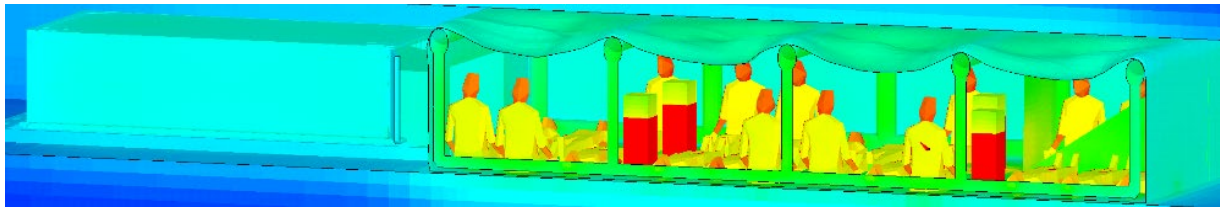
Occupancy Derating and Heat Mitigation Strategies to Meet the Apparent Temperature Limit



Dave Yantek

Lead Research Engineer

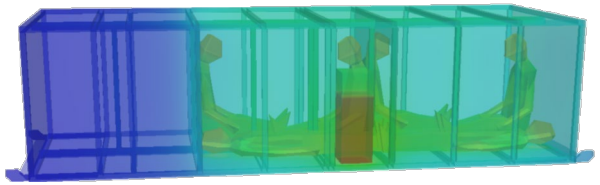
Pittsburgh Mining Research Division

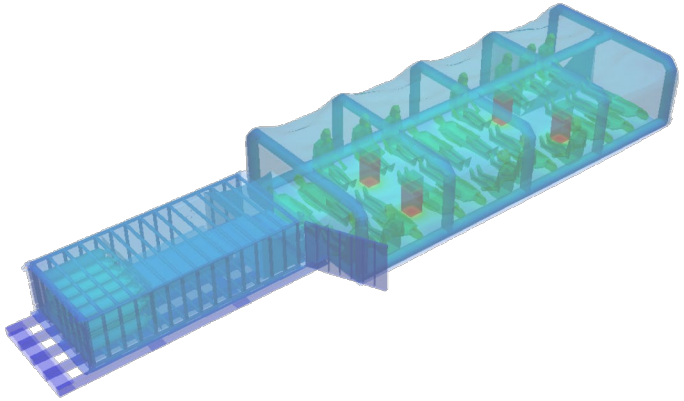
RA Partnership

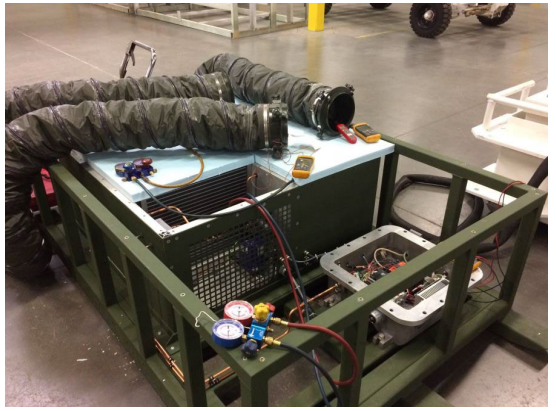
November 17-18, 2021

Outline

- Review of background information on RA thermal environment
- Occupancy derating
  - Field site temperature measurements
  - Simulation to determine apparent temperatures based on real mines
- Heat mitigation strategies
  - Borehole air supply
  - Carbon-dioxide-based cooling system
  - Battery-powered A/C system
  - Cryogenic air supply







The thermal environment of an RA could become severe due to heat buildup.

- RA heat sources include
  - Metabolic activity of ~117 W/miner
  - Carbon dioxide scrubber of 27.5 W/miner
- Heat is transferred from the RA to the mine through conduction, convection, and radiation
  - High resistance to conduction due to low thermal conductivity of mine strata materials
  - Low convection coefficient for natural convection

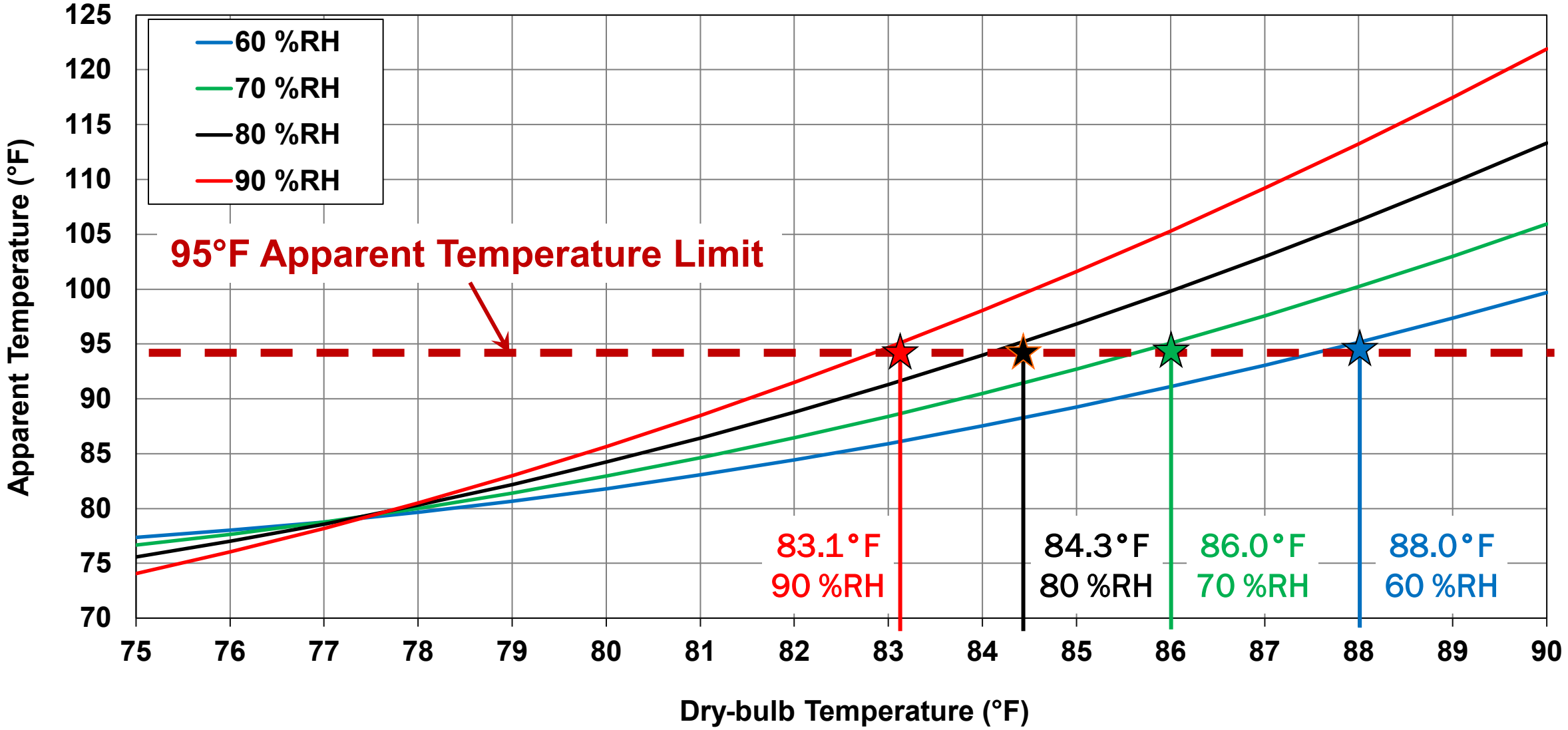
Material	Thermal Conductivity (W/m-K)
Copper	401
Aluminum	205
Carbon Steel	54
Slate	2.01
Sandstone	1.7
Limestone	1.26 – 1.33
Clay, dry to moist	0.15 – 1.8
Coal	0.22 – 0.55
Fiberglass	0.04

