Howard Kunreuther, a behavioral scientist and economist, joined forces in 2017 and suggested that this type of behavior—which they dubbed the Ostrich Paradox—arose from a confluence of six behavioral "defaults" (Meyer and Kunreuther, 2017):

- Myopia—our tendency to focus on short horizons.
- Amnesia—we often forget the lessons of the past.
- Optimism—this leads us to underestimate the probability of extreme events.
- Inertia—our propensity to maintain the status quo.
- Simplification—we have a difficult time focusing on all the relevant facts.
- Herding—our tendency to follow our neighbors and peers.

Developing an awareness of these tendencies could force us to be more cognizant of low-probability, high-consequence events. In fact, disruptors rarely occur as discrete events—instead, several are likely to occur simultaneously (e.g., pandemic, mandated shut-downs, supply-chain failures), each with its unique "fingerprint" with respect to intensity, frequency, and duration of impact. Breaking out of the Ostrich Paradox forces us to see our dependencies on external services, as well as how a lack of resilience in our own systems could impact the larger community. All of these considerations are essential when planning for resilience.

## Disruptors

The ability to maintain critical functionality of a system—its overall resilience—is constantly challenged by a variety of disruptors. These can occur within a system or be generated from external sources. As our world becomes more complex, so do the types and numbers of disruptors, accompanied by an increase in the probability and consequence of those disruptors. The World Economic Forum performs a yearly assessment of the top global risks across a range of socio-political, economic, and environmental categories (Figure 5). These risks are assessed both by the likelihood of occurrence, as well as their overall impact.

It is interesting to note that, though the impact of infectious disease was long-noted as being potentially significant (ranked the 10th highest under the Impact category), it did not even make the list of predicted "likely" events for 2019. As discussed previously, the current COVID crisis wasn't a Black Swan event that could not have been predicted, but rather a Gray Rhino event that most people chose to ignore—even in the face of previous predictions by subject matter experts.

**Long-Term Risk Outlook**

Top 10 risks by likelihood and impact over the next 10 years

**Multistakeholders**

| Likelihood | Impact |
|---|---|
| Extreme weather | Climate action failure |
| Climate action failure | Weapons of mass destruction |
| Natural disaster | Biodiversity loss |
| Biodiversity loss | Extreme weather |
| Human-made environmental disasters | Water crises |
| Data fraud or theft | Information infrastructure breakdown |
| Cyberattacks | Natural disasters |
| Water crises | Cyberattacks |
| Global governance failure | Human-made environmental disasters |
| Asset bubble | Infectious diseases |

*Figure 5. Long-term risk issues (multiple stakeholders). Source: World Economic Forum's Global Risk Report 2020 (World 2020).*

If we were to construct a similar ranking for labs, key areas of impact and likelihood would include deferred maintenance, obsolescence, climate change, natural hazards, pandemics, supply chains, and security. In fact, we suggest that in future years, a WEF-style exercise (a survey of perceived risks by lab owners and operators) be carried out within the I$^2$SL community to produce a similar, lab-focused Risk Report. For the purpose of this guide, we will focus our discussions around the previously listed disruptors. With that said, uncertainty and disruption are common to all hazards and solutions, and solving for one hazard has the potential to increase resilience to another.

### Deferred Maintenance

Deferred maintenance is an ongoing challenge throughout the built environment. In the U.S. alone, ASCE (2017) has estimated that there will be a $4 trillion gap in necessary infrastructure funding by 2030. This represents nearly 20% of the entire U.S. GDP, and a large percentage comes from aging infrastructure and deferred maintenance. The latest report (ASCE 2021) shows an ever-increasing gap.

For labs, deferred maintenance in combination with obsolescence can create a formidable challenge for annual budgeting and operational needs. Asset management programs can be useful in tracking the expected life of building systems, expected annual maintenance costs, scheduled replacements of key components and equipment, expected facility staff support hours, and so on. However, even with such systems in place, maintenance needs—particularly preventative ones—are often treated with less urgency than capital investments and/or emergency repairs. This results in a slow accumulation of deferred maintenance needs that, within even a decade, can become quite daunting.

Many lab owners and other shareholders have a growing appreciation of this backlog and the need for a more holistic assessment of life cycle costing. Within these analyses, physical impacts and operational considerations should be factored in, including the costs associated with continuity disruptions. The latter is often a key factor in determining the consequence of such a failure, and a useful tool in prioritizing need.

### Obsolescence

Designing a lasting laboratory is increasingly complicated.

Research needs change, technologies change, and the supporting infrastructure (e.g., electrification of the grid, carbon tax) changes. Lab planners, architects, and engineers have long considered issues of evolving building codes, research priorities, workplace norms, and user expectations. Designers have looked to accommodate these shifting priorities with architectural modularity, using open, reconfigurable, and reassignable lab spaces; allowing for conversion from dry-to-wet or wet-to-dry lab functions; and other accommodations to provide flexibility. Similarly, robust and accessible vertical and horizontal mechanical pathways can accommodate years of change in initial and undefined future ducts, piping, and wireways.

Flexibility will remain an essential component of resilient lab design, though the scope of what is meant by "obsolescence" may be expanded. Technological advances are perhaps the least predictable and most challenging changes to accommodate. Examples include the growth of computational research, the near horizon of robotic researchers, new generations of laboratory equipment, and the transition to an agile workforce. Labs will also face evolving external factors, including demographic shifts, climate change, and potentially even shifting political and regulatory considerations. A lab will need to be ultra-flexible to accommodate a wide variety of people, many styles of working, different and highly specialized research needs, and growing uncertainty.

### Security Risks

Labs have faced increased scrutiny, both by regulatory agencies and the public, in the past decade. Controversies involving scientific research and an increasing global presence have heightened security threats on both the physical and digital fronts. Espionage, both political and industrial, is an growing challenge for all kinds of research groups, from government labs, to universities, to corporations. Physical threats include intrusions, theft, and sabotage. Digital threats include a range of malicious behavior, from sophisticated IP theft to more randomized attacks. Examples include animal rights groups breaking into a facility to "liberate" research animals; criminals gaining access to university labs to steal laptops; and hackers use phishing attacks to steal research data. Ransomware, used by criminals to extort money, has also affected these types of facilities.

Security threats may be the most difficult type of risk to predict since they are perpetuated by people whose intentions can vary widely and who often fly under the radar until the threat event. Fortunately, security practices meant to deal with physical threats are well-established, and cybersecurity protocols are rapidly evolving. Even with the unpredictable nature of each, standard planning and preparedness practices can improve resilience to security threats by reducing the threats, mitigating their effects, and making recovery easier.

### Pandemics

Recent studies have suggested that pandemics and more regional epidemics may occur with greater frequency moving forward (Morens and Fauci, 2020). SARS, MERS, Ebola and H1N1 are all examples of significant outbreaks that have occurred within the last 20 years alone. Epidemics may become a long-term stressor with intermittent shocks. Some of those events may be localized, others could be more widespread, as with SARS-CoV-2.

Suppose projections are correct and epidemics do become more common and extensive, and suppose this happens amid increasing climate change impacts. Would lab stakeholders need to significantly change practices? Are current business models even valid in the context of these increasing challenges? How do we move from a reactive system to a more thoughtful, planned system with adequate adaptive capacity to accommodate this level of uncertainty?

Pop-up COVID-19 testing facilities, social distancing accommodations, and digital "reassurance" technologies focused on health and safety show how some facilities are striving to adapt and respond. Expect future changes as the threat of pandemics and epidemics continues.

### Climate Change

Until recently, historic weather patterns have been used to inform design. The implicit assumption has been that while there has been yearly variability in particular weather phenomenon, the overall trend would remain the same. In other words, the annual volume of precipitation, when averaged over several years and decades, would fall within a predictable range. The 1 in 100 year (or 1%) coastal flooding event would always yield a predictable maximum surge level and ice pack would remain constant. The number of extreme heat days (and associated heat waves) would not exceed a particular cap, etc. We now have evidence that climate change is negating these past assumptions. We are, in fact, seeing trends including an increase in the intensity and frequency of extreme weather events. Climate is also seen exacerbating other vulnerabilities—such as drought and wildfire risk.

This shift in environmental conditions has caused owners, operators, and designers of those assets to revisit previous assumptions. Base designs are starting to be informed by future climate projections. While there are industry examples of best practice, building codes and other design guidance have been slow to formalize protocols. Even if such criteria were more widely available, the overall risk tolerance for particular holdings, and even assets or uses, can be variable across different lab owners, as well as within their own facilities. Therefore, there is a degree of customization (and therefore the need to maintain some level of flexibility within the code) that will continue to be required. With that said, there is a growing archive of design projects—informed by academic advisors, owners, end-users, and climate experts—that can be used to frame a first-order assessment and prioritization of need, as well as action items moving forward.

### Supply Chain Vulnerability

Previously, labs would have sufficient storage space to allow for the bulk-ordering of PPE, glassware, and supplies. That business model has shifted, with many facilities now reliant on just-in-time delivery. With decreasing storage needs, and facing cost pressures, many lab buildings no longer have dedicated stock rooms, receiving areas, or staffed loading docks.

Labs now may have only a small exterior dock, or share a dock with several buildings. Also gone are large, basement stockrooms with a wide array of lab supplies—and the staff to service them. Now delivery companies carry on-line purchases right to the door.

