Requirements for Building Thermal Conditions and Indoor Air Quality under Emergency Operations in Cold Climates

IEA EBC Annex 93

EBC
Energy in Buildings and Communities Programme

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- Requirements to IAQ and Thermal Conditions under Black skies operations
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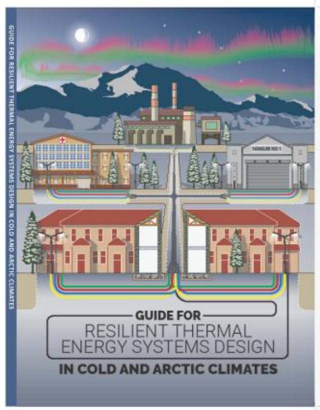
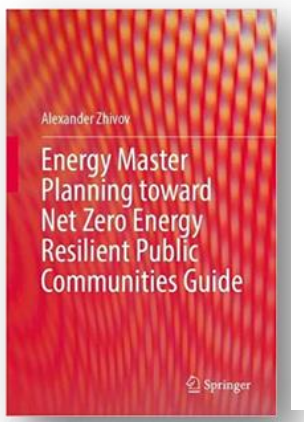
- Questions and Discussion

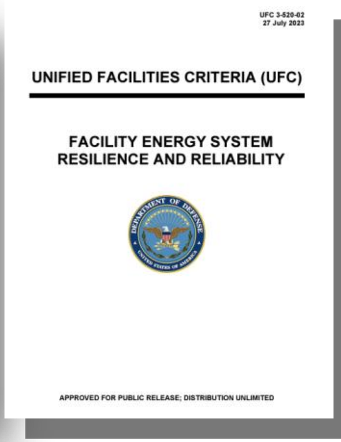
IEA EBC Annex 93“Energy Resilience of Buildings in Remote Cold Regions” - Collaborative Project (Participants from 10 countries)

- **Norway**
  - SINTEF, Norway
  - Norwegian University of Science and Technology (NTNU), Norway
  - UIT The Arctic University of Norway
- **Denmark**
  - DTU, Denmark
  - University of Southern Denmark, Denmark
  - Ministry of Defence, Denmark
  - COWI A/S
  - Aalborg University
- **USA**
  - US Army, USA (ERDC, USACE)
  - NREL
  - University of Alaska
  - National Personal Protective Technology Laboratory (NPPTL)/NIOSH/CDC,
  - ASHRAE
  - RDH Building Inc
  - ZAE
  - Design Alaska Inc
  - LBNL
  - Alaska Thermal Imaging
  - Danfoss
- **China**
  - Tsinghua University
- **Finland**
  - VTT, Finland
  - Arctic Construction Cluster Finland
- **Sweden**
  - Lund University, Sweden
  - Linköping University, Sweden
  - University of Gavle, Sweden
  - KTH, Sweden
  - Luleå University
  - LTU Business
  - Tekniska verken
- **Canada**
  - University of Toronto
  - RDH building science
  - Carleton University, Canada
  - Concordia University, Canada
  - HDA Engineering, Canada
  - Natural resources Canada
  - University of Ottawa
- **Japan**
  - Tokyo City University, Japan
  - Hokkaido University, Japan
- **UK**
  - Imperial College
- **Iceland**
  - Reykjavik University

