Thermal Energy System Resilience
Scope, Definitions, and Concepts

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Scope. The thermal energy system discussed in this white paper is comprised of both demand and supply side (Figure 1). The demand side includes mission-related active and passive systems including thermal demand by the process, HVAC systems maintaining required environmental conditions for the process and comfort for people, and a shelter/building that houses them. The supply side includes energy conversion, distribution, and storage system components. This paper discusses **requirements for thermal/environmental conditions** in the building, and the part these requirements play in housing critical mission-related processes and people in cold climate conditions. Ultimately, the goal of this work is to establish a way to address the **required level of reliability for energy supply systems** that will be capable of supporting necessary thermal conditions **under predominant threat scenarios**.

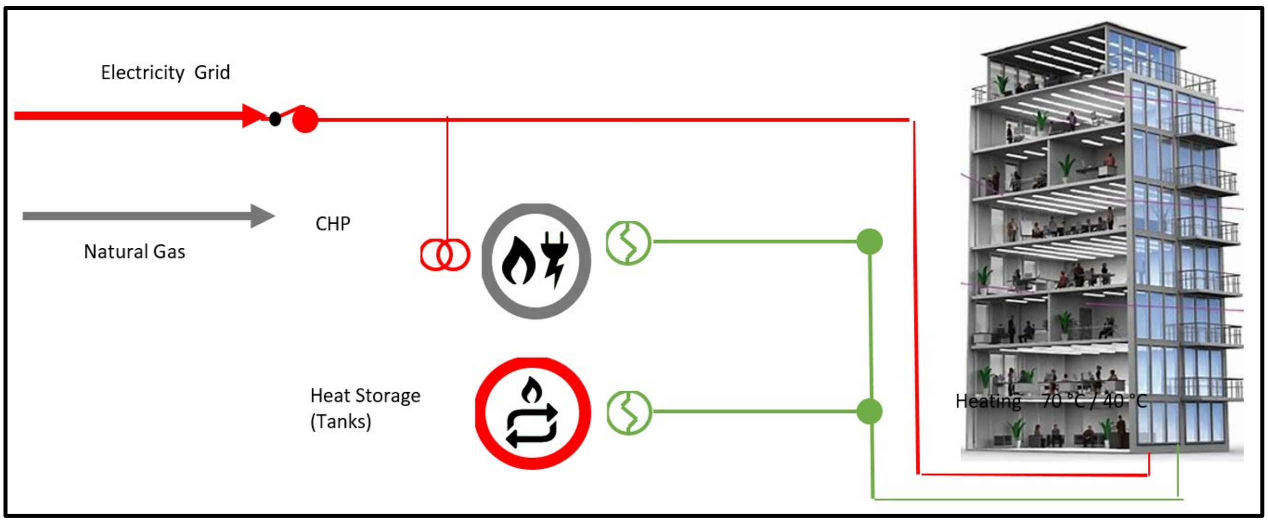

Figure 1. Component of the notional thermal system.

Thermal system performance requirements (primarily for heating dominated climate)

<u>Thermal requirements</u> include criteria to maintain thermal comfort and health, process needs, and prevention of mold, mildew, and other damage to the building materials or furnishings.

<u>Thermal comfort and health</u> criteria primarily involve the temperature and humidity conditions in the building. Too high a temperature means that occupants are uncomfortably hot. Too low a temperature means that occupants are uncomfortably cold. The wrong humidity (rooms typically do not have humidistats) means that occupants feel damp or sweaty or too dry. Thermal comfort is defined by ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy.

<u>Process related criteria</u> include temperature and humidity needed to perform the process housed in the building (e.g., painting, printing) or to operate process equipment such as electronics. While new design guidance for computer systems indicates a much higher tolerance for high temperatures than previously thought, there are specialized electronic and laboratory equipment that have fairly tight temperature and humidity requirements. An archival storage of important documents also involves relatively tight tolerances for temperature and humidity. Different areas of medical facilities may have special requirements for indoor environment.

Building materials and furnishings requirements. The environmental conditions (temperature and humidity) maintained in indoor spaces determines not only the comfort of the occupants of those spaces but also the long-term “health” of the building itself. Historically, only the dry-bulb temperature of indoor spaces was controlled to achieve comfortable indoor conditions for the occupants. Little attention was given to control moisture/humidity in the spaces. As a result, many existing Army buildings have significant mold/mildew problems.