Several aspects of RA regulations relate to the thermal conditions in an RA.

- 96-hour duration
- 95°F apparent temperature limit
- Space requirement per miner - 15 ft^2
- Volume requirement per miner based on mine height

Mining Height (inches)	Unrestricted Volume per Person (ft^3)
36 or less	30
36 to 42	37.5
42 to 48	45
48 to 54	52.5
54 or more	60

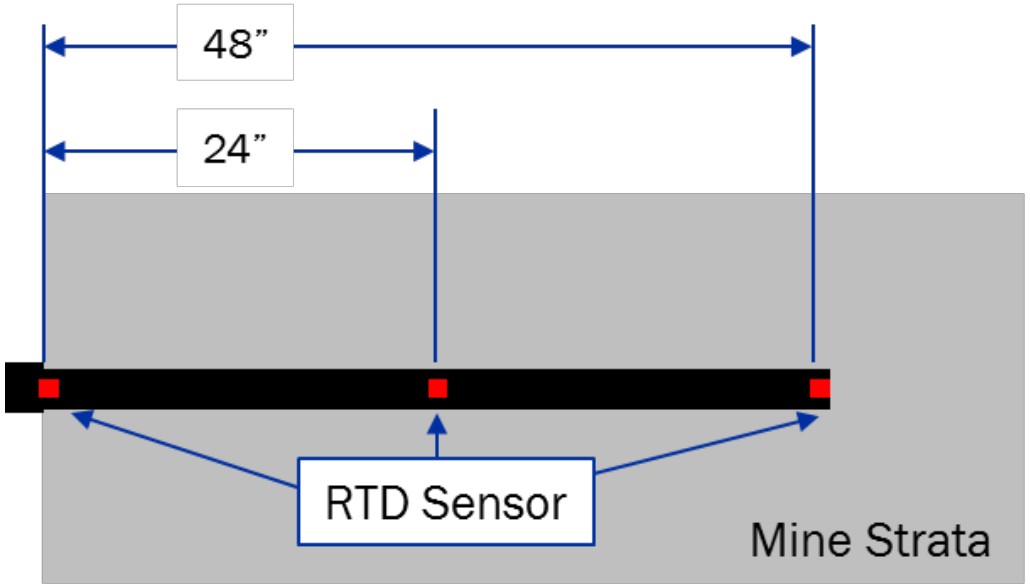
For an environment with no solar load and low air velocity, the apparent temperature is calculated based on the dry-bulb temperature and the %RH.



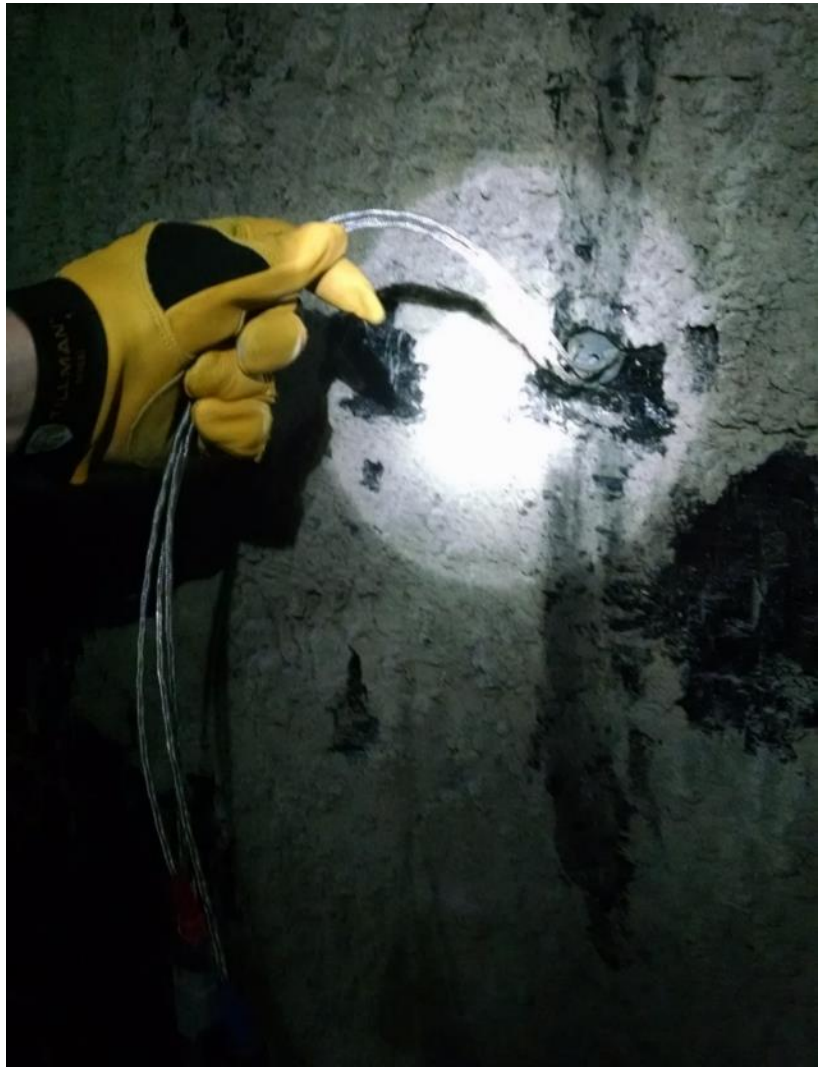
Steadman, R.G., 1979 The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science
https://doi.org/10.1175/1520-0450(1979)018%3C0861:TAOSPI%3E2.0.CO;2