Background: IEA EBC Annex 73 Research Results







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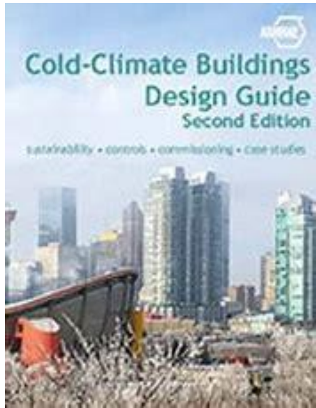
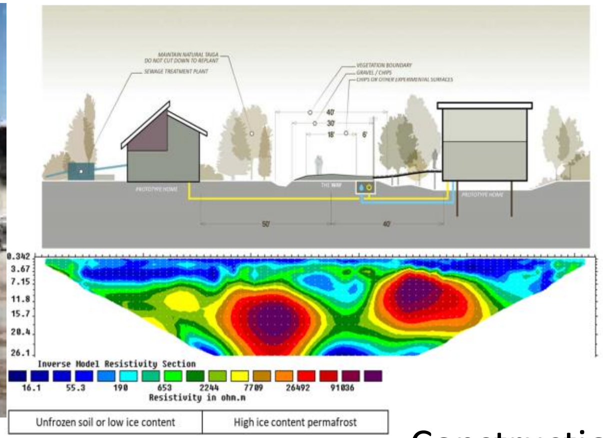


Challenges in Cold and Arctic Regions

Remoteness, shortage of resources (e.g. fuel)

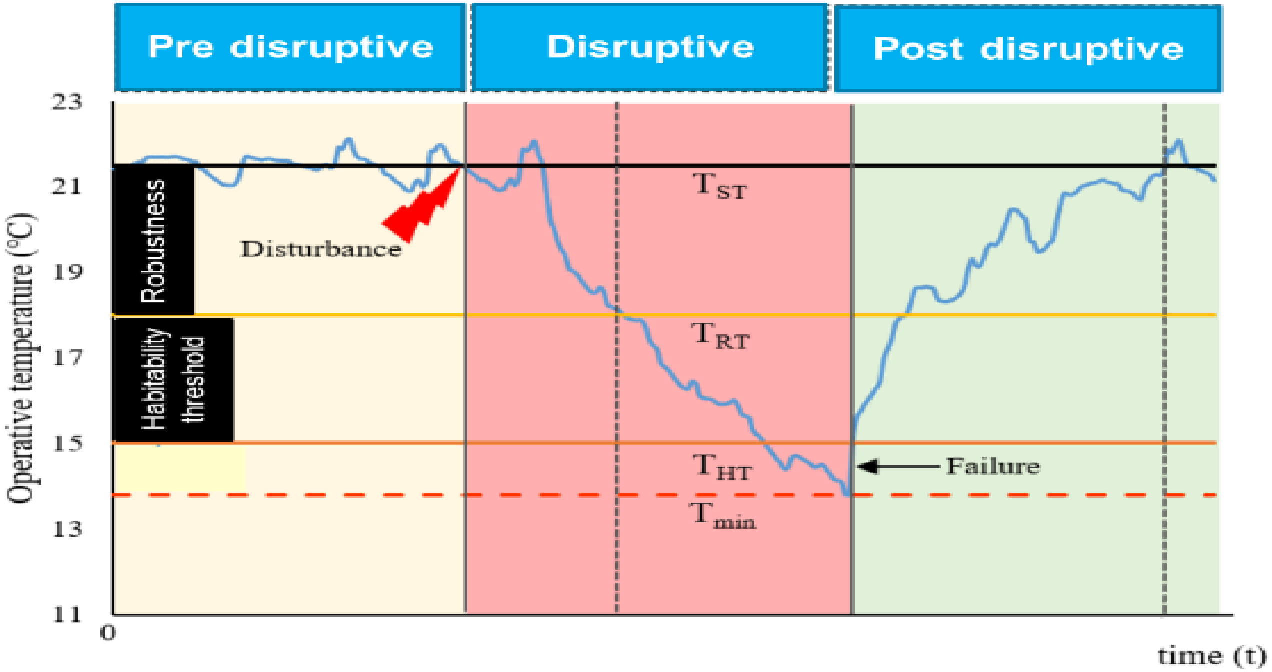
Cold wave



Construction challenges (permafrost)

Shortage of parts and limited maintenance, high costs, accessibility, delivery issues

Mold and other sustainability issues), Dry air during cold time of the year



Energy systems resilience: risks to missions, health and buildings sustainability