COVID highlighted the lack of resilience as supply chains, many of which are global in scale, became over-leveraged. Adequate supplies, the ability to transport those supplies, and last-mile delivery challenges once the supplies arrived all became issues. The pandemic also introduced new types of vulnerabilities, such as competition for PPE between hospitals and essential operations such as grocery stores and public transit. These disruptions led to some innovative solutions on both the production and operational fronts; however, they

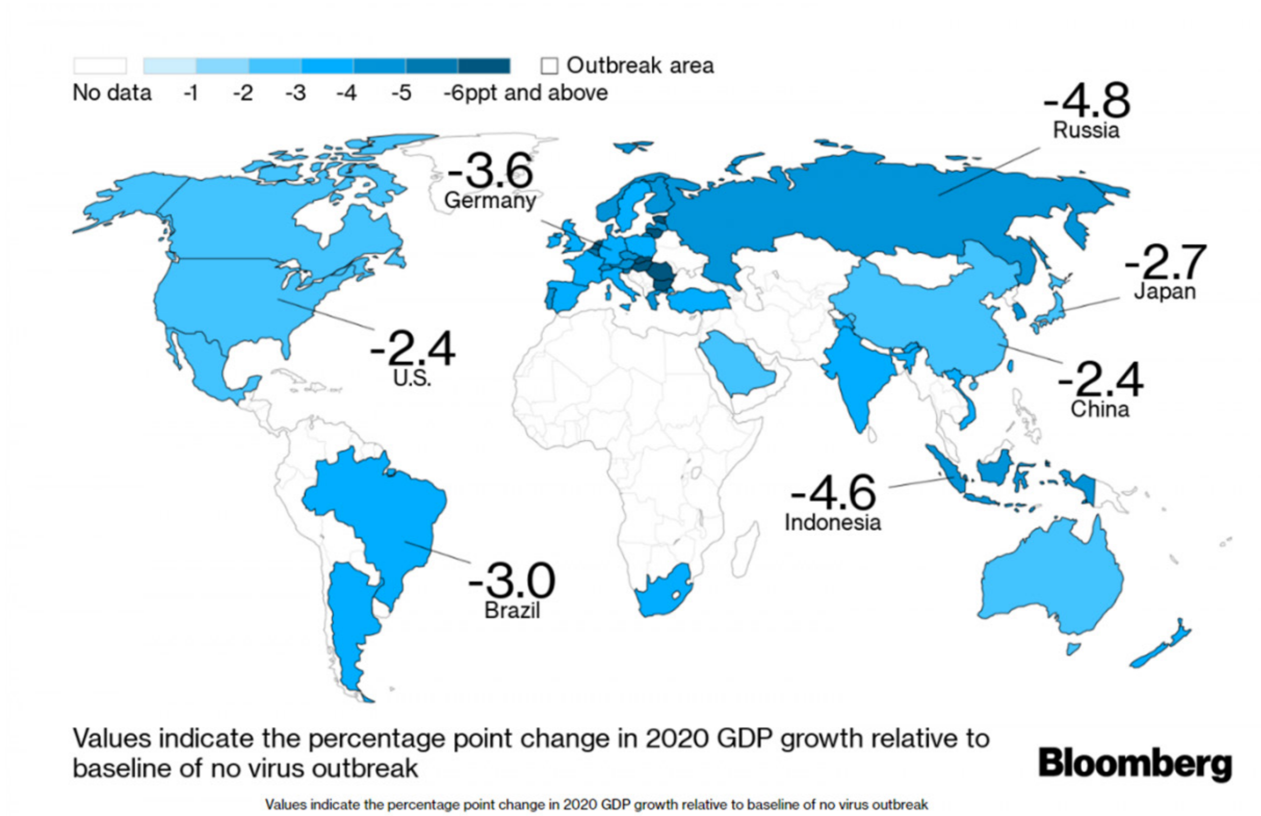



*Figure 6. A recent Bloomberg report estimated that there would be a $2.7 trillion impact to the global economy as a result of COVID. While this is a significant figure, it is eclipsed by the anticipated economic disruption that could occur with climate change, estimated at as much as $54 trillion as early as 2040. This is just another reminder of the need to think of resilience holistically, across various disruptors, geographies, systems, and time frames. Source: Orlik et al., 2020.*

also highlighted over-dependence on some global supply chains, coupled with a lack of adequate manufacturing capacity in the U.S. An anticipated increase in geo-political uncertainty could further erode supply chain resilience (World Economic Forum, 2020).

Laboratories depend upon a robust global supply chain for consumable products of all kinds, from PPE, to chemicals, to diesel fuel for emergency generators. Supply disruptions can have dramatic consequences for lab operations, regardless of the facility's hardening features, redundant systems, and operational preparedness. As we witnessed with COVID-19, the lab supply chain can be very fragile—especially when supplies include PPE and reagents desperately needed by the healthcare system. Relying on "just in time" materials may become risky.

Labs may be forced to reconsider pre-purchasing critical materials and storing them on site. Future designs may see a resurgence of the "receiving area," "stock room," and "supply closet" that many thought extinct.

**External Dependencies**

Local sites and building systems often depend on external factors.

These include "upstream" utilities such as electricity, water, and natural gas, as well as "downstream" utilities, like sanitary and storm sewer. Disruption to incoming water may prevent the use of lab sinks and equipment; similarly, inability to drain wastewater may also prevent their use—not to mention creating waste-holding problems.

External dependencies may be highly complex. For example, electrical power may depend on an electrical utility. In that case, power at the lab depends on the utility generation facility, on power lines from the utility to the building, and on electrical equipment in line. Damage or disruption to any element may stop the flow of power. Even backup power may entail external dependence, as diesel generators depend on a fuel delivery truck.

External dependencies include many other, subtler systems as well. Transportation networks are critical. Without passable roads or working public transit, personnel may be unable to reach the lab, or they may become stranded within the facility. Supplies cannot reach the facility, and operations may become impossible.

Similarly, communications are critical to both disaster response and to normal operations. Without internet, telephone, or cellphone communications, lab personnel will be unable to coordinate operations.

## Laboratory Resilience

The primary function of labs is to advance scientific research or to provide clinical services that will increase the quality of life for people and, in many cases, the health of the planet overall. Areas of focus and expertise vary within organizations and even within labs. Teaching labs focus on educating the future workforce and the community. Research labs focus on discovery and innovation. Applied research laboratories focus on developing new processes and products. Many labs are dedicated to missions like advancing human understanding, curing disease, mitigating environmental impacts, or solving societal challenges.

Resilience is the concept that ensures labs continue to meet those primary objectives. It often starts by identifying key performance criteria (e.g., must be able to operate for 96 hours; production of batches that cannot be interrupted). When criteria are identified, the physical and operational aspects can be put in place (through building or retrofitting) to ensure that those objectives can be met, accounting for a variety of disruptors. Some solutions will be readily within the control of the owner/operator (e.g., size of building, type of backup power onsite, overall programming of space). Others will be dependent on external parties (e.g., regional energy grid, transportation systems, supply chain).


*Figure 7. The idea of external dependencies is well understood in the emergency preparedness field. FEMA has highlighted key "Community Lifelines" that they see as essential for resilience. These same concepts are relevant to lab resilience. Source: FEMA, 2021.*

## What Has Already Been Said About Lab Resilience?

Previous studies have explored the application of disaster planning and preparedness to research and laboratory settings. A 2014 publication by the U.S. Dept. of Health and Human Services provided an exemplary review of post-Superstorm Sandy impacts to healthcare, which also included research labs (Guenther and Balbus, 2014). This narrative detailed both anticipated and, more important, many of the unanticipated failures that arose from an under-appreciation of cumulative impacts, the realization that such an event could happen, and the level of interconnectedness (both physical and operational) across various systems. The paper created a framework for assessing the general resilience of a healthcare setting (labs included) and laid the groundwork for self-assessments of preparedness through a recommended checklist.

The HHS' proposed Framework for Resilient Healthcare Settings included:

- Climate Risks and Community Vulnerability Assessment
- Land Use, Building Design, and Regulatory Context
- Infrastructure Protection and Resilience Planning
- Essential Clinical Care Service Delivery Planning
- Environmental Protection and Ecosystem Adaptations

In 2017, the National Academy of Sciences released a preparedness publication focused on the academic biomedical research community (Benjamin, Brown, and Carlin, 2017). While this publication focuses solely on academic facilities, it provides criteria and insights relevant across all labs. The report addresses how resilience can be achieved by leveraging lessons from prior disasters to inform a resilience strategy, including emergency response planning, recovery efforts and priorities, and capital planning considerations.

The Facilities Guidelines Institute (FGI) Emergency Conditions Committee has recently released a draft white paper providing guidance on designing health and residential care facilities that can adapt during emergency conditions (FGI, 2021). Revision after input from the health and residential care communities is expected.

## Laboratory Type

Laboratories vary considerably in purpose, function, size, shape, location, and operations. A lab may be a small facility for teaching science to children, a multi-story university facility for cancer research, or a large industrial facility for electronics product development. Labs are distinguished from other facilities by their dual purpose: to provide for occupant safety and to allow controlled experimental conditions.

The concept of laboratory type is often used to describe the characteristics or needs of a lab facility. In resilience terms, these are the "critical functions" of the laboratory type. Lab type may be described in many ways, for example by:

- Scientific discipline: biology, chemistry, physics
- Purpose: teaching, research, analytical
- Physical characteristics: dry lab, wet lab, high-bay
- Process: animal facility, cleanroom, tissue culture lab
- Instrument used: NMR lab, microscope lab
- Hazard level: Biosafety Level (BSL3), Occupational Exposure Band (OEB)

Lab type can be a useful framework for evaluating resilience. Examining laboratory type may help clarify the primary drivers of safety or experimental conditions for a particular facility (the critical functions). For example, a teaching lab may be primarily concerned with student safety, while an animal research lab may have a dual obligation to both human and animal health. The illustrations in Figure 8 describe some example resilience drivers by laboratory type.