To explore the thermal conditions for RAs in actual mines, NIOSH collaborated with five mines to collect annual temperature data.

The mines installed PVC rods with resistance temperature detectors (RTDs) and documented air temperature and strata temperatures for at least 1 year.



RTD thermometer



RTD probe in rib

The worst-case combinations of mine air temperature and mine strata surface temperature were determined from the collected data.

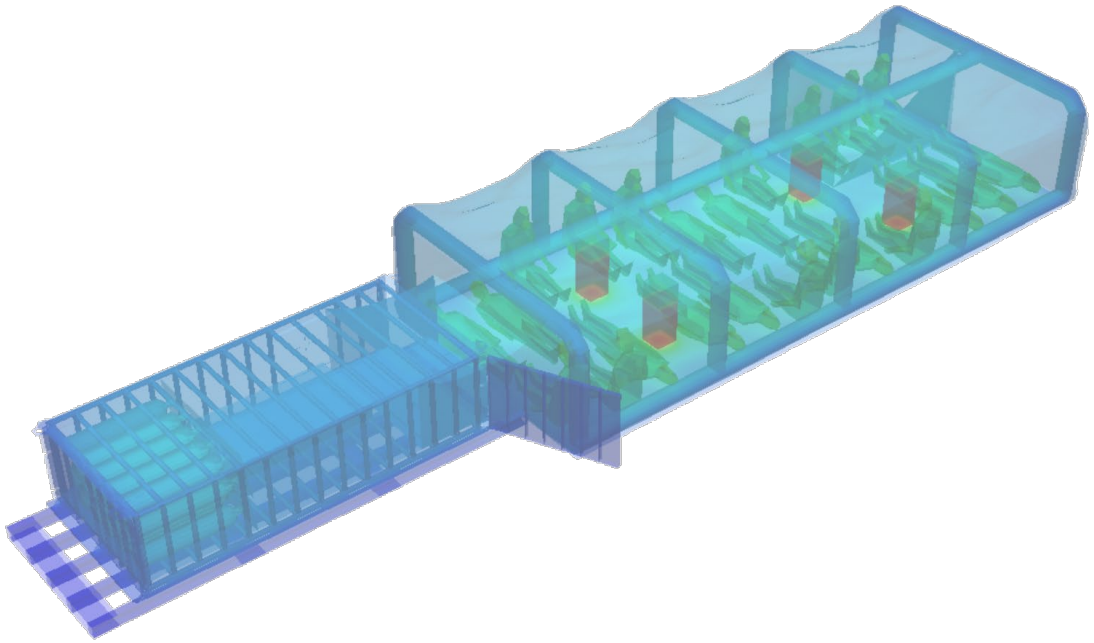
Mine	Width (ft)	Height (ft)	Temperatures (°F)			
			Mine Air	Strata Surface	Strata at 24"	Strata at 48”
Mine 1	19.5	9.5	66	65	66	66
Mine 2	18	5.5	69	67	65	64
Mine 3	21	9.6	81	83	80	79
Mine 4	16	8.5	63	59	59	57
Mine 5	19	7.25	66	63	63	63

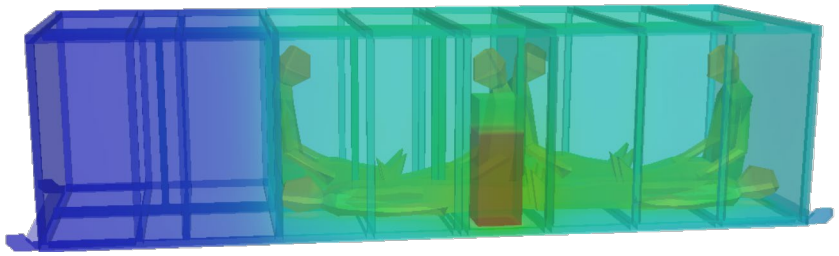
The mine dimensions and mine strata composition were tabulated for each mine to use in thermal simulations of RAs.

Mine	Width (ft)	Height (ft)	Strata Composition		
			Floor	Ribs	Roof
Mine 1	19.5	9.5	mudstone	bituminous coal	2.5' coal, 1.6' shale, 0.6' coal, mudstone
Mine 2	18	5.5	4' claystone, sandstone	bituminous coal	shale
Mine 3	21	9.6	shale	bituminous coal and shale	shale
Mine 4	16	8.5	bituminous coal	2" shotcrete, bituminous coal and mudstone	1' coal, 4' sandstone, coal
Mine 5	19	7.25	shale	coal/shale composite	coal, shale