Normal (Blue sky) and Emergency (Black sky) Situations

- **Blue Sky** operation of building or building community is an operation under normal/design conditions
- **Black Sky** situation refer to extreme disruptions to critical infrastructure, especially the power grid and thermal energy supply systems. Unlike typical emergencies that might affect a building, or a building community and can last between few seconds and few days, Black Sky events may affect building community, a city, a region, the entire country or several countries and can last for days, months or years. It can be caused by:
  - Natural disaster (e.g., earth quacks, hurricanes, floods, Arctic vortex…)
  - Major logistics problem with fuel supply to remote locations
  - Cyber attacks
  - Physical or electromagnetic pulse attacks
  - Geopolitical situation…

Requirements for Building Thermal Conditions and Indoor Air Quality under Normal Operations

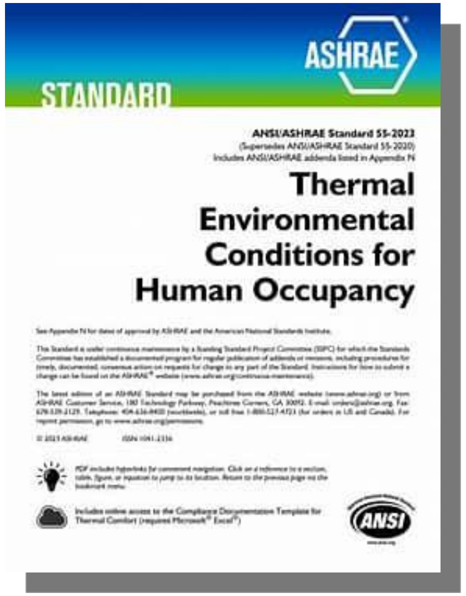
Three scenarios can be considered under normal (blue sky) operating conditions:

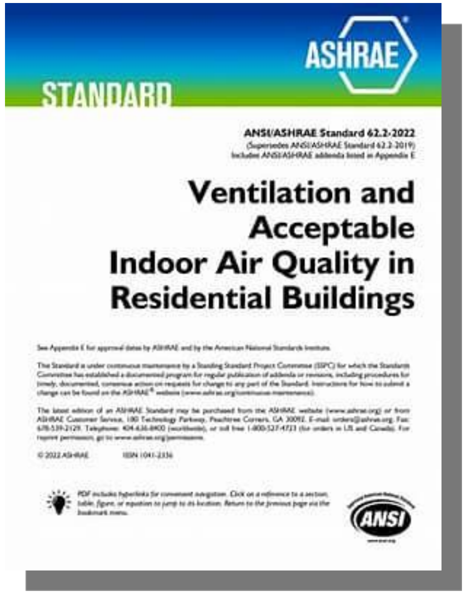
- Building/space is occupied,
- Building is temporarily (2-5 days) unoccupied, and
- Building is long-term unoccupied (e.g., when a building is hibernated).

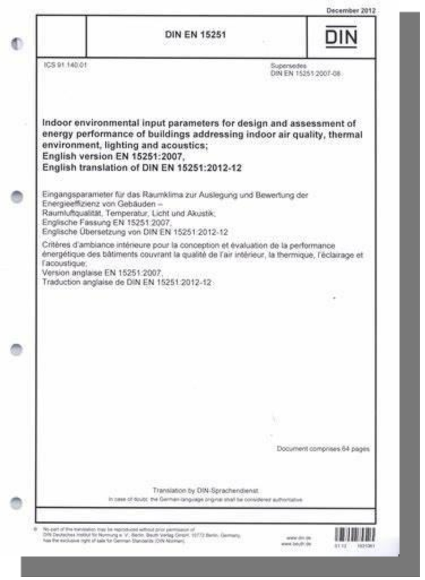
Maintaining thermal parameters is necessary to achieve one or several purposes:

- Perform the required work in a building safely and efficiently,
- Support processes housed in the building, and
- Provide conditions required for the long-term integrity of the building and its materials.