Eliminating mold/mildew from Army buildings requires year-round control of both the dry-bulb temperature and the dew point temperature (or air relative humidity) in the indoor spaces. Control of indoor humidity will also significantly improve the comfort of Army building occupants.

Building materials and damage to furnishings occurs when humid air meets a cold surface. Mold/mildew grows on a building’s surface when that surface’s relative humidity is above 85% for extended periods. This condition easily occurs in buildings even with low average air relative humidity when cold spots exist on poorly insulated supply air ducts and chilled water pipes, on supply air diffusers, on poorly insulated and non-airtight building envelope elements, on areas with thermal bridges, etc. Careful design and operation of the building envelope and the HVAC, ventilation, and exhaust systems is required to eliminate the potential for mold growth in Army buildings. Maintaining ALL the air inside the building above the dew point will reduce potential moisture related problems. According to the ASHRAE Humidity Control Design Guide, the suggested dew point limits which meet both health and mold problems requirements are < 57 °F in summer and > 35 °F in winter.

It is important that designers and O&M personnel design and maintain the building and HVAC systems, to satisfy all three categories of requirements. In most cases, thermal comfort requirements satisfy the process. Preventing moisture-related problems requires special attention to the design and building operation. Energy conservation shall not be achieved at expense of health, occupant’s wellbeing, and building sustainability. Certain strategies and technologies can minimize or eliminate premium energy use.

Thermal requirements to unoccupied spaces. Requirements for temperatures and relative humidity discussed above have been developed for occupied spaces (Table 1). Many DOD and other government buildings are not occupied at night or on weekends. Some DOD facilities including barracks, administrative buildings, and dining facilities may be unoccupied for an extended period of time due to training and deployment. So one energy conservation strategy may be to set back temperatures for heating or set up temperatures for cooling. One source of guidance on setback or setup temperatures is ANSI/ASHRAE/IESNA Standard 90.1-2004 *Energy Standard for Buildings Except Low-Rise Residential Buildings*. Standard 90.1-2007 does not regulate changes in thermostat settings (up or down), but it does regulate the capabilities of thermostats installed in buildings. Section 6.4.3.3.2 of Standard 90.1 Setback Controls – requires that heating systems in all parts of the United States outside of Miami FL and the tropical islands (that is, climate zones 2-8 as shown in the map below) must have a capability to be set back to 55 °F. Significant energy savings can be achieved without damage to building materials and furnishing if a combination of measures related to the building envelope and

HVAC maintain the requirements for ALL the air inside the building.

Table 1. Requirements to dry bulb temperature and relative humidity for occupied and unoccupied facilities to reduce the risk of moisture related problems.

Occupancy/Use	Humidity not to exceed	Maximum Dry Bulb Temp	Minimum Dry Bulb Temp
Occupied	50%	75 °F	70 °F
Unoccupied (Short term)	50%	85 °F	55 °F
Unoccupied (Long term)	50%	No Max	40 °F
Critical Equipment	50% or equip requirement if less	Equip max allowed	Equip min allowed

Resilience vs. reliability.

Resilience of the energy system impacts the primary functionality of the building and the installation, during disruptions. A resilient energy system is one that can prepare for and adapt to changing conditions, and recover rapidly from disruptions including deliberate attacks, accidents, and naturally occurring threats (PPD-21, U.S. Army 2015). Extending this definition, a resilient energy system prioritizes and maintains performance of important services such as mission-oriented functions, and safety and health oriented functions, food, water, shelter, etc.