## Minimal Operating Criteria Based on Lab Type / Critical Function

A laboratory's critical functions determine which systems and procedures are required for safe and effective operations. For some labs, even a temporary loss of a single mechanical system can be catastrophic. For others, prolonged utility outages are tolerable, provided that physical damage to the lab proper is avoided. Lab usage and specific needs drive system dependency. This is called the "minimal operating criteria."

System dependency can be complex. Complete loss of a system, even for a prolonged period, may be fine, provided other essential systems are intact. In the example (Figure 8), dry labs for physics or engineering research may be able to tolerate loss of domestic water, but are sensitive to loss of power. Evaluating dependencies requires systems thinking. Again, in the example, the dry lab's ventilation requires electrical power to run the HVAC system fans, and it may also require a heating source to prevent freezing in winter. Thus, the dry lab requires ventilation, heating, and power as minimum operating criteria.

Expectations also have a huge effect on minimum operating criteria. Labs that expect to continue with full operations during a disruption require substantially more robust systems, with redundancy. Animal research facilities and cleanrooms would be in this category. Labs that simply expect a safe shutdown and evacuation may be able to accept less. For these facilities, minimizing structural damage and protecting critical samples may be the primary resilience objectives. Many laboratories assume they are in this category.

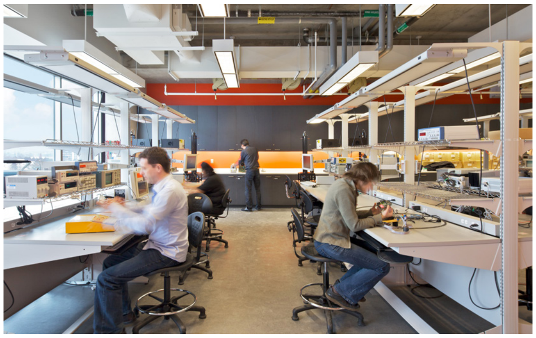
Labs that expect only to withstand the event, and that can tolerate superficial damage, may require even less system robustness. Unfortunately, without resilience planning, many labs find themselves involuntarily in this category (or worse), when unanticipated system failures arise.

## Design Considerations for Resilience

Design considerations for resilience are informed by a deep understanding of operational needs, and how to ensure critical functionality of those key systems in the context of uncertainty. Translating operational needs into design solutions requires the ability to consider all the ways the systems could be challenged and how to build in sufficient flexibility and redundancy. Design for resilience requires sufficient adaptive capacity for business continuity when facing one or more disruptors.

Sometimes it may be useful to think of resilience in terms of a specific hazard, or disruptor (Table 2, page 17). At other times, it's better to approach the subject from the perspective of a specific building system. We have attempted to accommodate both approaches, recognizing there will be some level of overlap, and therefore repetition within certain themes.

In addition to system types and disruptors, we have categorized lab types on a scale of dependence on systems, increasing generally from left to right in Table 3 (page 18), with office and write-up spaces the least dependent, and core labs, cleanrooms and vivaria among the most dependent.



**Physics/Engineering**
Physical damage
Instrument / electronics damage

**Biology**
Loss of samples / tissues / cells
Contamination of experiments

**Chemistry**
Safety / industrial hygiene
Fire / chemical spill

**Animal Facility**
Animal health / life support
Worker safety

**Cleanroom**
Loss of clean class / recertification
Safe shutdown

**Biocontainment**
Many site-specific concerns

*Figure 8. Lab types and example resilience concerns. Source: Perkins&Will. Credits: Physics, Lisa Logan Photography; Biology, Michael Robinson; Chemistry, Robert Benson; Animal Facility, Alain Jaramillo; Cleanroom, Charles David Smith; Biocontainment, Perkins&Will.*

Similarly, we have categorized disruptors on a scale of immediacy in Table 2, with terrorist activity, earthquakes and fire among the most immediate—meaning those offering the least time for advance preparation—and climate change and obsolescence among the least immediate. The distinction may influence the choice between a design mitigation feature (e.g., shatterproof glass) and a procedural solution (e.g., board up windows before a storm).

## Design Considerations by Disruptor Type

We first address the disruptor side of the matrix, as discussed in Table 2.

### Activist / Terrorist

Activist and terrorist threats must be assessed on a situation- or project-specific basis. Considerations range from targeted protests, to civil unrest, to armed intruders, to utility severance, to explosives. Strategic laboratory programming and planning can arrange spaces to make them less visible, less vulnerable, and easier to harden. Architectural design can address hardening of glazing/walls/structures, progressive collapse, vestibules that can trap and apprehend an intruder, and all aspects of vivarium operations.

### Earthquake, Mudslide, Unstable Soils

Earthquake-resistant design, while an established practice, may require in-depth consideration of potentially changing geotechnical conditions (e.g., fracking, drought, flooding, or other destabilizers). A plausible risk of land/mudslide damage should foster geo-technical and structural design measures for protection (e.g., outboard site retaining walls, viable paths around the lab) or for enhanced survival (e.g., fortified building walls) as a given locale may indicate.

### Wildfires and Uncontrolled Fires From Other Events

Fire and smoke have become recurring threats in many areas. Though external fire spread to lab buildings may not be well-codified, consider using massive non-combustible materials for exterior envelopes, protection of entrances, and air intakes at the top of multi-story buildings (with verification of exhaust dispersion for the lab and neighbors). Addressing particulate and gas-phase filtration may double as a response for air-intake-tampering risk. For research on IAQ measurements during California wildfires, see Pantelic et al., 2019.

### Hurricane, Tornado, and High Winds

Building envelope hardening may involve laminated/reinforced glazing systems, structures with progressive collapse-resistant design, elevated/protected air intakes, physical monitoring, intruder-retaining vestibules, walls around exterior tanks, and concealing functions of activist concern. Wind events are also a major cause of electrical service interruptions.

### Storms and Flooding

Floods have caused some of the greatest recorded laboratory losses, and the range of labs exposed to these threats is increasing with climate change, so we delve a bit deeper here.

Where flooding is plausible, configuring lower levels as much for infrastructure resilience as for access and amenities becomes a new architectural driver. Basement spaces—where MEP equipment has historically been relegated—may be intentionally avoided in new construction, or floodproofed to the extent feasible and assigned to more expendable program functions. Major renovations may allow basements to be filled in to eliminate issues of flood recovery, however infrequent.

Elevating substations, switchgear, generators, central HVAC and lab services to mezzanine,

## Table 2: Impacts and Disruptors

| Building System Impacts | From immediate threat > > to long term concern | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Activist, terrorist | Earth-quake | Fire in or outside | Tornado, hurricane | Storm, flood | Pandemic | Climate change | Obsoles-cense |
| Structure | D | D | D | D | D | | | D |
| Envelope / Exterior | D | D | D | D | D | I | | |
| Interior / Finishes | D | D | D | D | D | D | | D |
| Domestic Water | D | D | R | R | D | I | D | |
| Sewer / Lab Waste | R | D | R | R | R | I | | |
| Storm Drainage | R | D | R | R | R | | D | |
| Heating / Cooling | D | D | D | D | D | D | D | D |
| Ventilation / Exhaust | D | I | D | D | | D | D | D |
| Normal Power | D | D | D | D | D | | I | |
| Standby Power | D | I | I | I | D | | | |
| Data / Communic. | D | D | R | R | R | | | D |
| Service / Supplies | D | I | D | I | D | D | | |

**D** = *Direct threat to building,* **I** = *Indirect threat via disruption of supply,* **R** = *Regional threat from infrastructure failure*

*Table 2. System impacts by disruptor type.*

second-story, or penthouse levels requires a balancing act with traditional priorities of architectural design. If anticipated maximum water elevation is low relative to first-floor overhead structure, nominally "first-floor" equipment space for fire pumps, domestic water pumps, and lab services may simply be elevated on compacted fill, ideally with separate exterior access. Otherwise, they may be lifted above suitable functions as first-floor mezzanines, ideally avoiding the disruption of repetitious lab floor plates and fenestration that architects and lab planners often begin on the second level. Short of elevating equipment, flood walls and gates may be considered, with plans for an expeditious return to service if breached.

Routing many external services directly to a penthouse may offer synergy in source-to-load proximity, and may best accommodate architectural massing and fenestration design, though it complicates structural and equipment ingress design and requires special protection of high-voltage feeds. As noted above, fire and domestic water pumps are rarely candidates for this strategy, given their need for a minimum

## Table 3: Space Type Concerns

| Office / Writeup | Class Labs | Dry Labs | Wet Labs Life Science | Wet Labs Chemistry | Core Labs / Clean Labs | Animal Care | Biosafety BSL-3+ | Building System Impacts |
|---|---|---|---|---|---|---|---|---|
| Space types example concerns, increasing criticality - - - > | | | | | | | | |
| Safety | Safety | Vibration | Vibration | Vibration | Vibration | Vibration | Vibration | Structure |
| Weather-tight | Weather-tight | RH Control | Pressure | Pressure | Env. Control | Env. Control | Env. Control | Envelope / Exterior |
| Downtime | Downtime | Damage | Contam. | Samples | Certifica-tion | Animal Care | Exposure | Interior / Finishes |
| Downtime | Downtime | Downtime | Downtime | Downtime | Services | Animal Care | Safety | Domestic Water |
| Downtime | Downtime | Downtime | Downtime | Downtime | Downtime | Animal Care | Safety | Sewer / Lab Waste |
| Flooding | Flooding | Flooding | Flooding | Flooding | Flooding | Flooding | Flooding | Storm Drainage |
| | | Safety | Safety | Safety | Safety | Vivaria | Operate | Heating / Cooling |
| | | Safety | Biology | Chemical | Process | Vivaria | Operate | Ventilation / Exh. |
| | | Operate | Operate | Operate | Operate | Operate | Operate | Normal Power |
| Data | Data | Process | Samples | Process | Clean-room | Vivaria | Operate | Standby Power |
| | | Operate | Operate | Operate | Operate | Operate | Operate | Data / Communic. |
| | | | Operate | Operate | Operate | Operate | Operate | Service / Supplies |

*This table represents example concerns. These will vary according to individual lab operations.*

*Table 3. System impacts by space type.*

suction pressure and/or direct exterior access. Fire command rooms are another function requiring near-grade placement.