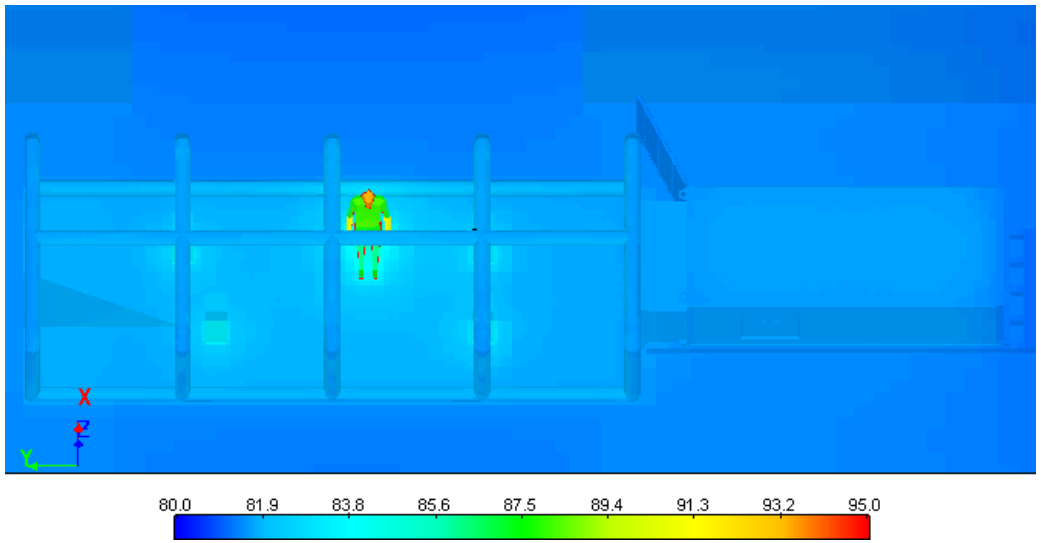
Previously developed thermal simulation models were used to determine the resulting RA thermal environment.

- Validated models of a 23-person tent-type RA and a 6-person rigid RA in the NIOSH Experimental Mine were used as the starting point
- Human thermal models were used to input metabolic heat at 117 W per person
- 4-day transient simulations calculated RA, human, and mine temperatures
- If the interior apparent temperature exceeded 95°F, the number of occupants was reduced (derated)





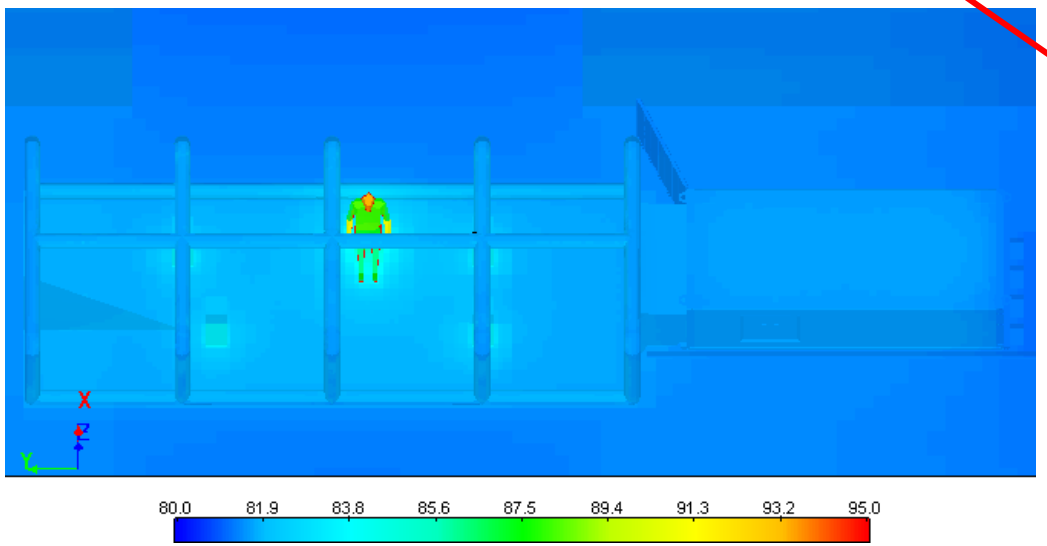
For the 23-person tent-type RA, Mine 2 and Mine 3 were predicted to require derating to meet the 95°F apparent temperature limit.



Mine	# Occ.	Initial Mine Air Temp (°F)	Final RA Air Temp (°F)	Final RH (%)	Final App. Temp (°F)
Mine 1	23	65.6	82.5	92.5	93.7
Mine 2	23	69.4	83.4	93.3	***97.4***
	21	69.4	82.2	91.9	92.8
Mine 3	9	81.3	87.2	99.4	***116.8***
	3	81.3	83.5	98.8	***100.2***
	1	81.3	82.1	99.3	94.5
Mine 4	23	62.7	78.9	84.9	82.3
Mine 5	23	66.4	80.6	88.6	87.1

For the 23-person tent-type RA, Mine 2 and Mine 3 were predicted to require derating to meet the 95°F apparent temperature limit.

With T = 83°F and %RH = 93,
App T = 96°F



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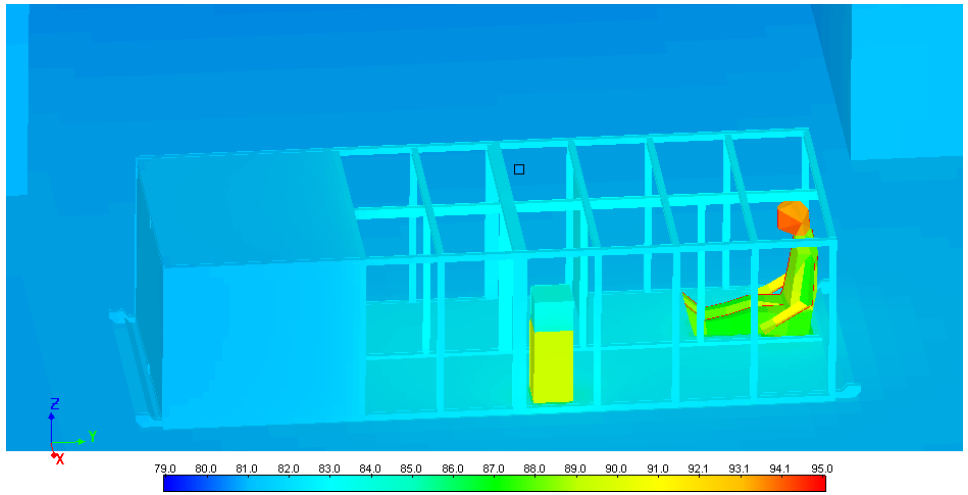
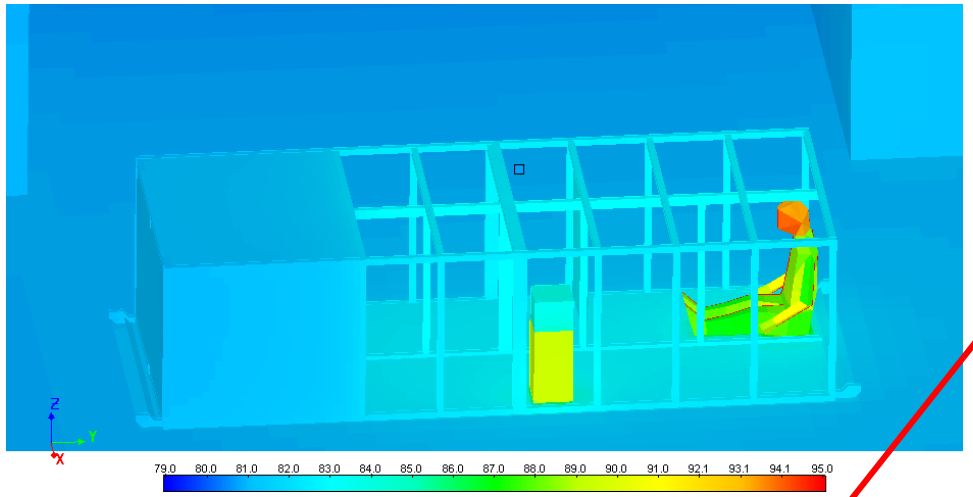
Mine 4	23	62.7	78.9	84.9	82.3
Mine 5	23	66.4	80.6	88.6	87.1