Resilience is contextual – it is defined in terms of threats or hazards. A system resilient to hurricanes may not be resilient to earthquakes. It applies to hazards with low probability with a potential for high consequence and therefore naturally fits within a risk-based planning approach. Figure 2 shows a graphical description of system performance subject to a single event. In this figure, an event occurs that degrades overall system performance. System 1 and System 2 are two alternative energy system designs subject to the same disruption; System 2 is depicted as more resilient

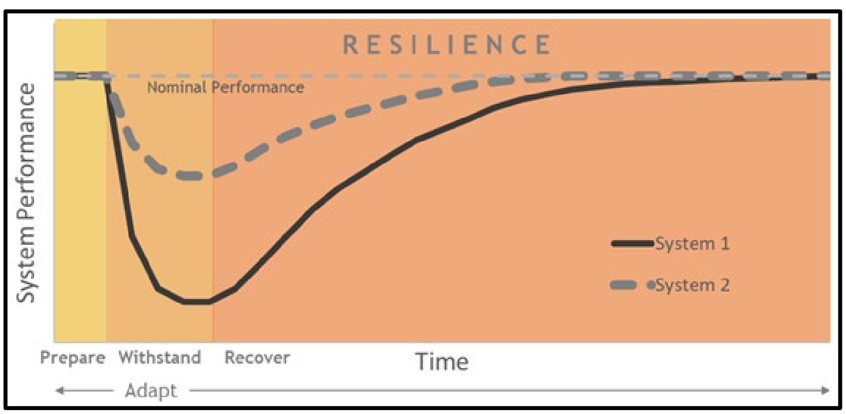

Figure 2. System performance subject to a single event.

This overall system performance is highly dependent on the energy system's performance during the event. Energy system performance at key loads in the system enables the system performance, for example a water treatment plant enables drinking water for the community. The performance-based resilience metric "system impact" (SI) is the integral over time of the actual system performance minus the target (or nominal) system performance, as shown by:

$$SI = \int_{t0}^{tf} [TSP(t) - SP(t)]dt. \qquad (1)$$

(1)

where TSP(t) is the targeted system performance through time – the nominal performance of the system without a disruption, and SP(t) is the system performance subject to the disruption (Vugrin et al. 2010).

Figure 3 shows the difference between reliability and resilience. The primary difference between reliability-focused planning and resilience-focused planning is the type of events included in the process and the methods used to quantify the impact of the events. Reliability-focused planning limits itself to high-probability events with relatively low consequences (U.S. DOE 2017). **System** reliability is the desired level of system performance. Besides information on statistical system element failure, system reliability should be adjusted for commonly expected threats and hazards for the locality of interest, which are called Design Basis Threats (DBTs). Probability of system element damage as a function of threat intensity can be described using Fragility curves, which are built for each DBT (see example in Figure 4).

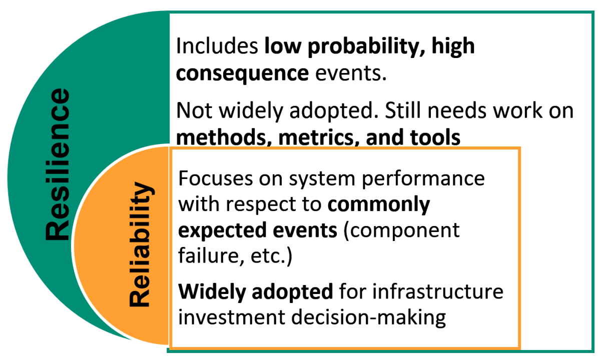

Figure 3. How resilience and reliability are related.