The particular vulnerability of elevator pits requires special consideration. FEMA requires elevator components subject to flooding to have corrosion resistance and other special provisions, vs. those never expected to see water (FEMA, 2019). For new building design, if feasible, consider avoiding basements and raising the first-floor elevation to be clearly above the flood threat levels. If necessary, consider the combination of an elevated main elevator lobby with accessible ramp and shuttle elevator access, recognizing that shuttle service may be disrupted.

For existing buildings, barring a major renovation, the challenging alternative may be a positive means for temporary physical isolation of elevators during an event. Considerations include practical mobilization, durable effectiveness, and maintained ingress/egress. As a last resort, provisions for accommodating a flood event may be investigated, given an interim loss of service, with the intent on rapid recovery and reinstatement of viable elevator service.

Exterior equipment, such as liquid/gaseous nitrogen, other delivered gasses, generators, trash compactors, lab waste monitoring wells, and other services may require creative site design involving available topography, platforms, or special arrangements with service providers.

### Pandemics

Addressing COVID-19 and the specter of future pandemics requires an integrated approach with HVAC, architecture, operational considerations, and commitments to responsible individual action.

Regarding HVAC, the airborne primary transmission path of SARS-CoV-2 may be addressed at one level by the inherent high ventilation rates, once-through airflow, and high filtration associated with many existing laboratory HVAC systems. However, further analysis would address the HVAC drivers of individual labs (e.g., ventilation rate, hood exhaust, thermal load/reheat); air movement within labs (e.g., diffusers, exhausts); space pressure differentials or intentional transfer of air from non-lab areas (e.g., human contamination, base filtration); cross-contamination from energy recovery systems; and potential exhaust re-entrainment. Many of these aspects can benefit from detailed CFD analysis.

In terms of HVAC system selection for future labs, SARS-CoV-2 may increase attention to key, low-entropy strategies that separate lab ventilation load from lab thermal loads, particularly where such is advanced by the presence of locally recirculating air via chilled beams, chilled boxes, fan coils, variable refrigerant flow terminals, or chilled sails with destratification fans. Chilled boxes and other fan-based terminals offer the opportunity to include MERV-13 local filtration for local capture of bio-aerosols, with or without additional purification means. Chilled sails with destratification fans offer particular synergy with upper room UV germicidal irradiation (UVGI) as an ultra-low-energy means of treating higher-occupancy write-up and collaboration areas before such air is transferred to lab spaces.

UVGI purification can have the same impact on COVID as multiplying outside air change rates, without the high energy cost or system impact. It also has the support of nearly a century of practice. In contrast, other air purification methods offer significant promise but with a wide range in the level of industry-standardized guidance. The IES has a useful recent paper on the subject of germicidal UV (IES, 2020).

In-duct UV-C light can deactivate organic content—often installed downstream of wet cooling coils to attack biofilm production—though increasing UV “dosage” can also achieve a high kill-rate in supply air bioaerosol content for central systems with recirculating air or in local fan-based terminal units. (The use of shorter wavelength light, called FAR-UV, at 222 nanometers, is a much newer technology that some claim allows direct exposure to full rooms, though its long-term safety has not been established.)

Bipolar ionization may activate in-room air to disable microorganisms, dismantle volatile organic compounds, and agglomerate ultra-fine material for enhanced filter capture. The benchmark for this technology is outdoor air, which has many times the positive and negative ion concentration of indoor air. However, industry-wide guidance is still being sought for this technology, and selection considerations include proof of zero ozone production (UL 2998 confirmation is advised), the potential for partial dismantling of organic compounds into other compounds of concern, minimizing recurring maintenance, ion longevity as applied, and assessment of whether a biological lab's research operations (petri-dish or more automated cultivation) might be influenced by any technology that actively disables microorganisms.

Maintaining relative humidity between 40 and 60% RH has been shown to reduce the rapid desiccation of aerosols into long-traveling nuclei; to reduce viral longevity in aerosols/nuclei and on surfaces; to increase human resistance to infection; and to increase human response mechanisms. Many lab systems already employ humidification, so this may be a case of controlled augmentation. But before increasing cold-climate vapor pressure, with the possible risk of condensation, one must analyze and address building envelope limitations in terms of windows, frames, walls, and roofing systems.

See Karidis and Thompson, 2020 for climate visualizations and discussion of climate-informed RH setpoints.

For further input on these and other HVAC design aspects, checklists, and additional sources of guidance, see the ASHRAE Epidemic Task Force's Guide (ASHRAE, 2020) and FAQ (ASHRAE, 2021).

## Climate Change

Anticipated climate changes in the United States can be found in numerous on-line resources. While there is variation in the areas of focus, they offer an easily grasped understanding of what is in store.

- For an understanding of national, regional, and state summaries, consult: The National Climate Assessment (USGCRP, 2018).
- For localized climate projections: Climate Toolbox (Univ. of California-Merced, 2021).
- For mapped flooding projections: NOAA's Sea Level Rise Viewer (NOAA, 2021); Climate Central's Surging Seas Risk Finder maps (Climate Central, 2021), and the USGS CoSMoS tool (USGS, 2021).

Canadian lab stakeholders can investigate these Climate Data Portals, supported by the Canadian Center for Climate Services (CCCS, 2021):

- Climate Atlas of Canada (uses mapping and storytelling).
- Climate Data (downloadable, location-specific climate data by variable or sector).
- Power Analytics and Visualization for Climate Science (in development: climate data processing and visualization tools).

Addressing weather-related increases in maximum and minimum design temperatures for HVAC systems may require additional or different equipment, notably more air-based cooling and heat recovery in lieu of cooling tower use. An increase in flooding—whether via inland precipitation or coastal events—could lead to increased operating costs, supply chain interruptions, disruption in the transport system, and overall business continuity challenges. Ongoing challenges could also lead to longer-term climate-based migrations that could affect the workforce.

The inclusion of climate-resilient design criteria has become increasingly common on new construction. However, significant challenges remain for existing facilities. The cost of including resilience measures in new construction can often be 1% or less of the overall project cost. That figure is less achievable for existing facilities. (Refer to the case studies in the matrix at the end of this guide for inspiration and ideas.)

## Obsolescence

Lab planners, architects, and engineers have long considered issues of flexibility and adaptability, often addressing changing lab priorities with architectural modularity, open/configurable/reassignable lab spaces, and conversion from dry-to-wet or wet-to-dry lab functions. Similarly, robust and accessible vertical and horizontal pathways accommodate initial and undefined future ducts, piping, and wireways.

These will remain essential components of resilient lab design, though the scope of obsolescence may be expanded to include other factors, including the rapid growth of computational research, the near horizon of robotic researchers, and changes associated with community-scale disruptors.

In computational research, the efficacy of nano-scale computer modeling of chemical/biological processes is displacing workers at fume hoods and making wet-to-dry change more common, to the extent that some may question whether all researchers ultimately will be proximate to wet lab functions, either in the same building or the same urban center.

The anticipated proliferation of robotic assistants and mechanized processes may render key, long-standing ergonomic and respiratory constraints of human-based planning and fume hood design obsolete. A 10′-6″ or 11′ lab module under a 10′-0″ ceiling with 34-in.-deep hoods, daylighting, and six air changes per hour may be immaterial if robots are doing the dangerous biological/chemical work and humans are merely servicing them during down times. (A precursor of such disruption may be the machine-centric changes in data center design conditions.)

## Design Considerations by System Type

We now address the system side of the matrix, as discussed in Table 4 (page 23).

### Heating and Cooling

District steam often provides robust redundancy in boiler units, and sometimes also in distribution paths. Nevertheless, city-wide losses do occur. Grand Rapids, MI, lost district steam for days in deep winter (December 25-27, 2017), requiring exceptional efforts on the part of lab (and hospital) operators to stay in operation.

Proactive measures include back-up boilers, and critical air handling systems with electric preheat, introducing high kW demands (along with concerns that dust build-up on rarely-operated coils may set off smoke detectors). Chilled water service may be district- or building-based. The former is likely highly reliable, albeit dependent on distribution, with dual pathways desirable. The latter depends on robust HVAC design and, often, on backup for domestic water.

Natural gas providers may allow only one service per building, precluding a back-up gas service. In-building, gas-fired steam or hot water boilers may allow alternate firing with fuel/diesel oil, possibly with fuel storage tanks (in elevated vaults as opposed to underground), or trucked natural gas where available. Traditional in-lab uses of natural gas may be replaced by alternate techniques. Ultimately, decarbonization efforts will drive more lab buildings to avoid combustion altogether, eliminating the loss of a fossil fuel service as a potential disruptor.

### Ventilation and Exhaust

HVAC system considerations include redundancy, alternate flow approaches, and the gamut of options discussed under the Pandemics section above.

### Electrical: Normal Power and Standby Power

Electrical service reliability is subject both to gradual changes, such as the general shift toward electrification, and to instantaneous threats, such as hurricanes, tornadoes, or foreign cyberattacks. Since power is fundamental to lab services, on-site generator backup in the substantial-to-100% range is the primary alternative, requiring suitable space at a suitable elevation, fuel-handling capability, and exhaust dispersion.