Current Standards







Acceptable ranges of indoor air temperatures and humidity:

Temperature in winter: 20°C to 23°C (68°F to 74°F)

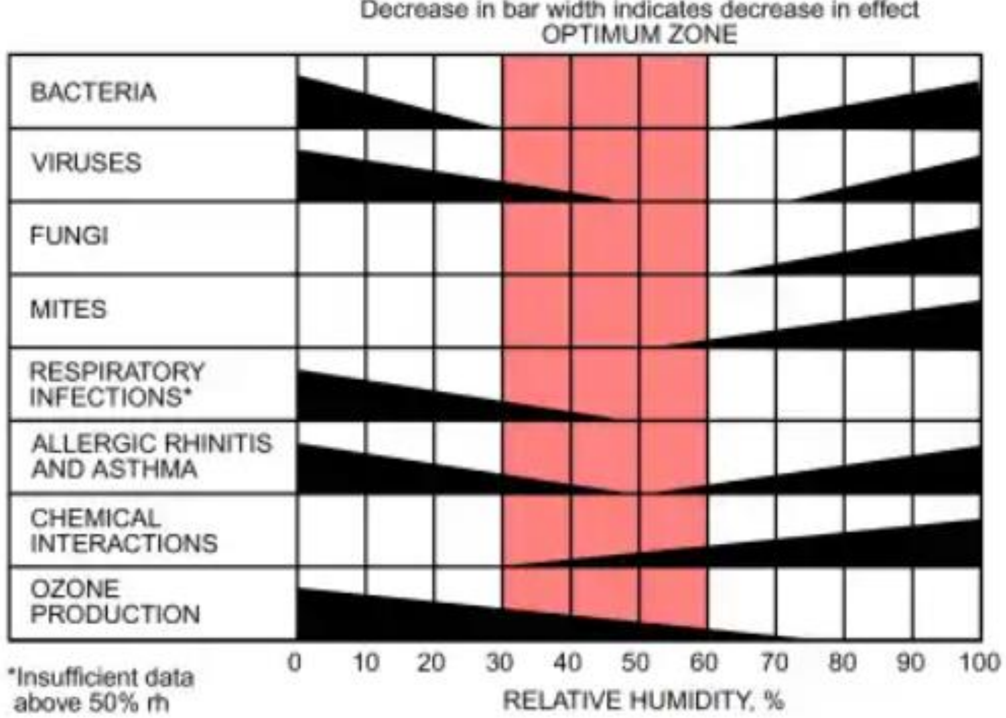
Temperature in summer: 22°C to 26°C (72°F to 80°F)

Relative humidity: 30% to 65%

Ventilation rate: ASHRAE Std 55 Vs EN15251 (B. Olesen, 2012)

Type of building/ space	Occupancy	Categ-ory	Minimum ventilation rate, i.e. for occupants only l/s person		Additional ventilation for building (add only one) l/s·m²				Total l/s·m²	
	person/m²	EN	ASHRAE R_p	EN	EN Very low-pollut.	EN Low-pollut.	EN Not low-pollut.	ASHRAE R_a	EN Low Pol.	ASHRAE
Single office	0,1	I	2,5	10	10	1,0	2,0	0,3	2	0,55
		II		7	7	0,7	1,4		1,4	
		III		4	4	0,4	0,8		0,8	
Land-scaped office	0,07	I	2,5	10	10	1,0	2,0	0,3	1,7	0,48
		II		7	7	0,7	1,4		1,2	
		III		4	4	0,4	0,8		0,7	
Conference room	0,5	I	2,5	10	10	1,0	2,0	0,3	6	1,55
		II		7	7	0,7	1,4		4,2	
		III		4	4	0,4	0,8		2,4	
Classroom	0,5	I	3,8	10	10	1,0	2,0	0,3	6	2,2
		II		7	7	0,7	1,4		4,2	
		III		4	4	0,4	0,8		2,4	