For the 6-person rigid RA, Mine 3 was predicted to exceed the 95°F apparent temperature limit with even 1 occupant.



Mine	# Occ.	Initial Mine Air Temp (°F)	Final RA Air Temp (°F)	Final RH (%)	Final App. Temp (°F)
Mine 1	6	65.6	81.8	90.0	90.8
Mine 2	6	69.4	82.7	91.6	94.2
Mine 3	2	81.3	86.0	98.6	***110.4***
	1	81.3	83.5	98.3	***99.9***
Mine 4	6	62.7	75.8	83.3	76.4
Mine 5	6	66.4	79.8	85.7	84.4

For the 6-person tent-type RA, Mine 3 was predicted to exceed the 95°F apparent temperature limit with even 1 occupant.



With T = 83°F and %RH = 93, App T = 96°F

Mine	# Occ.	Initial Mine Air Temp (°F)	Final RA Air Temp (°F)	Final RH (%)	Final App. Temp (°F)
Mine 1	6	65.6	81.8	90.0	90.8
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Mine 3	2	81.3	86.0	98.6	***110.4***
	1	81.3	83.5	98.3	***99.9***
Mine 4	6	62.7	75.8	83.3	76.4
Mine 5	6	66.4	79.8	85.7	84.4

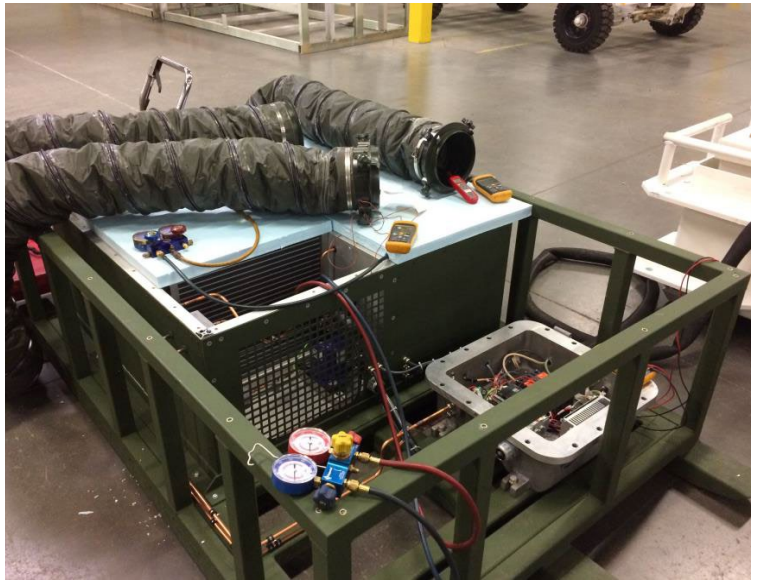
Based on testing and the derating analysis, portable RAs may exceed the apparent temperature limit for mine temperatures as low as 60°F to 65°F.

Range of Initial Mine Temperatures	% Derating Needed for Compliance
60°F to 65°F	0% to 30%
65°F to 70°F	20% to 50%
70°F to 75°F	25% to 70%
75°F to 80°F	60% to 90%

Note: The table above is based on the RAs tested by NIOSH in the Safety Research Coal Mine (10-person tent-type RA training unit) and the Experimental Mine (23-person tent-type RA and 6-person rigid RA).

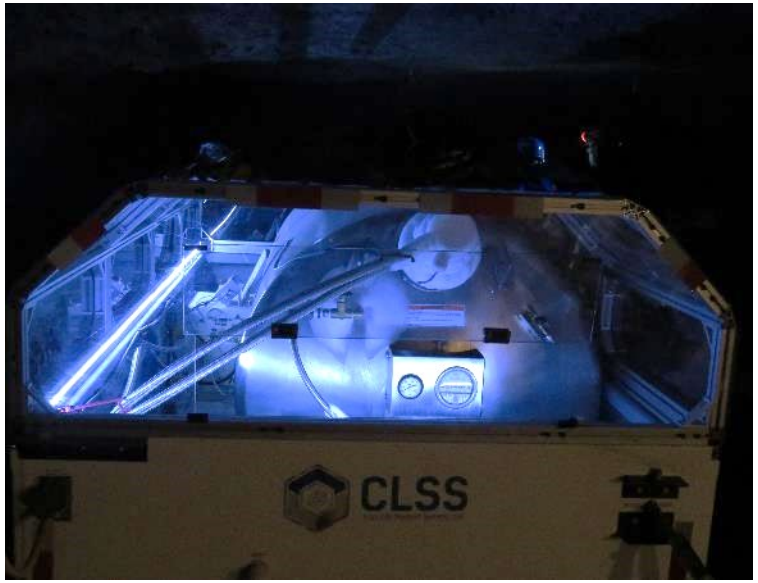
NIOSH conducted testing on several heat mitigation devices.