The extended electric power and natural gas crises in Texas in February 2021 illustrated a vulnerable interdependence between regional energy systems (Rhodes, 2021). This event highlighted the need for a more robust electrical grid as the nation moves toward decarbonization (Bryce, 2021).

Other major factors include high maintenance cost of fuel generators, limitations of on-site fuel storage, and reliance on suppliers for operations longer than 72 or 96 hours of backup. Augmentation strategies include LN2 backup for critical freezers/sample storage, or on-site solar or wind turbines plus batteries to provide backup for some discrete systems. These can reduce the overall demand on the backup generator, allowing for longer run time. Looking forward, robust battery storage, rotational energy storage, green hydrogen fuel cells, and other techniques may serve both as sustainable and resilient strategies.

### Domestic Water

Domestic water supply can be crucial not only for staff but for cooling tower makeup, steam boiler makeup, and process needs. Alternate service entrances with separated paths are desirable, and on-site storage for a defined number of days may be essential. With the latter, design must include constant refreshing of the water volume and other provisions to avoid contamination. The collection of cooling coil condensate may serve as makeup for RO/DI water systems. An increase in the use of dry coolers is addressing water scarcity, and such may take over during cooler weather for evaporative towers to further reduce water use and need.

### Sanitary Waste

Sanitary waste is vulnerable to floods, affecting not only lavatory and kitchen use, but also sterilizers and lab waste systems, including acid waste neutralization. The trend toward in-lab waste-handling protocols can counter part of this risk.

### Stormwater

Roof and perimeter drainage must handle anticipated climate-based increases in maximum rainfall intensity, maintain use of primary and secondary outlets, and accommodate sump pump resilience (e.g., submersible pumps may be more resilient than those with above-floor motors, given resilience in electrical service).

### Data and Communications

Uninterruptible data connectivity may require redundant services with separated entry paths, and/or N+1 fully alternate means of connectivity, as well as appropriate power backup.

### Building Structure and Exterior Envelope

Design of building structures and exterior envelopes should address a range of disruptors—from earthquakes, terrorist activity, floods, and external fires to longer-term issues of air pressure barrier performance and obsolete vibration performance. External fire threats are now more grave, and may warrant rethinking of time-honored wall construction practices, such as the use of non-fire-retardant Styrofoam insulation behind masonry facades.

### Building Interiors, Furnishings, and Equipment

Building interiors, furnishings, and equipment considerations include floods, fires, the accessibility of staff and the public, and the provision and maintenance of important lab air pressurization relationships, humidity control, and biocontamination control.

## Services and Supplies

Critical outside lab services and supplies vary but can include lab gases, chemicals, diesel fuel, animal feed/bedding, PPE, water chemical treatment and softening salt, postal/package delivery services, and consumables for lab operations and general office functions.

## Operational Considerations for Resilience

*"In an ideal academic research institution, all the buildings and infrastructure systems that support the research enterprise would have been designed, constructed, and maintained to withstand serious disasters with little interruption to the programs and occupants. The academic research buildings and supporting infrastructure systems would remain operational; the experiments, research-related assets, and research animals would not be affected; and only a few hours or days would be needed to clean up the mess and get back to normal. Unfortunately ... this is not the case."* (NASEM, 2017.)

Laboratories are different from other buildings. This is particularly true during disruptive events, like natural disasters and power outages. Laboratory users have different concerns, experience different hazards, and are prepared with different advantages than the occupants of other buildings.

Resilience in laboratory operations requires careful planning. Each disruptor will impact a different profile of services. Each service may depend upon several others for their function. A systems thinking approach is critical. Careful planning and design can help to reimagine supply chains, work processes, and personnel to minimize interruptions due to loss of infrastructure and/or external services.

Operational resilience planning is a key area for further study and additional guidance. Recently, many lab operations have been impacted by major storms, including Hurricanes Sandy and Maria. Others have experienced wildfires and smoke in the

### Table 4: Systems Resiliency Options

| Systems Resilience | Options<br>From conventional backup > > to resilient and sustainable planning | | | |
|---|---|---|---|---|
| Structure | Hardening | Low vibration | | |
| Envelope / Exterior | Air barriers | Hardening | Force set-backs | Design for fire |
| Interior / Finishes | Hardening | Raised lobby/MEP | Vestibule traps | UVGI |
| Domestic Water | Flow-through storage | On-site fire storage | Use prioritization | Dry coolers ILO towers |
| Sewer / Lab Waste | | Holding tanks | Living machine recycling | Composting toilets |
| Storm Drainage | Site hold/pump | Flood mitigation design | Bioswale | Green roof |
| Heating / Cooling | Alt. campus sources | Geothermal | Low-entropy campus | Fuel cells on green H2 |
| Ventilation / Exh. | Alt. equipment/flows | Filtration | UVGI | Air purification options |
| Normal Power | Dual feeds | Utility collab. on subs | Microgrids | PV ± Wind |
| Standby Power | UPS | Dual feeds | N+1 generators | PV + Battery / Rotary |
| Data / Communic. | Prioritization | Alt. 2N connectivity | Multiple feeds | |
| Service / Supplies | Stockpiles | Contracted alt. sources | Triage-mode resuse plans | |

*Table 4. Systems resiliency options, from conventional to resilient/sustainable.*

western United States. And many have experienced disruption due to the COVID pandemic. These labs have harrowing stories of disaster and recovery. They also have meaningful stories of resilience.

We look forward to a future guide focused on Resilient Laboratory Operations.

## The Business Case for Resilience

*"Mitigation represents a sound financial investment. This study examined five sets of mitigation strategies and found that society enjoys a benefit-cost ratio (BCR) of 11:1 for adopting the 2018 International Residential Code (IRC) and International Building Code (IBC),the model building codes developed by the International Code Council (also known as the I-Codes), vs. codes represented by 1990 era design; a BCR of 4:1 for investments to exceed select provisions of the 2015 IRC and IBC; a BCR of 4:1 for a variety of common retrofit measures for private-sector buildings; a BCR of 4:1 for a select number of utilities and transportation infrastructure study cases; and a BCR of $6 for every $1 spent through mitigation grants funded through select federal agencies."* (NIBS, 2019.)

Inherently, there is general agreement that being more resilient will lead to fewer unexpected expenditures and a greater efficiency in operations overall.  Likewise, various studies have looked to capture the return on investment associated with resilience, with estimates ranging from the often quoted 6:1 estimate (NIBS, 2020) to as high as a 15:1 payback (Cunningham and Parillo, 2013; Healy and Malhorta 2009).

However, these metrics are often focused primarily on direct, physical damage. They fail to account for (or generally underestimate) the indirect and cumulative impacts. These include interruptions in business continuity, cascading and regionalized economic impacts, erosion of the existing tax bases (and therefore revenue sources), reduction in the life expectancy of impacted assets, and even the temporary or permanent relocation of businesses and workforces. When these attributes are considered, there is the potential for an ROI that greatly exceeds $6 saved for every $1 spent.

The impact of extreme events on labs, including both the immediate and cascading consequences, has been captured in various publications (e.g., Guenther and Balbus, 2014; Benjamin et al., 2017); at professional conferences (e.g., Matthiessen and Graeff, 2019; Mische and Wilkerson, 2019; Williams and Dickson, 2019; Messervey et al. 2019; Patterson, 2020); and by mainstream media (e.g. Sifferlin, 2013; FDA, 2017; Thomas 2017). The loss of years' worth of research at NYU Langone Health post-Sandy, the inability to effectively distribute critical medicines immediately following Hurricane Maria, and the lack of PPE and other operational impacts post-COVID, are well-known examples of just how extreme events can impact the core missions of labs and the larger biomedical ecosystem that they support.

Clearly, risks are present and mitigation is possible. The challenge becomes creating a business case for resilience. How do we value avoided risk? And how is that incorporated into planning and investment decisions?

Laboratory operations are complex and expensive. Capital projects are equally so. Scope, schedule, and budget are constant factors. With many specific research needs, fixed budgets, and tight schedules, everything comes under the microscope. The demands of immediate short-term needs can loom large relative to planning for the future. Likewise, when thinking of resilience, there is a tendency to focus inward, while the greater and more significant dependencies (e.g., water, energy, transport, telecommunication systems) often come from outside of the organization. It is not reasonable to expect a single entity to solve for all of these, but it is useful in considering the overall resilience of a particular site and municipality when making such major investments in capital.

Resilience also requires a longer-term perspective. If we reset risk every year (as is common practice in underwriting and insurance assessments), then we are dismissing the actual probability of an event happening during the lifetime of that asset. For example, a yearly 1% event has a 26% chance of occurring over 30 years—something that is definitely within the expected life of most laboratory installations. By underestimating risk, we undervalue resilience. Without a more realistic planning horizon, we also fail to account for the required maintenance and operational needs that create their own type of resilience crisis, as we are seeing with the massive backlog of deferred maintenance. The key is to reframe our risk assessments from short-lived one- to five-year projections to longer time frames (30 years and longer) that are more in keeping with actual life expectancies of these facilities and operations.

Reframing the value of resilience in business terms can help when working with stakeholders of analytical, financial, or business backgrounds. Putting resilience measures in the context of other investments, insurance options, or risk mitigation measures can help everyone understand their purpose. Finding measures that simultaneously meet several business objectives, and clearly articulating their benefits, can keep them off the chopping block when the budget is tight. Finding synergies with other business objectives, such as reduced operating costs, and quantifying their net present value can be effective.