Relative Humidity



Optimum Humidity Range for Human Comfort and Health (Adopted from Sterling et al 1985)

ASHRAE Standard 55 does not specify a minimum humidity level.
However, low RH effects: skin dryness, dryness of eyes, dehydrate the mucous membranes nose and throat, and make them vulnerable to infections from colds and flu.
Multiple epidemiological studies show statistically significant **reduction in respiratory infections and absenteeism** in the occupants in mid-range buildings RH levels compared to occupants of buildings with low RH.
In buildings located in continental cold climate regions RH in the range between 5% and 10% is common.

Process Requirements (example): Recommended and Allowable Conditions for Data and Electronic Equipment Centers

Conditions	ClassA1/ClassA2 (ASHRAE 2019a)		NEBS (ASHRAE 2005)	
	Allowable level	Recommended level	Allowable level	Recommended level
Temperature control range		64 °F-80 °F (18 °C–27 °C)	41 °F-104 °F (5 °C–40 °C)	65 °F-80 °F (18 °C–27 °C)
A1	51 °F - 89 °F (11 °C – 32 °C)			
A2	51 °F - 91 °F (11 °C - 33 °C)			
Maximum temperature rate of change	9 °F/hr (31 °F/hr)[1] (5 °C/hr [2 °C/hr])		2.9 °F/hr (1.6 °C/hr)	
RH control range		15 °F - 51 °F dewpoint (-9 °C - 11 °C) dewpoint and 60% RH	5%-85% 82 °F (28 °C) Max dewpoint	Max 55%
A1	10 °F (-12 °C) dewpoint and 8% RH to 62 °F (17 °C) dewpoint and 80%RH			
A2	10 °F (-11 °C) dewpoint and 8% RH to 69 °F(21 °C) dewpoint and 80%RH			

[1] 9 °F/hr (5 °C/hr) for tape storage, 31 °F/hr (2 °C/hr) for all other IT equipment and not more than 9 °F (5 °C) in any 15 min period.

Thermal Environment Requirements for Selected Spaces in Medical Facilities

Space	T °F	T °C	RH, %
Operating/surgical cystoscopy rooms	68-75	20-24	30 to 60
Critical and intensive care	70-75	21-24	30 to 60
Radiology	70-75	21-24	Max 60
X-ray (surgery/critical care and catheterization)	70-75	21-24	Max 60

Recommended Thermal Conditions for Buildings Located in Cold and Arctic climates – Normal (Blue Sky) Operations

Type of Requirement	Space occupancy						
	Occupied			Unoccupied (Short term)		Unoccupied (Long-term/ Hibernated)	
	Normal Operations (regular business hours)			Unoccupied for a short time period (e.g., few days)		Unoccupied for extended period of time (e.g., weeks) Building freezing/ not Freezing	
	DP	Maximum Dry Bulb Temp	Minimum Dry Bulb Temp	DP	Minimum Dry Bulb Temp	Humidity not to exceed	Minimum Dry Bulb Temp
Human Comfort	< 63 °F/17.2 °C[1]	82 °F/27.8 °C[1]	68 °F/20 °C[1]	< 63[1]	55 °F/12.7 °C[4]	N/A	
Process Driven	Process specific			Process specific		N/A	
Building Sustainment	Humidity not to exceed		Minimum Dry Bulb Temp	Humidity not to exceed	Minimum Dry Bulb Temp	Humidity not to exceed	Minimum Dry Bulb Temp
	80%[3]		40 °F/ 4.4 °C[2]	< 80%3	40 °F/4.4 °C**	80%***	40 °F /4.4 °C**, or N/A if drained