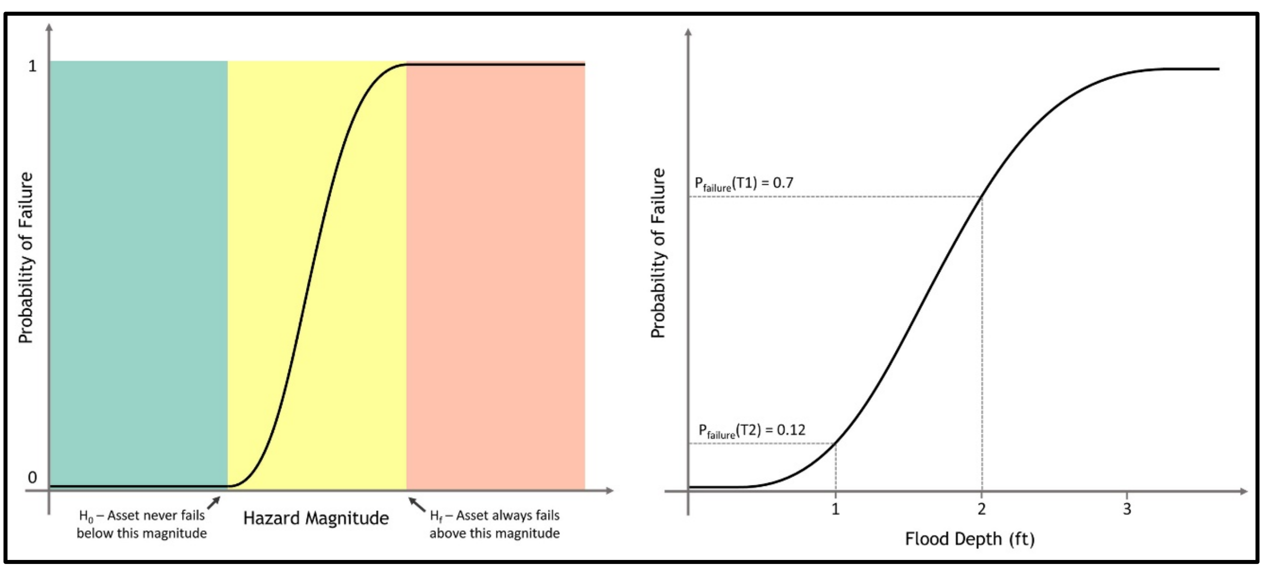

Figure 4. Example fragility curves: (a) Hypothetical fragility curve generated by subject matter expertise, and (b) Transformer fragility for notional system.

METRICS TO BE USED FOR ENERGY RESILIENCE ANALYSIS

Energy Quality

According to ISO 8528-1, power quality required by electrical equipment can be described using the four performance classes specified in Table 2.

Table 2. Performance class transient limits (UFC 3-540-01)

Parameter	Performance Class			
	G1	G2	G3	G4
Frequency Deviation (Percent) for 100 Percent Load Increase	<-15	<-10	<-7	TBD
Frequency Deviation (Percent) for 100 Percent Load Decrease	<+18	<+12	<+10	TBD
Frequency Recovery Time (Seconds) for 100 Percent Load Change	<10	<5	<3	TBD
Voltage Deviation (Percent) for 100 Percent Load Increase	<-25	<-20	<-15	TBD
Voltage Deviation (Percent) for 100 Percent Load Decrease	<+35	<+25	<+20	TBD
Voltage Recovery Time (Seconds) for 100 Percent Load Change	<10	<6	<4	TBD
Frequency Droop (Percent)	<-8	<-5	<-3	TBD
Steady-State Frequency Band (Percent)	<2.5	<1.5	<0.5	TBD
Steady-State Voltage Regulation (Percent)	<5	<2.5	<1	TBD
Note that column for performance class G4 states “TBD,” which means that a site-specific analysis is required to determine the voltage and frequency limits.				

For thermal energy reliance, energy quality required by the building/mission can be described in terms of type of thermal energy required by the process and thermal comfort systems. This may include: steam, high temperature, medium temperature or low temperature hot water, chilled water, water-antifreeze mixture, electricity for heating or cooling, gas, or other fossil fuel, etc. Energy quality concept for thermal energy system is less important than for electric systems. If the internal system is water based or uses antifreeze, the energy supply system can be steam or hot water based, and can use a steam-to-hot-water heat exchanger. The conversion from steam to hot water energy supply system requires a system of heat exchangers, radiators, or convectors inside the building to support its heating loads. If some processes, e.g., sterilization or industrial processes, require steam, a local steam boiler can be installed to complement the heating system, which would be converted to hot water. In most cases, a closed loop building heating system can be designed to accommodate any type of thermal energy that is provided to the building; supplemental thermal storage can be added to the system to accommodate variations in energy flow.

Energy Availability (based on TM 5-698-1 [2007])

Energy Availability is defined as the percentage of time that an energy system is available to perform its required function(s). It is measured in a variety of ways, but it is principally a function of downtime. Availability can be used to describe a component or system but it is most useful when describing the nature of a system of components working together. Because it is a fraction of time spent in the “available” state, the value can never exceed the bounds of $0 < A < 1$. Thus, availability will most often be written as a decimal, as in 0.99999, as a percentage, as in 99.999%, or as it is commonly termed, “five nines of availability.” Energy availability can be calculated using one of two equations:

$$EA = MTBF/(MTBF + MTTR) \times 100\% \quad (2)$$

or

$$EA = Uptime/(Uptime + Downtime), \quad (3)$$

where: MTBF = mean time between failures, MTTR = mean time to repair.