Business considerations that will be influenced by a lab's approach to resilience include:

- Operational readiness and the ability to maintain business continuity during acute shocks and in response to longer-term stressors.
- Adequately accounting for longer-term operations and maintenance costs over the life expectancy of the organization; this includes reassessing life expectancies following impacts.
- Investment and due diligence decisions: recognizing the evolving landscape with respect to risk and financial disclosure related to certain types of disruptors, as cited by the Taskforce on Climate-Related Financial Disclosures (Financial Stability Board, 2021); how might that impact investment or divestment decisions either within the current portfolio of assets or with respect to future acquisitions/relocations/employee recruitment and retention, etc.
- Insurance: what are the current underwriting criteria, and how might those change as disclosure brings greater transparency to an organization's overall adaptive capacity? How might force majeure triggers evolve? Is there a concern of increasing premiums and longer-term insurability implications? Is there a way to improve existing resilience to reduce some of that future uncertainty and reduce insurance costs?
- Dependency on external systems to ensure facility resilience: how resilient is the surrounding geography, underpinning infrastructure, and economic tax base with respect to potential shocks and stressors? How might that be quantified with respect to ensuring the lab's continued ability to operate? Is there significant adaptive capacity within the organization itself or across the external entities (e.g., transportation or energy utilities) to withstand repeated shocks and stressors?
- Reputation: what aspects of resilience are critical to ensuring that the lab maintains its reputation, including the ability to continue

with its core services and attract additional funding and researchers? Are there elements of resilience that could influence employee recruitment and retention efforts?

These types of questions are essential in developing a more quantitative answer regarding the cost of inaction and creating a monetized value proposition for resilience. It forces us to be explicit about our assumptions regarding what a "normal" business environment entails, and what the implications are if certain aspects become less reliable. From there, the discussions naturally evolve into scenario-based, visioning exercises that require us to capture the value of losses (or, inversely, avoided losses) and prioritize investments based on what is needed to ensure the resilience of those key services and operations.

## Closing Thoughts and Next Steps

The diversity across lab types and complexity of operations within each can prove a challenge to constructing a standardized approach to resilience. However, the task becomes less daunting when we think of resilience as it relates to critical functions and core performance expectations.

In its simplest form, a resilient lab is one that continues to operate in the midst of a dynamic and sometimes disruptive environment. The lab operates within a system of systems, at scales that can range from individual equipment components to the vast distribution system that lab products feed and on which they depend. The key is to understand the core, critical functions within each lab and the various systems—physical and operational, internal and external, human-driven or automated—required to keep it functional.

This guide presents a broad definition of resilience, focused on understanding the critical functions of labs, and building out from there. We offer examples of how this can be scaled and interpreted across various perspectives. We remind ourselves of the need to consider both internal and external factors, including dependencies on systems outside of an entity's control; the cascading impact of failures in other systems; and the need to consider long-term stressors in addition to abrupt shocks.

We offer specific examples of what resilience means in terms of physical (designed) and operational (managed) improvements, as well as case studies where resilience interventions may have failed, and how those lessons learned are being used to optimize resilience in new projects.

The intent of this guide is to develop a shared understanding of what is meant by resilience in the context of labs. It is our hope that by advancing a shared vision, we can also accelerate the uptake of resilient design and planning in the further development of labs.

As with all first editions, there remain areas for further exploration. These include operation-specific details, programming issues related to storage and supply chains, and even aspects of biomimicry that might be consulted to further inform our range of solutions. And, of course, we await development of detailed design guidelines that offer a standardized and codified approach to ensuring resilience at both the building systems and operational levels. These are all exciting pieces of work that we hope to inspire.

In closing, the authors acknowledge the generous support of I$^2$SL and our colleagues with their time, guidance, and insightful commentary on the earlier versions of this work. It has been a multi-disciplinary undertaking that benefited from perspectives across a broad band of practitioners and experts. A listing of those contributors can be found in the acknowledgements section. The end product is definitely improved based on their contributions, and we look forward to continuing those collaborations beyond this particular reference.

## Laboratory Resilience Checklist

1. **Do you know what the top three hazards are for your site(s)?** Have you considered weather events, natural disasters, health disasters, social disruption, and climate change?
2. **What impacts could these events cause?** If there is a major storm, will your basement flood? Will your roof leak? Do you expect wind damage?
3. **Have you prepared for likely events?** Purchased flood barriers? Installed sewer backflow preventers? Stocked emergency supplies?
4. **Do you have a plan for communications during an emergency?** How prepared are you if cell phone systems fail? Do you have radios, satellite phones?
5. **Have you identified an emergency response team?** Do you have an emergency plan or procedure? A business continuity plan?
6. **Can you operate for 96 hours during an emergency / weather disaster?** OR can you safely shut down operations in 24 hours?
7. **Do you have backup fuel and essential supplies for 96 hours of operations?** Including food and medical supplies for stranded workers?
8. **Do you know your neighbors?** How would you contact people in neighboring buildings during a disaster? How could you share resources? How would you alert your neighbors if there were a fire or other hazard within your facility?
9. **Are you prepared for extended disruption beyond your facility?** Loss of utilities? Loss of transportation to/from the site? Supply chain issues?
10. **What would you do if local and state emergency personnel could not reach the site during an emergency?**

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## Case Studies: Purpose and Scope

Case studies can be useful in illustrating key aspects of resilience—both in terms of the challenges and potential solutions. We are grateful to those colleagues who responded to our call to share best practices with the readers of this guide. The case studies included in the matrix below represent a variety of applications, interventions, and client needs. We invite those with projects highlighting aspects of resilience, as discussed in this guide, to submit their own case studies for potential inclusion in the I²SL E-Library. Visit https://www.i2sl.org/elibrary/index.html (Resilience section) for more information.

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| Photo | Project Info | Project Description and Resilience Approach | Resilience Strategies |
| --- | --- | --- | --- |
|  Photo: California Institute of Technology | **Tianqiao & Chrissy Chen Neuroscience Research Building**<br>Owner: California Institute of Technology<br>Submitter: AEI<br>Scope: 145,000 gsf<br>Location: Pasadena, CA<br>Completed: 2020 | The three-story, 145,000-sf research building will be home to the Tianqiao and Chrissy Chen Institute for Neuroscience at Caltech and the Institute's hub for neuroscience research. LEED Gold certification is anticipated.<br>The primary electrical power service is provided by a 1.25 MW natural-gas-fired fuel cell farm, as part of a Power Purchase Agreement with Bloom Energy, with redundant service from Pasadena Water and Power. This allows the entire building load to be maintained, without interruption, during a disruption or loss of electrical service from either the fuel cell farm or the local utility. The double-ended unit substation is equipped with a programmable logic control and automatic switching between the two independent services. Emergency loads within the building are served by a central inverter with optional standby loads served by an existing 750KW generator, which also feeds the existing Broad Research Building. A commitment was made to purchase ultra-high-efficiency -80°C ULT freezers to reduce generator load and take advantage of the existing infrastructure. | • Utility feeds from on-campus and off-campus sources<br>• Substation can switch between two independent sources<br>• Optional standby loads backed up by shared generator<br>• Installation of ultra-high-efficiency freezers to reduce load |

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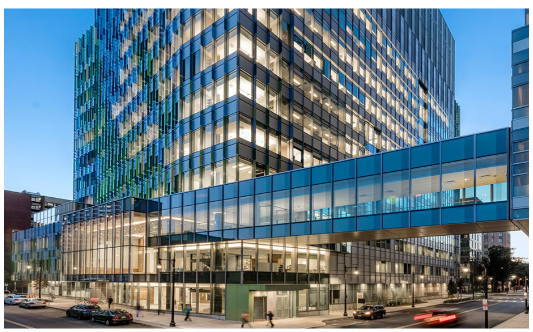
|  | **Project Legacy Replacement Medical Center, Research Building**<br>Owner: Southeast Louisiana Veterans Healthcare System<br>Submitter: BR+A<br>Scope: 125,000 gsf<br>Location: New Orleans, LA<br>Completed: 2016 | This four-story research facility is housed in a former brewery building. Fifteen laboratories are located on the second and third floors, with a small-animal vivarium on the fourth floor. The building supports investigators developing non-addictive analgesics and better treatments for addictive disorders, and conducting biomedical investigations related to cancer, diabetes, PTSD, and dementia.<br>The facility is located within a new 1.7 million-sf, 30-acre campus development that replaced a VA hospital lost during Hurricane Katrina. The campus has been designed as “VA Mission Critical” and has the capability to “defend in place” by providing all systems necessary (infrastructure, power, fuel, potable water, fire protection, water, and sanitary storage facilities) to survive for seven days without connection to city utilities, housing 1,000 individuals (patients and staff). The campus complies with the federal mandate of using 30% less energy than ASHRAE 90.1 (based on extensive modeling of both the skin of the various buildings and the MEP systems). | • Ability to shelter in place for seven days, housing 1,000 individuals<br>• Uses 30% less energy than ASHRAE 90.1<br>• Achieved LEED Silver equivalent<br>• Complete facility power generation with 10 2.5-MW generators (standby and emergency)<br>• Fuel storage for seven days within waterproof enclosure above 500-year flood line (320,000 gal of fuel)<br>• 280 Kgal potable water storage<br>• 1.2M gal process water storage<br>• 280 Kgal sanitary storage collection tank<br>• 120 Kgal fire protection storage tank<br>• 250 Kgal bleed water storage tank |
|  | **Hale Building for Transformative Medicine**<br>Owner: Brigham and Women’s Hospital<br>Submitter: BR+A<br>Scope: 650,000 SF<br>Location: Boston, MA<br>Completed: 2016 | This new research lab and clinical building is located on the former Mass Mental Health Center site, consisting of 12 above-grade floors, two below-grade floors, a 400-car garage, and a below-grade central heating plant (featuring hot water boilers and a 4.0-MW reciprocating engine cogeneration facility). The cogen has a resilient black-start capability and supports 100% island-mode operation for the adjacent Shapiro Cardiovascular Center. This allows the building to remain in operation independently in case the local or national grid power experiences outages. The facility contains a 7T imaging and cyclotron suite, bridge and tunnel connections to the Shapiro building, neurosciences ambulatory care, conference center, and a 30,000-sf vivarium. It is LEED Gold certified with 37% energy cost savings. | • Black-start cogen capability<br>• Ability for 100% island mode operation during grid outages<br>• 37% energy cost savings |