1ASHRAE Standard 55

2 To prevent water pipe rupture, with factor of safety

3 To prevent interior surface mold growth, with no factor of safety

4 To prevent long time recovery and a significant energy loses

Indoor Air Temperature during Black Skies Operations

- Based on studies and analysis conducted by Jon Williams 2021, Parsons 2003, Wargocki and Wyon 2017 and recommendations by ACGIH, indoor air temperature in mission critical facilities during emergency situations, shall be above 60.8 °F (16 °C) (ACGIH 2018) and the Wet Bulb Globe Temperature(WBGT) shall be below 87.8 °F (31 °C) not to impair the performance of mission operators.
- With the indoor air temperature below 60.8 °F (16 °C), occupants experience symptoms of hypothermia, e.g. numbness (tactile sensitivity, manual dexterity decreases), shivering, cold becomes a distraction, muscle stiffness, cognitive changes (confusion, apathy, loss of attention, reduced memory capacity, etc.), loss of sensory information (blurred vision), cardiovascular effects, etc.
- With the WBGT below 87.8 °F (31 °C), occupants experience symptoms of hyperthermia, e.g., feelings of subjective discomfort due to heat, Sweating (leading to loss of body fluid that must be replaced by drinking fluids), increased heart rate from decrease in body fluids, increased perception of thirst (not a good indicator of the level of dehydration), heat cramps, altered cognitive function, dizziness or lightheadedness (especially getting up from seated position), etc.

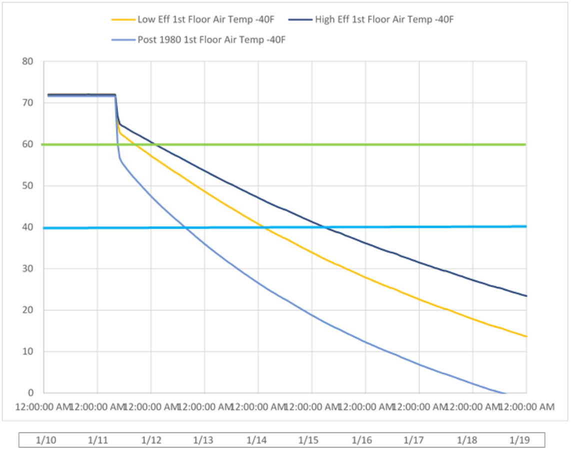
Recommended Thermal Conditions for Buildings Located in Cold and Arctic climates – Emergency (Black sky) Operations

Scenario Type of Requirement	Emergency (Black Sky) Space Occupancy					
	Mission-Critical Operation		Tertiary Space (Non-Mission-Critical Bordering Mission-Critical Space)		Hibernated: Can Be Unoccupied for Extended Period of Time (from Days to Weeks) Building Freezing/ Not Freezing	
	DP	Minimum Dry Bulb Temp	Humidity Not To Exceed	Minimum Dry Bulb Temp	Humidity Not to Exceed	Minimum Dry Bulb Temp
Human Comfort	< 63 °F (17.2 °C) [1]	**> 60 °F (16 °C) [5]**	N/A		N/A	
Process Driven	Process specific – see examples in Tables D-1 & D-2		N/A		N/A	
	Humidity not to exceed	Minimum Dry Bulb Temp	Humidity not to exceed	Minimum Dry Bulb Temp		
Building Sustainment	80%[3]	**40 °F (4.4 °C)[2]**	80%[3]	**40 °F (4.4 °C)[2] 55 °F (12.7 °C)[4]**	80%[3]	N/A **40 °F (4.4 °C)[2] or N/A if drained**