Borehole Air Supply w/ Air Conditioning



Battery-powered A/C System

Carbon-dioxide-based Cooling System



Cryogenic Air Supply

The borehole air supply (BAS) was tested with a 60-person built-in-place RA with the borehole air supply delivering 55°F dew point air at 750 to 800 CFM.

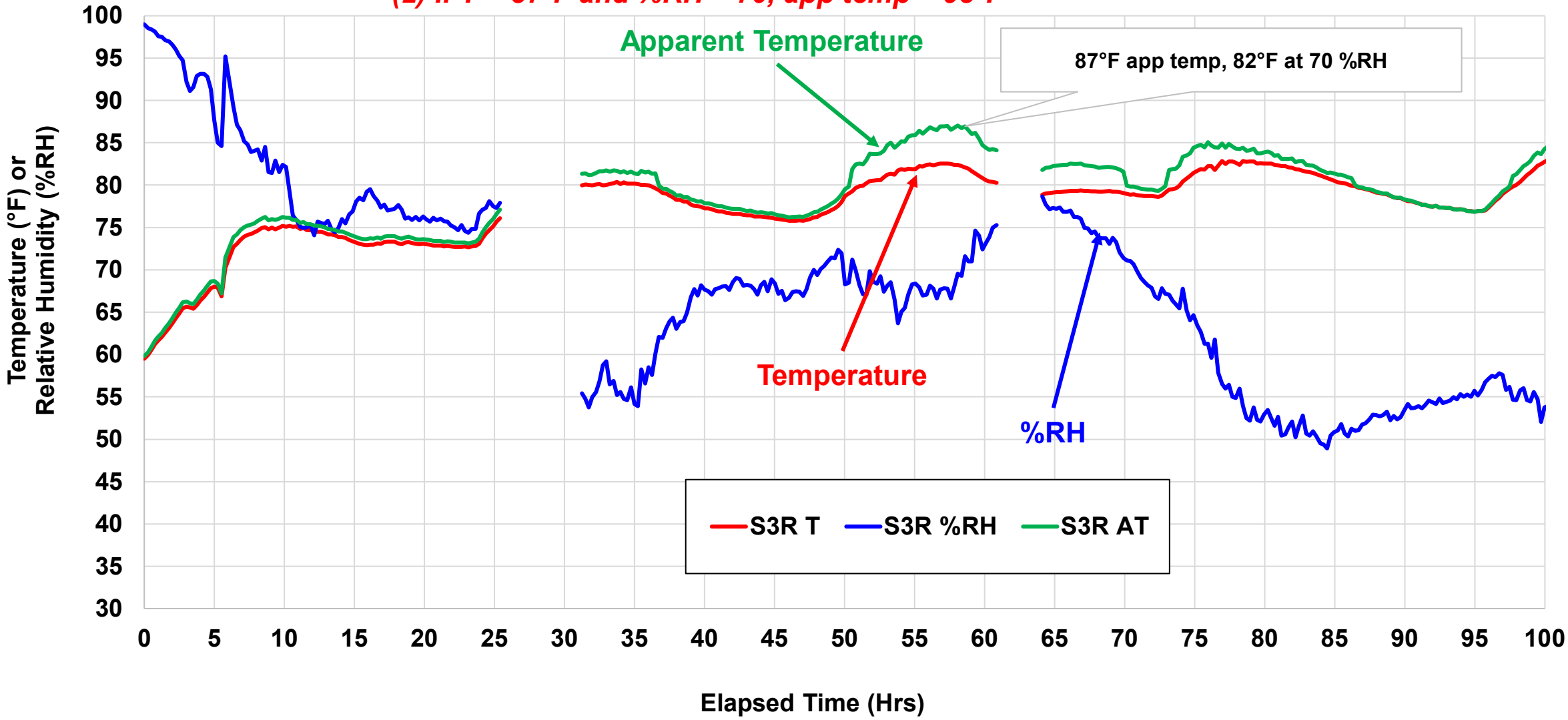
surface

underground

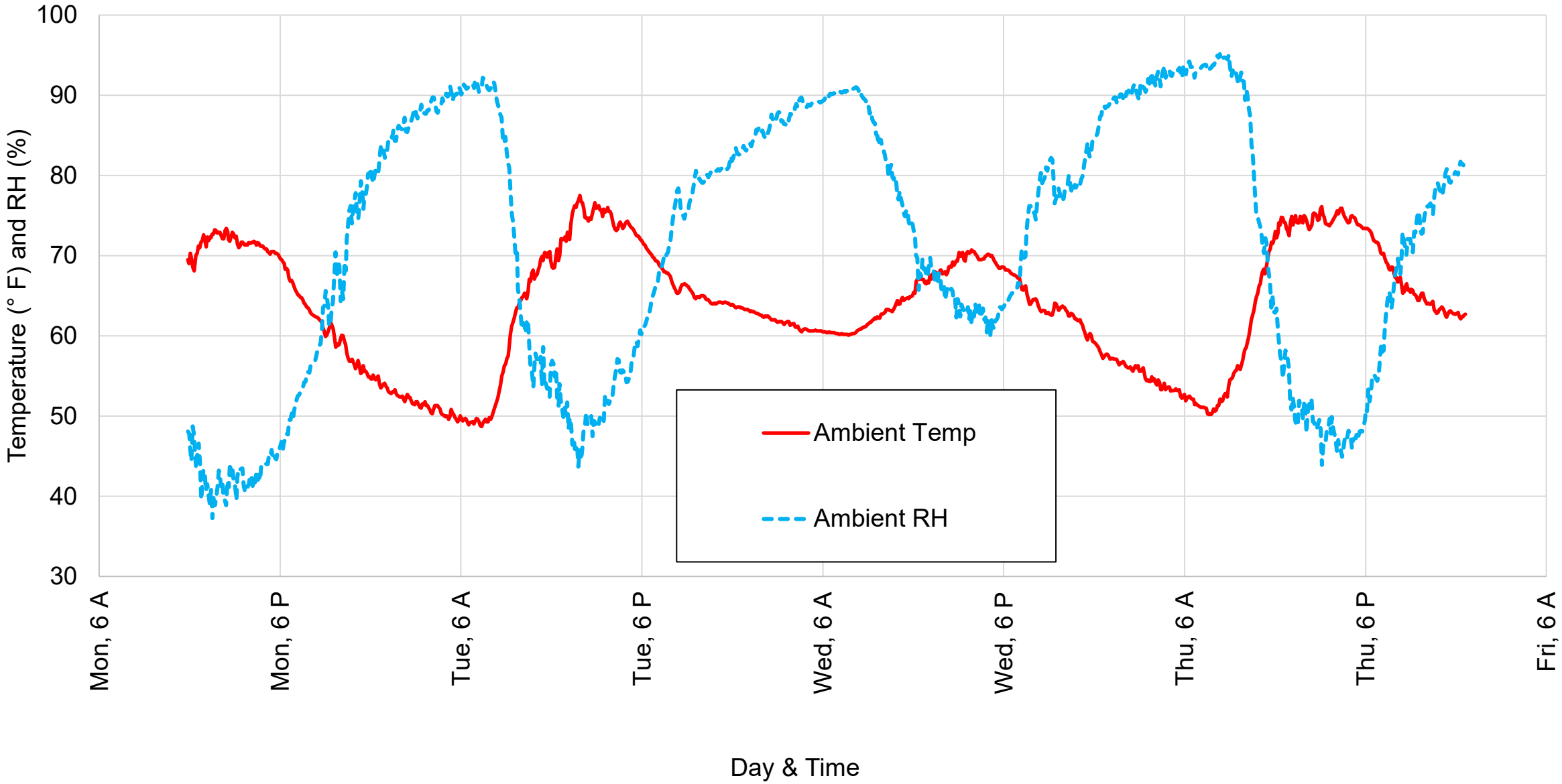
underground

Tests with moderate outside ambient conditions showed the BIP RA could reach the apparent temperature limit in hot ambient conditions.