Practical data-based availability studies have their origins with electrical and mechanical data collected by the Institute of Electrical and Electronics Engineers (IEEE) and the U.S. Army Corps of Engineers. Data gathered by these organizations has made years of developed theory and analysis possible.

Reliability.

Reliability is concerned with the probability and frequency of failures (or more correctly, the lack of failures). A commonly used measure of reliability for repairable systems is the mean time between failures (MTBF). The equivalent measure for non-repairable items is mean time to failure (MTTF). Reliability is more accurately expressed as a probability of success over a given duration of time, cycles, etc. For example, the reliability of a power plant might be stated as 95% probability of no failure over a 1000-hour operating period while generating a certain level of power.

According to TM 5-698-1 [2007], reliability of the system with components installed in series can be calculated using the following equation:

$$R_S = R_1 \times R_2 \times \ldots \times R_n, \qquad (4)$$

where: R_i is reliability of component i.

Figure 5 shows example of calculation reliability of the system with two components installed in series.

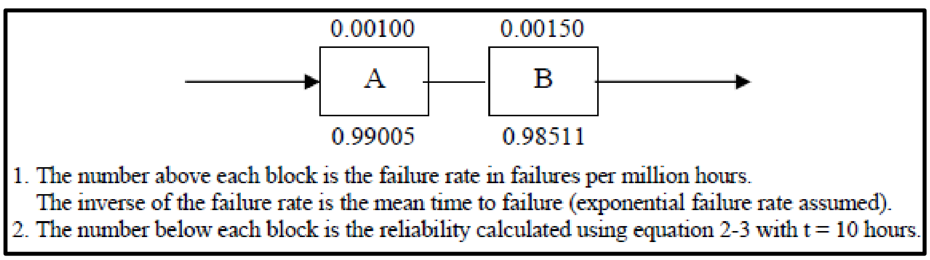

Figure 5. Block diagram illustration of reliability of components installed in series.

The system reliability shown in this example $R_S = R_A \times R_B = 0.99005 \times 0.98510 = 0.9753$.

Reliability with redundancy. The system shown in Figure 6 has the same components (A and B in series denoted by one block labeled: A-B), but two of each component are used in a configuration referred to as redundant or parallel. Two paths of operation are possible.

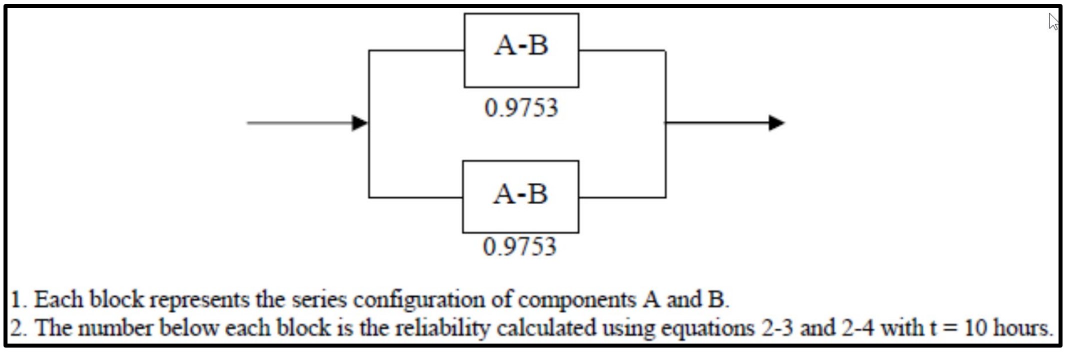

Figure 6. Block diagram illustration of reliability of components installed in parallel.

The paths are: top A-B and bottom A-B. If either of two paths is intact, the system can operate. The reliability of the system is most easily calculated by the following equation:

$$R = 1 - (1 - R_s) \times (1 - R_s) = 0.9994 \quad (5)$$

Adding a component in parallel, i.e., redundancy, improves the system's ability to perform its function.