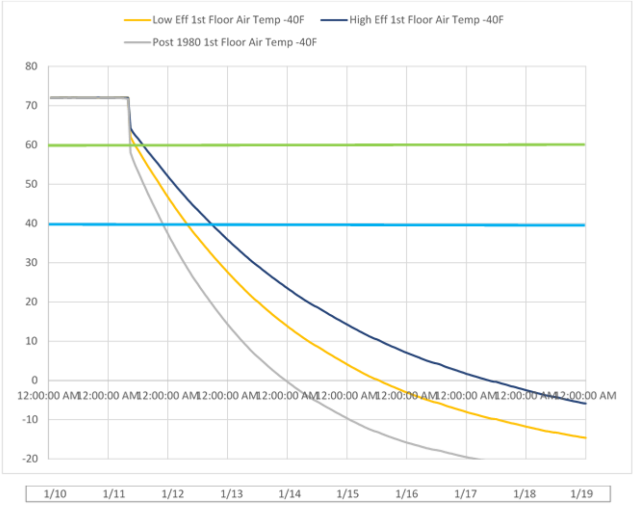
Affect on Thermal Energy Systems Resilience Metrics: Maximum Time to Repair (example)

Building Parameters	Temp ODB	Mass Building			Frame Building		
		Typical/Post 1980	Low Efficiency	High Efficiency	Typical/Post 1980	Low Efficiency	High Efficiency
Walls (R-Value IP)		20.5	40	50	20.5	40	50
Roof (R-value IP)		31.5	45	60	31.5	45	60
Air Leakage cfm/ft^2		0.4	0.25	0.15	0.4	0.25	0.15
Window (R-Value / U value)		Double Pane; R= 1.78 / U=.56	Double Pane; R= 3.34 / U=.3	Triple Pane; R= 5.25 / U=.19	Double Pane; R= 1.78 / U=.56	Double Pane; R= 3.34 / U=.3	Triple Pane; R= 5.25 / U=.19
MTTR Hab. (60F)	-60 F	< 1 hours	2 hours	5 hours	<< 1 hour	1 hours	2 hours
MTTR Sust. (40F)	-60 F	9 hours	28 hours	41 hours	4 hours	14 hours	21 hours
MTTR Hab. (60F)	-40 F	1 hours	3 hours	10 hours	< 1 hour	2 hours	4 hours
MTTR Sust. (40F)	-40 F	20 hours	36 hours	51 hours	10 hours	18 hours	24 hours
MTTR Hab. (60F)	-20 F	2 hours	6 hours	15 hours	1 hour	3 hours	6 hours
MTTR Sust. (40F)	-20 F	31 hours	46 hours	60 hours	15 hour	22 hours	28 hours
MTTR Hab. (60F)	0 F	3 hours	13 hours	29 hours	2 hours	5 hours	9 hours
MTTR Sust. (40F)	0 F	43 hours	59 hours	90 hours	21 hours	28 hours	33 hours
MTTR Hab. (60F)	20 F	10 hours	28 hours	45 hours	3 hour	8 hours	15 hours
MTTR Sust. (40F)	20 F	60 hours	78 hours	95 hours	28 hours	35 hours	40 hours
MTTR Hab. (60F)	40 F	29 hours	54 hours	72 hours	8 hour	17 hours	23 hours
MTTR Sust. (40F)	40 F	93 hours	112 hours	123 hours	41 hours	47 hours	50 hours

Mass Building:



Frame Building



Ventilation – Black skies

- While IAQ thresholds and ventilation strategies for buildings in normal (blue skies) situations are well established, IAQ during emergencies (black skies) lasting between few days and few weeks and requirements to ventilation systems in such situations are not well understood. Such situations may include power, heat and cooling energy supply interruption and a shortage of fuel available for normal or emergency operations.
- The use of fuel available for emergency operations can be significantly extended if the amount of energy used for preheating and precooling of ventilation air can be reduced by reduction of outdoor air use.
- This also effects the time to repair of the energy supply system if no fuel is available for the emergency situation.