Note: (1) Outside ambient temperature of 23°F to 68°F with an average of 41°F
(2) If T = 87°F and %RH = 70, app temp = 98°F



With outside temperatures of 50°F to 75°F and relative humidity from 40 to 95 %RH, the apparent temperature was kept below 95°F by the BAS.



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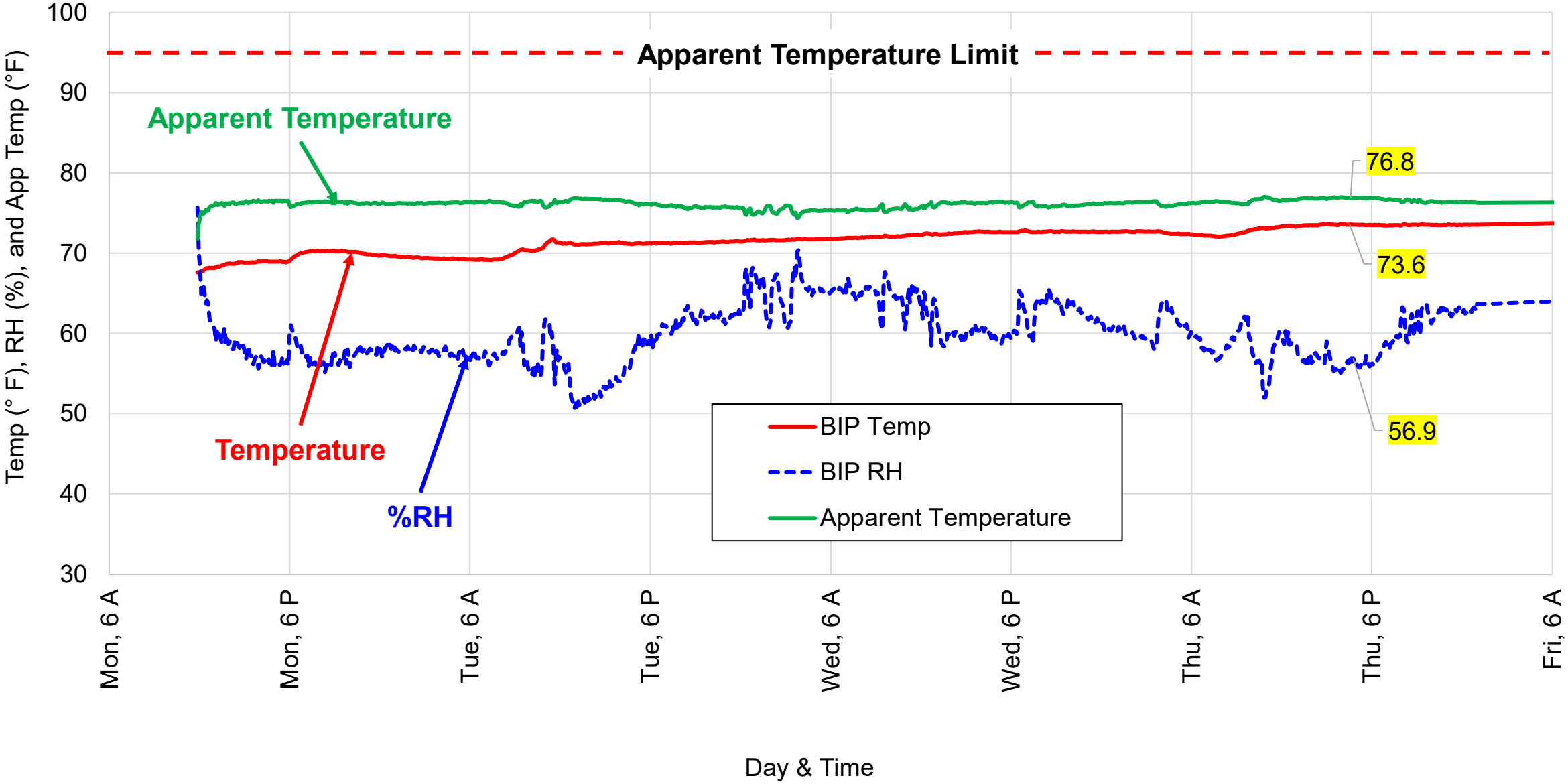
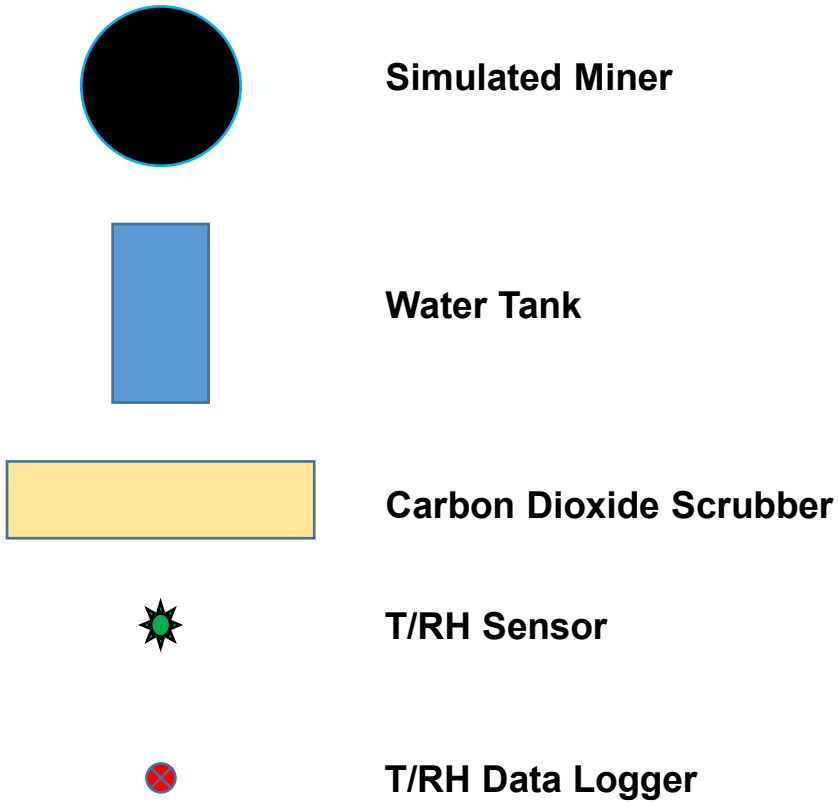