Maintainability

Maintainability is defined as the measure of the ability of an item to be restored or retained in a specified condition. Maintenance should be performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair.

Simply stated, maintainability is a measure of how effectively and economically failures can be prevented through preventive maintenance and how quickly system operation can be restored following a failure through corrective maintenance. A commonly used measure of maintainability in terms of corrective maintenance is the mean time to repair (MTTR).

Maximum time to repair of thermal system can be defined in terms of how long the process can be maintained or the building remains habitable or protected against damage from freezing of water pipes, sewer, fire suppression system, protect sensitive content, or the start mold growth during extended loss of energy supply with extreme weather events. Thermal resilience design guide [2019] defines the threshold for building habitability during heating season as 59 °F (15 °C) and for cooling season as 86 °F (30 °). Mission operators may select different thresholds based on age, health, or level of training of inhabitants.

A building's total heat consumption per the unit of time can be calculated using the following equation:

$$Q_{tot} = Q_{loss\ tr} + Q_{inf} + Q_{vent} - Q_{int} \quad (6)$$

where

$\mathbf{Q_{loss\ tr}}$ = heat flow to compensate for thermal losses due to heat transfer by conduction
$\mathbf{Q_{inf}}$ = heat flow to heat outside air due to infiltration, $\mathbf{Q_{vent}}$ - heat flow to heat ventilation air
$\mathbf{Q_{int}}$ heat = internal heat flow from people and internal processes.

$$Q_{loss\ tr} = U\ A\ (T_{out} - T_{in}), \quad (7)$$

where:

U = overall coefficient of heat transfer
A = total area of fenestration
($T_{out} – T_{in}$) = a difference between inside and outside air temperatures.

$$Q_{inf} = AL\ A\ C_p\ (T_{out} - T_{in}), \quad (8)$$

where:

AL = air leakage rate
C_p = specific heat of air.

$$Q_{vent} = L\ C_p\ (T_{out} - T_{in}), \quad (9)$$

where L = outside air ventilation rate.

Based on these simplified equations, the major factors affecting the heat flow rate and therefore the time, when the internal temperature reaches threshold based on building habitability or sustainment include:

- Difference between inside and outside air temperature
- Building envelope leakage rate
- Building envelope insulation properties, including insulation levels of its components, and thermal bridging
- Internal thermal load (people and appliances/equipment connected to electric power).

Also, thermal mass of the building structures composed of concrete, masonry, or stone materials that constitute a high level of embodied energy enables the building to absorb and store heat to provide "inertia" against temperature fluctuation. The amount of heat that can be absorbed by the building mass can be calculated using the following equation:

$$Q_{storage} = M\ Cp\ \Delta T, \quad (10)$$

where:

$Q_{storage}$ = amount of energy that can be stored by the building mass
M = building mass
C_p = specific heat of the building material
ΔT = is allowable change in the room air temperature.

Figure 7 shows how these factors will influence building habitability and sustainment.