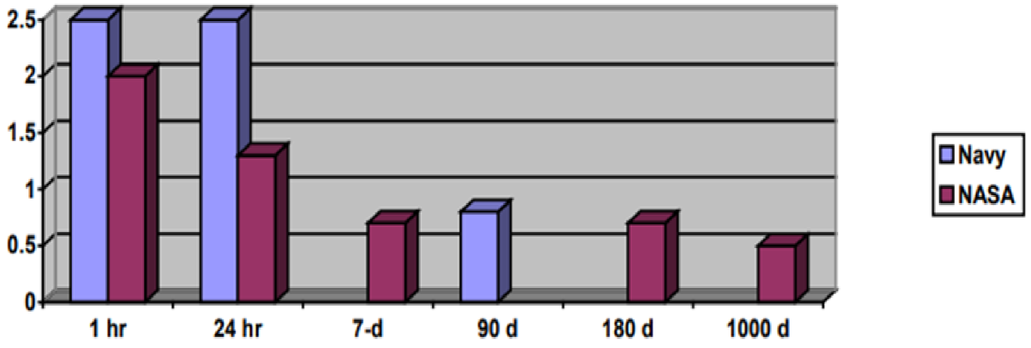
Selecting Ventilation Requirements for Emergency Situations

- Multiple research studies of residential and commercial buildings show that a single value of the CO_2 concentration in indoor air can be used as an indicator for IAQ.
- CO_2 Earth-normal CO_2 levels are approximately 0.5 mmHg [500 ppm], but the levels have been rising dramatically in the past few decades. Considering the supply air CO_2 levels, ventilation rates in different countries have been selected to be based on between 800 and 1000 ppm.
- The closest situations to the one we are analyzing are those with NASA spacecrafts and Navy submarines. In 2004 the U.S. National Research Council (NRC) proposed Continuous Exposure Guidelines (CEGLs) and Emergency Exposure Guidelines (EEGLs) to the U.S. Navy. Similarly, in 2008 the NASA Toxicology Group, in cooperation with another subcommittee of the NRC, revised Spacecraft Maximum Allowable Concentrations (SMACs) for a 1000-day exposure limit.

Selecting Ventilation Requirements for Emergency Situations (Cont.)

- The spacecraft maximum allowable concentration (SMAC) for CO_2 for the Apollo missions and the Space Shuttle was 7600 ppm;
- CO_2 aboard the ISS was set at 5300 ppm in 1994 to prevent hyperventilation and headaches and in 2008 a 1000-day SMAC for exploration-class missions was set at 3800 ppm to prevent headaches, with the 7-180 days SMAC left at 5300 ppm.
- In 2007 the National Research Council Committee on Toxicology, based on scanty evidence, recommended for US Navy a continuous exposure guidance level for a 90-day patrol of 8,000 ppm (6.1 mmHg).
- In 2003 the Institute of Naval Medicine of the UK recommended a level of 7000 ppm as a health-based ceiling limit, not to be exceeded during a 90-day patrol.

Proposed Recommendations for Ventilation Rates



Exposure limits (%) proposed for various times in submarines and adopted by NASA in cooperation with NRC (% CO_2 vs. time of exposure) [John James et al 2009].

- The above data shows that the CO_2 concentration level allowed by NASA and the Navy is 5 times higher than the level adopted by ASHRAE for buildings.
- Therefore, the outside airflow rate can be significantly reduced in emergency situations.
- The outdoor airflow rate can be further reduced, or the HVAC system can operate in recirculation mode when gas air scrubbers are installed along with MERV 14 particle filters.

Summary of Recommendations for Discussion

- Increase RH inside buildings to 25-30% in cold season (with subsequent improvement in building envelop- airtightness, internal vapor barrier, external thermal barrier, reduced thermal bridging) – improves immune system, protects from airborne viral infection, reduces absenteeism, improves productivity;
- Introduce habitability levels for IAQ and thermal conditions inside buildings for emergency/Black skies operations:
  - $T > 60^oF$, $WBGT < 83^oF$,
  - $TLV_{CO2} < 5000ppm$ (with shutting down or significantly reducing OA flow rate and scrubbing recirculated air)

Thank you for your attention.

Questions and Discussion?

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