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| <br>Photo: ©HGA | **University Hall**<br>Owner: UMass Boston<br>Submitter: HGA<br>Scope: 191,000 sf<br>Location: Dorchester, MA<br>Completed: 2016 | University Hall is a four-story building containing general-purpose classrooms and three significant academic departments: Art, Performing Arts, and Chemistry. The intentional blending of Arts and Sciences creates a unique, collaborative learning experience. The facility incorporates state-of-the-art sustainable design strategies and received LEED Gold certification.<br>To address storm surge flooding risk, the ground floor was elevated 10 feet above the FEMA-recognized floodplain. Limited areas of the ground floor below this elevation were extensively waterproofed and pumps placed on backup emergency power, with most mechanical equipment and the emergency generator located in a penthouse. To address high winds and intense precipitation, the building envelope and its supporting structure, including the extensively glazed atrium overlooking Boston Harbor, was designed and constructed with enhanced wind and water resistance. | • Ground floor elevated 10 ft above floodplain<br>• Some areas below ground were waterproofed<br>• Pumps placed on emergency power<br>• Most mechanical equipment and generator located in penthouse<br>• Envelope designed to address high winds and extreme precipitation |
| <br>Photo: ©HGA | **The Brooks Building**<br>Owner: IYRS School of Technology & Trades<br>Submitter: HGA<br>Scope: 20,000 gsf<br>Location: Newport, RI<br>Completed: 2017 | The campus of the International Yacht Restoration School (IYRS) is sited within a working waterfront business district in downtown Newport, RI. It sits on Spring Wharf (a FEMA VE flood zone), set back approximately 75 ft from the water. The program for the building includes two floors — 20,000 sf — of classroom and trade teaching areas for Composites Technology, Marine Systems, and Digital Modeling & Fabrication programs. Much of the program is technology-based and related to the use of modern materials.<br>Teaching areas are located above an open parking level of 10,000 sf at grade, within the flood elevation. Utility, equipment, and machine rooms are located above the flood elevation, as are elevator components vulnerable to flooding. At grade, columns are encased in concrete to resist wave action, and foundations are designed to resist erosion related to storm surge. Walls at grade are limited in area, and other enclosures are designed as lightweight screens to partition storage and conceal parking. These enclosures are designed to break away in a severe flood event. | • Vulnerable equipment and elevator components located above flooding elevations<br>• At-grade columns encased in concrete to resist wave action<br>• Foundations design to resist erosion associated with storm surge<br>• Breakaway enclosures for severe flood event |

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|  Photo: Mark Herboth Photography LLC | **Coastal Studies Institute**<br>Owner: Coastal Studies Institute<br>Submitter: Clark Nexsen<br>Scope: 52,000 gsf<br>Location: Outer Banks, NC<br>Completed: 2013 | Located on the Outer Banks of North Carolina, the Coastal Studies Institute (CSI) is designed to withstand and respond to the harsh dynamic coastal environment. Due to threats of hurricanes and flooding, the building's infrastructure and architecture are designed around the principles of resilience, minimizing energy, and protecting the surrounding water and ecosystems.<br>This new 200-acre research campus includes a marine services building and a 52,000-sf research laboratory building. Sited along an east-west orientation, the research building is elevated and features a bent form maximizing both daylighting and views. The design includes rainwater collection, clerestory windows, south-facing sun shading, condensate collection, a borrowed well-water geothermal system, on-site wastewater treatment, and created wetlands and bioretention areas to restore the natural habitat. During an event such as a power outage, a back-up generator is utilized to allow key research to continue and preserve all critical research samples and data. The passive solar design allows occupants to continue working, as 95% of the spaces receive daylight and all offices employ natural ventilation. | • Independent on-site stormwater system of wetlands and bioretention ponds<br>• Independent on-site wastewater system<br>• Borrowed well water geothermal system<br>• Elevated form, lifting all primary education and research spaces up a floor<br>• Passive solar design |
|  Photo: Anton Grassl, courtesy GoodyClancy | **James E. Clyburn Research Center**<br>Owner: Medical University of South Carolina<br>Submitter: GoodyClancy<br>Scope: 208,000 gsf<br>Location: Charleston, SC<br>Completed: 2011 | The Clyburn Research Center, comprising the Drug Discovery Building and the Bioengineering Building, brings together scientists, faculty, and students from the state's three research universities — MUSC, the University of South Carolina, and Clemson University — as well as representatives from private industry, to advance biomedical research and technology transfer. This complex provides research laboratories, teaching laboratories, vivarium, imaging, and convening facilities. Occupying an important site on the MUSC campus, it shapes a new outdoor green space. As Charleston is subject to hurricanes and significant storm surge, the design incorporates multiple responses to climate change.<br>Buildings in historic Charleston have traditionally sat directly on natural grade. However, the revised FEMA flood map requires the buildings be raised more than five feet. The new landscaped quad negotiates the grade change from street level up to the new first floor. Nevertheless, to maintain full accessibility, the complex includes a grade-level vestibule with an elevator. That vestibule is constructed of impervious materials and incorporates special fittings at the entry doors to receive flood-protection boards when required. | • Primary MEP equipment located at roof/penthouse<br>• Vivarium located on top floor<br>• First-floor elevation set above flood level<br>• Crawlspace below structured slab allows flood waters to pass<br>• At-grade vestibule constructed of impervious materials<br>• Glazing specified to resist wind-blown debris |

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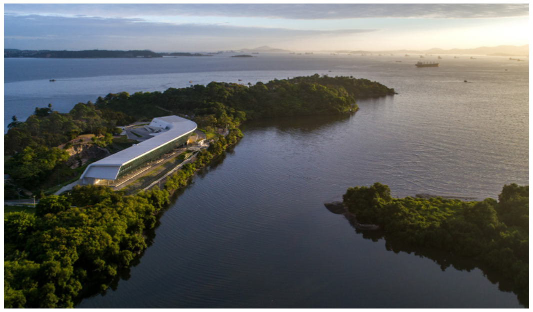
|  Photo: ©James Steinkamp Photography | **L'Oréal Research & Innovation Center**<br>Owner: L'Oréal<br>Submitter: Perkins&Will<br>Scope: 142,420 gsf<br>Location: Ilha de Bom Jesus, Rio de Janeiro, Brazil<br>Completed: 2017 | The new L'Oréal Corporate Research & Innovation Center, strategically located on a waterfront site in Rio de Janeiro, Brazil, establishes a new research identity for the international beauty products leader in Brazil. The project represents L'Oréal's deep commitment to sustainability. A common theme throughout the design is adaptability at multiple scales: in the building's approach to the environment; in its research focus and organization; and, in a more extreme sense, in laboratory design allowing rapid reconfiguration.<br>Design inspiration comes from the legacy of modern Brazilian architecture's relationship to nature, conforming itself into the landscape, emerging as a sinuous object, interfering with the existing ecology as minimally as possible. The health of interdependent systems appears throughout the project in many forms. The entire site is carbon neutral and designed to meet the Living Building Challenge, in addition to LEED Platinum targets. As a "green lung" infiltration system, it takes in contaminated water, filters the water through building and ecological systems (like filtration gardens, toilets, a green roof, even some processes in the lab), and, through gravity, returns clean water to the bay. | • Photovoltaic (PV) array designed to generate 15% of demand<br>• 100% back-up generator power<br>• Filtering gardens (on-site building waste treatment)<br>• Water re-use collection cisterns |
|  Photo: Tom Arban Photography Inc. | **Vale Living with Lakes Centre**<br>Owner: Laurentian University<br>Submitter: Perkins&Will<br>Scope: 28,441 gsf<br>Location: Sudbury, ON<br>Completed: 2011 | The Living with Lakes Centre is a collaborative, working laboratory situated on the drinking water reservoir for the City of Greater Sudbury in Ontario, Canada. Beneath the surface of this picturesque landscape lies an immense mineral wealth of metals, which were retrieved through the burning of sulfide minerals to extract nickel, causing sulfur dioxide and acid rain and a blackened wasteland. The design led to the inclusion of a rain and grey water reuse system that is filtered through limestone and a bioswale before being collected in an existing wetland. The Centre draws water from the wetland for flushing toilets, cleaning, and irrigation — reducing potable water use by almost 80%. Energy needs were addressed through the use of a closed-loop ground-source heat pump system, combined with in-floor radiant heating/cooling (and an HRV unit) for the majority of energy use.<br>Through the implementation of these strategies, the Centre uses 77% less energy, almost 80% less water, and costs $75,000 less per year to operate than a conventional building. | • Rain and grey water reuse, reducing potable water needs by 80%<br>• Heat pump system that led to efficiency as well as redundancy in energy needs<br>• 77% less energy dependence than a comparable conventional facility |

