Thermal Energy System Resilience
Scope, Definitions and Concepts

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Fairbanks, AK
January 22, 2020
Organizers

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THERMAL ENERGY SYSTEMS RESILIENCE IN COLD/ARCTIC CLIMATES
CONSULTATION FORUM
Fairbanks, AK
January 22-23, 2020

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11. NATIONAL CODES
    Decrease of the Ministry of the Environment (Finland) on the Energy Performance of Buildings, 2024
    Greenland Building Code, BR 2006D, Bygningereglement 2006
    Norwegian Building Authority, 2017
    Regulations on Technical Requirements for Construction Works. An unofficial English translation of the regulation "Forskrift om tekniske krav til byggeverk (byggesaks forskrift)"

12. GUIDELINES
    Canada Mortgage and Housing Corporation
    Optimal Northern Wolf Design Guidelines. RDI Project 80717.300
    Odgeir Gudmundsdottir and Jan Eric Thorsten (Heating Segment, Denmark)
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13. OTHER USEFUL REFERENCES
    Richard Armstrong (Alaska Housing Finance Corporation)
    A White Paper on Energy Use in Alaska’s Public Facilities
    Peter Eder (Copenhagen School of Design and Technology)
    Passive Houses in a Cold Climate
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    Energy Efficient Housing Guidelines for Whistler, YT: Energy Optimized House
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    An Energy Efficient Building for the Arctic Climate. Is a Passive House Sensible Solution for Greenland?
Forum Objectives

• Buildings in cold climates face unique challenges, not only due to the cold outside temperature, but also remoteness, limited utilities (resulting in many cases in a single point of failure), permafrost and seasonally frozen or thawed soils, and extreme temperature shifts.

• Special consideration must be paid to efficiency of envelopes, reliability of mechanical systems and their maintenance needs, durability of piping systems, robustness of building controls, and commissioning.

• In addition to reliable and resilient power supply, mission critical operations in Cold and Arctic climate require reliable and resilient thermal energy supply systems

• This Forum was organized to bring together researchers, practitioners and facilities managers to present and discuss different aspects of thermal systems resilience and reliability, that can result in practical information for developing a Planning Guide on Resilient Thermal Energy System for Cold and Arctic Climates.

• This Forum contributes to projects funded by the U.S. Congress, DASA, ESTCP and IEA EBC Program
Thermal Energy System

- Thermal energy system discussed is comprised of both **demand** and **supply** side.
- **Demand side**: 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.
- **Supply side**: energy conversion, distribution and storage system components.
Demand Side - Requirements to thermal/environmental conditions

• Thermal comfort and health criteria
• Process related criteria (IT technologies, medical facilities, industrial, etc.)
• Building materials and furnishings requirements (mold, mildew, freeze protection, etc.)
• Thermal requirements to unoccupied spaces (energy conservation and sustainability)

Requirements to dry bulb temperature and relative humidity for occupied and unoccupied facilities

<table>
<thead>
<tr>
<th>Occupancy/Use</th>
<th>Humidity not to exceed</th>
<th>Maximum Dry Bulb Temp</th>
<th>Minimum Dry Bulb Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupied</td>
<td>50%</td>
<td>75 °F</td>
<td>70 °F</td>
</tr>
<tr>
<td>Unoccupied (Short term)</td>
<td>50%</td>
<td>85 °F</td>
<td>55 °F</td>
</tr>
<tr>
<td>Unoccupied (Long term)</td>
<td>50%</td>
<td>No Max</td>
<td>40 °F</td>
</tr>
<tr>
<td>Critical Equipment</td>
<td>50% or equip requirement if less</td>
<td>Equip max allowed</td>
<td>Equip min allowed</td>
</tr>
</tbody>
</table>
Resilience Vs. Reliability
Resilience

- 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).
- 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 – defined in terms of threats or hazards. It applies to hazards with low probability with a potential for high consequence and therefore naturally fits within a risk-based planning approach.