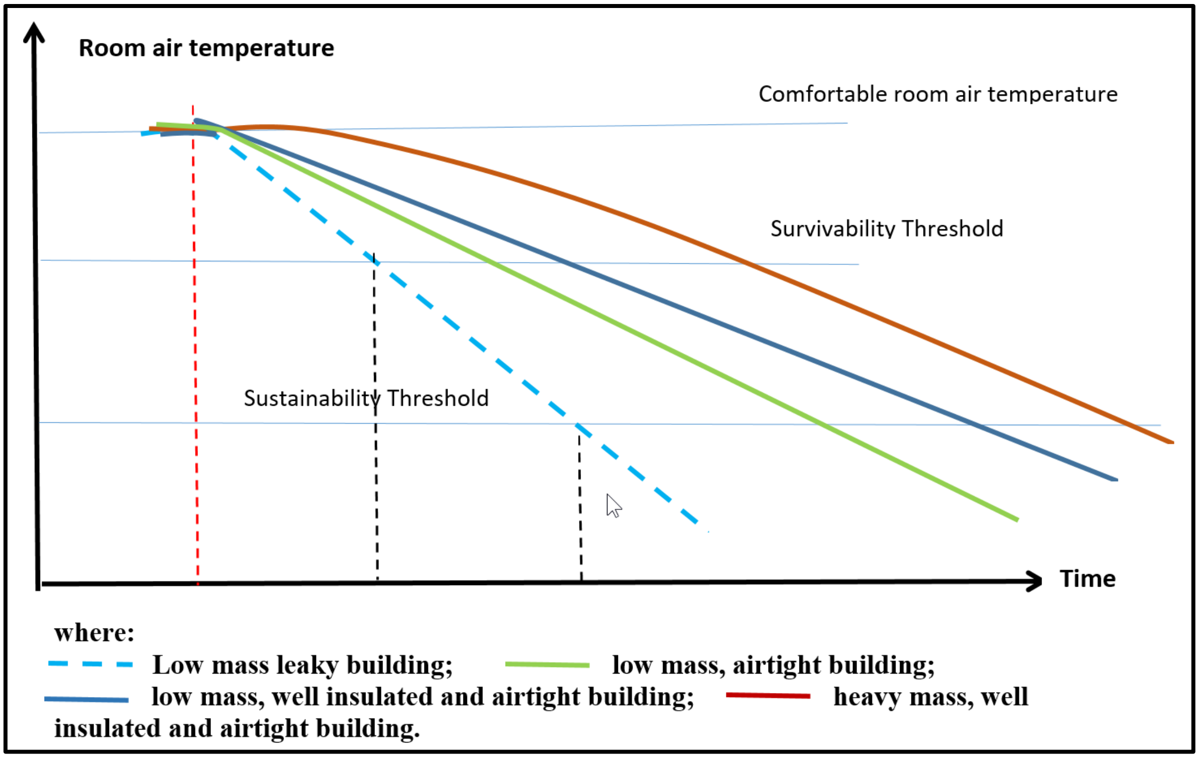

Figure 7. Notional example of temperature decay rate for different types of building envelope.

Blue-sky and Emergency Energy Demands

During a normal (blue-sky) scenario, energy generated on site or imported from outside the area of interest can be consumed by ALL end uses (mission critical and non-mission critical building functions, industrial processes, central services – compressed air/water/sewer, etc.). This quantity of energy will also include distribution losses (hot water, chilled water, and steam network, onsite electrical) and onsite conversion losses (turbines, boilers, engines).

During emergency scenarios, some generation, distribution, and storage thermal system components may be compromised, e.g., components may be out of order, or fuel supply to the campus can be limited. To maintain critical functions, the need for energy by both critical and non-critical functions can be reduced, and those functions must be prioritized (to denote where and how energy will be used). Priority for energy supply must be given to buildings and their areas with mission critical uninterruptable or interruptible processes. These mission critical areas may include the whole building, or in some cases, as little as 5% to 10% of the total building area.

The amount of thermal energy to be supplied to non-critical areas of a building or to non-critical buildings can be significantly reduced without jeopardizing mission critical, life, or safety functions; or building sustainability, to extend the use of limited resources. Figure 8 shows that, while the room air temperature in the mission critical area of the building must be maintained close to the normal temperature, air temperature in surrounding areas can be reduced to the level of survivability. Air temperature in non-mission critical facilities can be temporarily dropped to the level above the sustainability threshold. If possible, ventilation systems shall be designed and adjusted to accommodate zonal control to reduce airflow rate in non-mission critical zone to the level required to building pressurization.

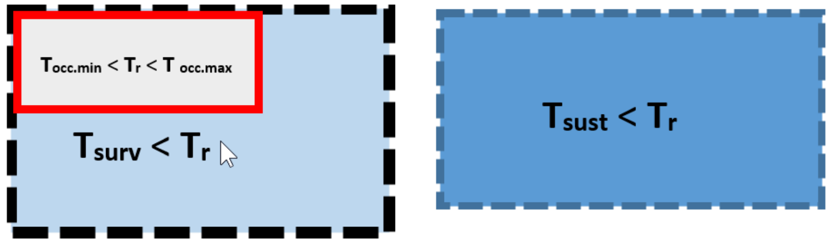

Figure 8. Temperature reduction concept in mission critical and non-mission critical areas/buildings.

Nevertheless, due to their specific use in emergency scenarios, some buildings may use more energy (e.g., shelters, dining facilities, etc.).