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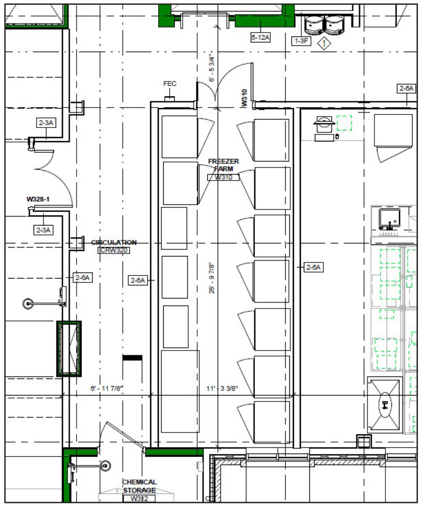
| <br>Photo: UC Boulder | **Co-localization of research equipment**<br>Owner: CU Boulder<br>Submitter: CU Boulder<br>Scope: New wing of existing research building<br>Location: Boulder, CO<br>Completed: 2020 | The University of Colorado Boulder (CU Boulder) is connecting co-localization of research equipment with laboratory building projects (renovation, new construction) benefiting energy savings, resilience, and reduced infrastructure costs. An example is the creation of a freezer room in a newly constructed research wing of the Ramaley Biology building. In 2020, when research groups moved into the wing, instead of placing their ultra-low temperature (ULT) freezers in individual labs as before, the majority were placed in a secure, shared freezer room. This approach reduced construction costs by 1) concentrating freezer infrastructure needs; 2), improved energy efficiency by focusing cooling to the shared space; and 3) increased resilience through the co-localizing of critical cold storage units, making the freezer room a clear priority for redundant power and support if an extended power outage occurs.<br>Resilience is enhanced by the fact that ULT freezers have monitors to notify lab members if there is a freezer failure, and, as more freezer rooms are created in multiple buildings, it opens up the opportunity for coordination between the freezer rooms for duplication of the most critical research samples. | • Secure, shared spaces with co-localized equipment<br>• Cost-effective approach to redundant power infrastructure<br>• Easily located critical resources in emergencies<br>• Equipment monitoring technology<br>• Copies of critical samples in multiple locations |
| <br>Photo: ©HGA | **Health \| Science \| Technology**<br>Owner: Lehigh University<br>Submitter: Vanderweil & HGA Architects and Engineers<br>Scope: 194,000 gsf<br>Location: Bethlehem, PA<br>Completed: 2021 | The HST Building creates a home for Lehigh University's new College of Health and dramatically increases Lehigh's capacity for interdisciplinary research while subtly promoting the health, well being, and individual resilience of researchers, staff, and visitors. The design team incorporated the new college's goal for promoting health into the conceptual design to develop creative solutions satisfying other intersectional goals, like fostering collaboration.<br>The design includes strategies that are shown to reduce stress, enhance creativity, improve well being, and expedite healing. These include active design (e.g. prominent stairs); biophilic design (e.g. living wall, planters, natural materials); enhanced indoor air quality (e.g. MERV-13 filtration, DOAS system); reflective spaces (e.g. meditation, lactation rooms); and outdoor amenities (e.g. café, terrace, reflection garden). A brise soliel screen on the south façade features an organic cellular pattern visually representing the research within; casts a forest-like light within the write-up and collaboration spaces; and provides shade contributing to the 60% energy savings vs. its $I^2SL$ benchmark. The design is on track for both LEED-NC Gold and Fitwel Three Stars certifications. | • Fitwel certification for occupant health, biophilic design, enhanced indoor air quality, reflective spaces<br>• Emergency preparedness policies, notifications<br>• Reclaimed water for toilet flushing |

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| <br>Photo: Payette / Cape Cod Community College / Commonwealth of Massachusetts | **Wilkens New Science & Engineering Center**<br>Owner: Cape Cod Community College<br>Submitter: Vanderweil & Payette<br>Scope: 39,000 gsf<br>Location: Barnstable, MA<br>Completed: 2022 | The Wilkens Science and Engineering Center is intended to exemplify commitment to net zero emissions, as CCCC was one of the original signatories to the American College & University Presidents' Climate Commitment. It replaces an existing building. Through detailed energy modeling and life cycle cost assessment, the design team concluded that an electric-driven air-source heat pump solution would pay back within the life of the equipment. Several energy conservation measures proactively minimize the annual EUI to 52 kBtu/sf, with rooftop PV-reducing net EUI to 19 kBtu/sf and a parking PV canopy making the facility net positive energy.<br>To continue operation and mitigate damage from extended loss of power during winter storms and maintain heating during extreme cold weather, the air source heat pump system is supplemented by a high-efficiency boiler. An energy and emissions analysis determined that the net effect of the boiler on emissions over the life of the system was negligible, while providing fuel and equipment redundancy as well as net cost savings on emergency generator capacity. | • Air-source heat pump heating<br>• Backup condensing boiler<br>• 224kW rooftop and 330kW parking PV arrays<br>• High-performance envelope, thermal sweater corridor reduce heating<br>• Energy recovery ventilation, minimized hood exhaust |
| <br>Photo: Behnisch Architekten | **Allston Science and Engineering Complex**<br>Owner: Harvard University<br>Submitter: van Zelm Engineers/Behnisch Architekten<br>Scope: 544,000 gsf<br>Location: Allston, MA<br>Completed: 2020 | Harvard's new Science and Engineering Complex is designed to house numerous critical academic and research programs with approximately 100,000 sf of programming located below grade, some as deep as 30 feet below. The resilience planning focused on flooding and was informed by climate change projections. A design flood elevation (DFE) of 20.5 feet above present sea level was established, below which the building and site were designed to prevent water intrusion. The 1.5-MW emergency generator and main emergency power distribution equipment were located on the roof. Electrical substations were located at least 15 feet above the lowest basement level. All critical mechanical equipment was located on a mezzanine at least 6 feet above the lower basement levels. No below-grade air intakes or areaways were provided.<br>The lowest level was compartmentalized with bulkheads (like a ship). High-capacity flood evacuation pumps were provided in each section, as a last line of defense should flooding occur based on water intrusion. All below-grade foundation penetrations were carefully sealed.<br>The project has been awarded LEED Platinum certification and obtained the Living Building Challenge Materials Petal certification. | • Design flood elevation informed by climate change projections<br>• Critical equipment located above DFE when possible<br>• Critical equipment raised above lower basement elevations<br>• No below-grade air intakes or areaways<br>• Bulkheads installed in lower levels<br>• Waterproof sealing and landscape buffers for flood protection<br>• Installation of flood evacuation pumps<br>• Provisions for PV array on roof<br>• Rainwater recapture with 78,000 gal on-site storage<br>• Full-building electrical back-up by off-site power generation<br>• Redundant main electrical feeders to building |

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| <br>Photo: Bill Timmerman | **Energy Systems Integration Facility**<br>Owner: U.S. Department of Energy NREL<br>Submitter: SmithGroup<br>Scope: 182,500 gsf<br>Location: Golden, CO<br>Completed: 2013 | The mission of the Department of Energy's National Renewable Energy Laboratory (NREL) includes education. So its Energy Systems Integration Facility both promotes and exhibits energy efficiency, heat recovery, and resilience. Its expandable high-performance data center makes 100°F water at its racks — enough now to heat administrative and conference spaces, and eventually enough for high-bay energy research labs and/or other campus buildings.<br>In the summer, the data center needs no chillers, as excess heat flows to cooling towers after thermosyphon precooling. The up-to-10mW data center boasts a world-class power usage effectiveness (PUE) of only 1.04 — beside the "free campus heater" benefit.<br>The administrative wing's advanced fenestration design, natural ventilation, and host of other low-energy features limit energy use intensity to 25 kBtu/sf/year. When including significant process needs in its labs — which promote our smart grid and hydrogen economy — the facility's overall EUI of 191 kBtu/sf/year contributed to a LEED V2.2-NC Platinum Rating. Energy efficiency is important to everyone, and we can realize significant energy improvements — and greater resilience — through integration. | • Up-to-10mW data center needs no chillers<br>• Data center also serves as a direct building heater<br>• Thermosyphon halves cooling tower water use<br>• 25 EUI office wing, 1.04 PUE data center |
| <br>Photo: SmithGroup | **Biological & Environmental Program Integration Center (BioEPIC)**<br>Owner: University of California Regents, U.S. Department of Energy<br>Submitter: SmithGroup<br>Scope: 74,000 gsf<br>Location: Berkeley, CA<br>Completed: Under Construction | BioEPIC is the second of four to five research buildings planned at the Lawrence Berkeley National Lab Bayview site. BioEPIC houses biological and environmental sciences, supported by EcoPOD environmental chambers, growth chambers, open and dedicated lab spaces, a greenhouse, and an electron microscope suite.<br>BioEPIC is on a brownfield site over 10 to 70 feet of existing fill. Remediation of contaminated soils and the design of a stormwater retention system (bioretention) limits filtration into the aquifer and prevents settlement. Earthquake monitoring sensors will study how BioEPIC performs in a seismic event. This research will be used to advance the resilient design of future buildings.<br>Medium chilled water is provided from a central Modular Utility Plant at 55 to 58°F, providing free cooling from the combination of cooling towers and plate-and-frame heat exchangers for over 50% of the year. Supplemental cooling and all heating are provided by a combination of water and air source heat pumps. Resiliency in the power system is achieved by a medium-voltage substation fed from two sources. | • No natural gas used for space or water heating (lab bench turrets only)<br>• Dual sources to medium-voltage substation<br>• Daylight and visual connection provided by optimized envelope, mitigating solar gain, glare<br>• EUI: 196 kBtu/sf/year full building, 137 without process loads (48% better than ASHRAE 90.1)<br>• LEED Gold target |