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:

\[ SI = \int_0^\infty [TSP(t) - SP(t)] dt. \]

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).
Energy Availability and System Recovery

Using availability concepts, we can quantify the overall resilience of a system in two phases: absorption of the event, and recovery.

Consider an event occurring as shown in Figure below. Immediately following the event, there is a sharp drop in mission availability. The change in mission availability from the baseline to the degraded state represents the robustness of the system to that particular event. The lower the change in mission availability, the more robust the system.

The time required to restore the system to its baseline state is referred to as recovery. This is based on the mean-time-to-repair (MTTR) of any assets affected by the event, and may be affected by several factors including site remoteness, event severity, and environmental conditions.
Energy Availability Vs Energy System Recovery

Depending on mission needs, it may be more important to prioritize either robustness or recovery. For example, Figure 2 shows two systems with different levels of resilience. The two systems have the same recovery time, but System 2 has a lower initial decrease in mission availability. System 2 is more resistant to the postulated event, and is more resilient than system 1 despite having the same recovery time. This may be beneficial for improving overall resilience at remote sites where recovery time is limited by the physical demand of getting replacement parts to the site.
Difference between Resilience and Reliability

• 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, it should be adjusted for commonly expected threats and hazards for the locality of interest, which are called Design Basis Threats (DBTs).

• Resilience planning is based on low probability. High consequence events.
Energy Resilience Metrics

• Energy Quality
• Energy Availability
• Reliability
  • Maintainability
Energy Quality

• **Power systems**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Performance Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Deviation (Percent) for 100 Percent Load Increase</td>
<td>G1</td>
</tr>
<tr>
<td>Frequency Deviation (Percent) for 100 Percent Load Decrease</td>
<td>&lt;+18</td>
</tr>
<tr>
<td>Frequency Recovery Time (Seconds) for 100 Percent Load Change</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Voltage Deviation (Percent) for 100 Percent Load Increase</td>
<td>&lt;-25</td>
</tr>
<tr>
<td>Voltage Deviation (Percent) for 100 Percent Load Decrease</td>
<td>&lt;+35</td>
</tr>
<tr>
<td>Frequency Droop (Percent)</td>
<td>&lt;-8</td>
</tr>
<tr>
<td>Steady-State Frequency Band (Percent)</td>
<td>&lt;-2.5</td>
</tr>
<tr>
<td>Steady-State Voltage Regulation (Percent)</td>
<td>&lt;5</td>
</tr>
</tbody>
</table>

*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.*

• **Thermal systems** energy quality 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 Availability (based on TM 5-698-1)

- *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 (EA) 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: $0 < EA < 1$ (e.g., 0.99999, or 99.999%)

- Energy availability can be calculated using one of two equations:

  $$EA = \frac{MTBF}{MTBF + MTTR} \times 100\%$$

  or

  $$EA = \frac{Uptime}{Uptime + Downtime}$$

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

- Reliability of the system with components installed in series: \( R_s = R_1 \times R_2 \times \ldots \times R_n \)

- Reliability of the system with redundant or parallel components: 
  \[
  R = 1 - (1 - R_s) \times (1 - R_s) = 0.9994
  \]
Maintainability

• Maintainability is defined as the measure of the ability of an item to be restored or retained in a specified condition. A commonly used measure of maintainability in terms of corrective maintenance is the mean time to repair (MTTR).

• US Army Corps of Engineers - Power Reliability Enhancement Program (PREP) database:

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>CLASS</th>
<th>Reliability</th>
<th>Inherent Availability</th>
<th>Operational Availability</th>
<th>Unit Years</th>
<th>Failures (Failures/Year)</th>
<th>MTBF</th>
<th>MTTR</th>
<th>MTTM</th>
<th>MDT</th>
<th>MTEM</th>
<th>Hrdy/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Water</td>
<td></td>
<td>0.764449454</td>
<td>0.999679234</td>
<td>0.997055390</td>
<td>2561.4</td>
<td>688</td>
<td>0.260598373</td>
<td>32014</td>
<td>3.94</td>
<td>4.08</td>
<td>7.02</td>
<td>2587</td>
</tr>
<tr>
<td>H06-100 Boiler, Hot Water</td>
<td></td>
<td>0.764449454</td>
<td>0.999879234</td>
<td>0.997055390</td>
<td>2561.4</td>
<td>688</td>
<td>0.268599373</td>
<td>32614</td>
<td>3.94</td>
<td>6.48</td>
<td>7.02</td>
<td>2587</td>
</tr>
<tr>
<td>Steam</td>
<td></td>
<td>0.556019215</td>
<td>0.998367529</td>
<td>0.994011997</td>
<td>2559.0</td>
<td>1502</td>
<td>0.586952425</td>
<td>14925</td>
<td>24.40</td>
<td>6.70</td>
<td>9.37</td>
<td>1556</td>
</tr>
<tr>
<td>H08-210 Boiler, Steam, High Pressure (15 psig)</td>
<td></td>
<td>0.436732634</td>
<td>0.996253408</td>
<td>0.990627330</td>
<td>942.7</td>
<td>781</td>
<td>0.828434003</td>
<td>10574</td>
<td>30.77</td>
<td>5.52</td>
<td>6.84</td>
<td>653</td>
</tr>
<tr>
<td>H08-220 Boiler, Steam, Low Pressure (15 psig)</td>
<td></td>
<td>0.640121314</td>
<td>0.999325624</td>
<td>0.994945943</td>
<td>1616.2</td>
<td>721</td>
<td>0.446087568</td>
<td>19637</td>
<td>13.25</td>
<td>45.03</td>
<td>40.86</td>
<td>8044</td>
</tr>
</tbody>
</table>
Maximum Time to Repair of Thermal System

• MTTR 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

• MTTR can be estimated based on a building’s total heat consumption per the unit of time using the following equation:

\[ Q_{\text{tot}} = Q_{\text{loss tr}} + Q_{\text{inf}} + Q_{\text{vent}} - Q_{\text{int}}, \]

where

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

\[ Q_{\text{loss tr}} = U A (T_{\text{out}} - T_{\text{in}}), \quad \text{where:} \]
\[ U = \text{overall coefficient of heat transfer} \]
\[ A = \text{total area of fenestration} \]
\[ (T_{\text{out}} - T_{\text{in}}) = \text{a difference between inside and outside air temperatures.} \]

\[ Q_{\text{inf}} = AL A C_{p} (T_{\text{out}} - T_{\text{in}}), \quad \text{where:} \]
\[ AL = \text{air leakage rate} \]
\[ C_{p} = \text{specific heat of air.} \]

\[ Q_{\text{vent}} = L C_{p} (T_{\text{out}} - T_{\text{in}}), \quad \text{where} \]
\[ L = \text{outside air ventilation rate.} \]
Major Factor Affecting MTTR

- Major factors affecting 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 and stored can be calculated using the following equation:

\[ Q_{\text{storage}} = M \cdot C_p \cdot \Delta T, \]

where: 
- \( M \) = building mass,
- \( C_p \) = specific heat of the building material
- \( \Delta T \) = is allowable change in the room air temperature.

Notional example of temperature decay rate for different types of building envelope.
Improving Thermal Energy Resilience

• Temperature reduction in mission critical and non-mission critical areas/buildings

\[ T_{occ.min} < T_r < T_{occ.max} \]
\[ T_{surv} < T_r \]

\[ T_{sust} < T_r \]

• Total and critical load control (example for a notional data center and a barracks building.)
Major Topics to be Addressed during the Forum

• Specifics of construction in Arctic climate
• International experiences from Nordic Defense Agencies and sub-Arctic and Arctic infrastructure managers
• Major natural, unintentional, and manmade threats
• Resilience of thermal energy systems serving mission critical facilities – Requirements and Best Practices
• Current and best practices of building envelop designs
• Air Barrier in Cold and Arctic Climates
• Current and best practices of HVAC system designs
• Energy generation, storage, and delivery strategies
• Energy efficiency and renewable energy strategies
• Thermal energy resilience studies
Thank you.

Questions?

Welcome to the Forum!