To be resilient, a community/campus/military installation must serve its energy demands during disruption scenarios. To plan, develop, and evaluate resilient designs, the planner must stay informed of the dynamic demand of each asset or building during a disruption scenario, and must scale energy supplies up or down to meet the demand for each critical function. The characteristics of the critical energy load can vary significantly between functions. For example, a communications function may require a large but steady supply of power to meet its equipment and conditioning needs. A shelter, on the other hand, may have little to no critical power demand, but may have a large but variable heating demand to protect occupants from environmental conditions. Figure 9a gives an overview of how critical and non-critical loads are broken out within buildings, while Figure 9b illustrates 24-hour load profiles for the disruption scenario. Profiles for blue-sky scenarios could be drastically different. As has been described above, to prevent significant damage to non-critical buildings, minimum thermal requirements shall be maintained in these buildings during extremely low outside air temperature that will require thermal energy to these buildings, but at the significantly reduced rate. Temperature control in these buildings can be done manually, or through the use of a building automation system (BAS).

There are also large variations in energy-demand profile based on the function's location. For example, the acceptable system disruption period will be significantly shorter for a heating system coping with an Alaskan winter than for one in the relatively temperate climate of Seattle, WA.

These variations in type, magnitude, and schedule of critical energy requirements are essential considerations when developing resilience system performance metrics such as energy availability and MTTR.

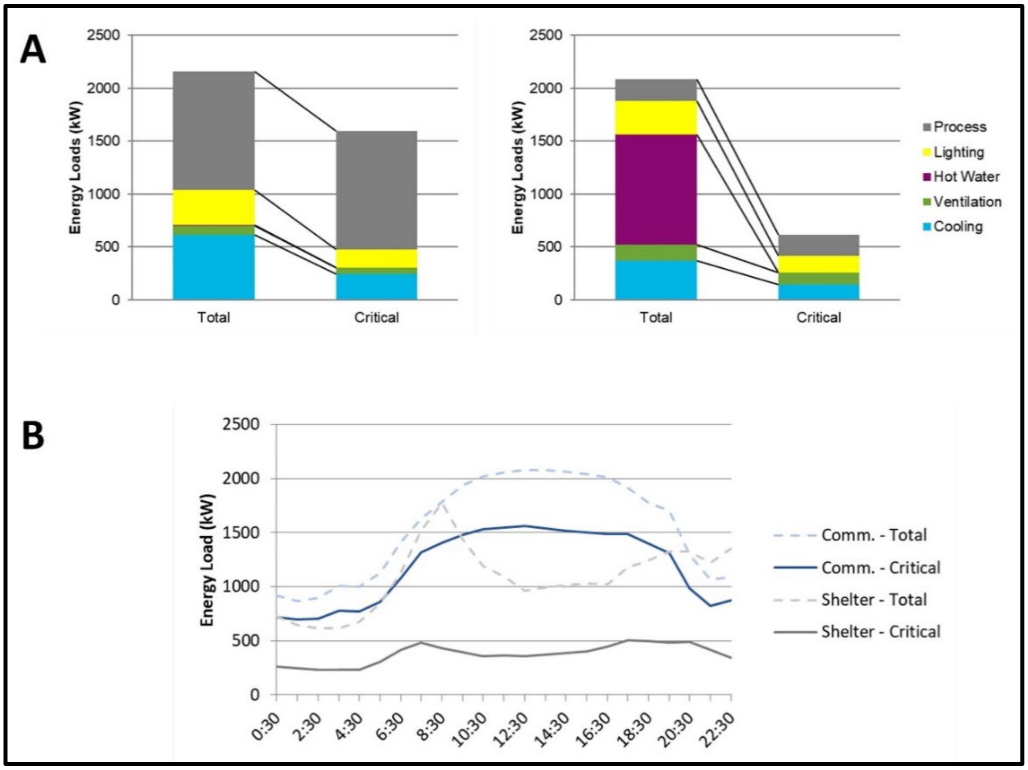

Figure 9. Total and critical electrical demands: (a) Total and critical electrical demand load for a data center (left) and a dormitory (right), and (b) Critical electrical demand hourly profiles for communications and shelter over a 24-hour period.

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