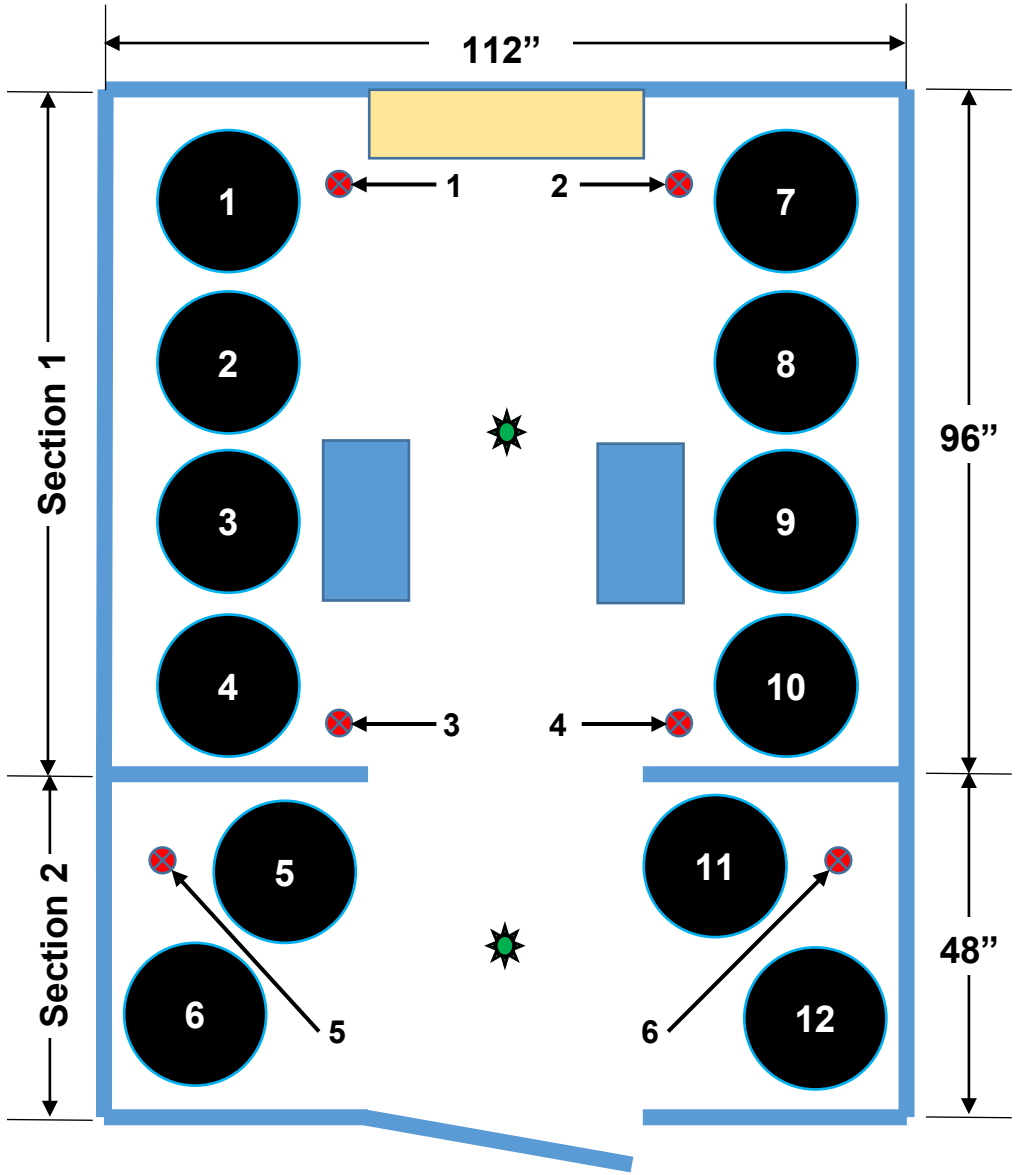
We conducted field heat/humidity testing of a portable rigid RA with a carbon-dioxide-based cooling system at Warrior Met Coal #4.

- As-sold capacity of 12 people
- 2018 capacity of 6 people (15 ft^2/person)
- Two tests:
  - w/o carbon-dioxide-based AC system
  - w/ carbon-dioxide-based AC system

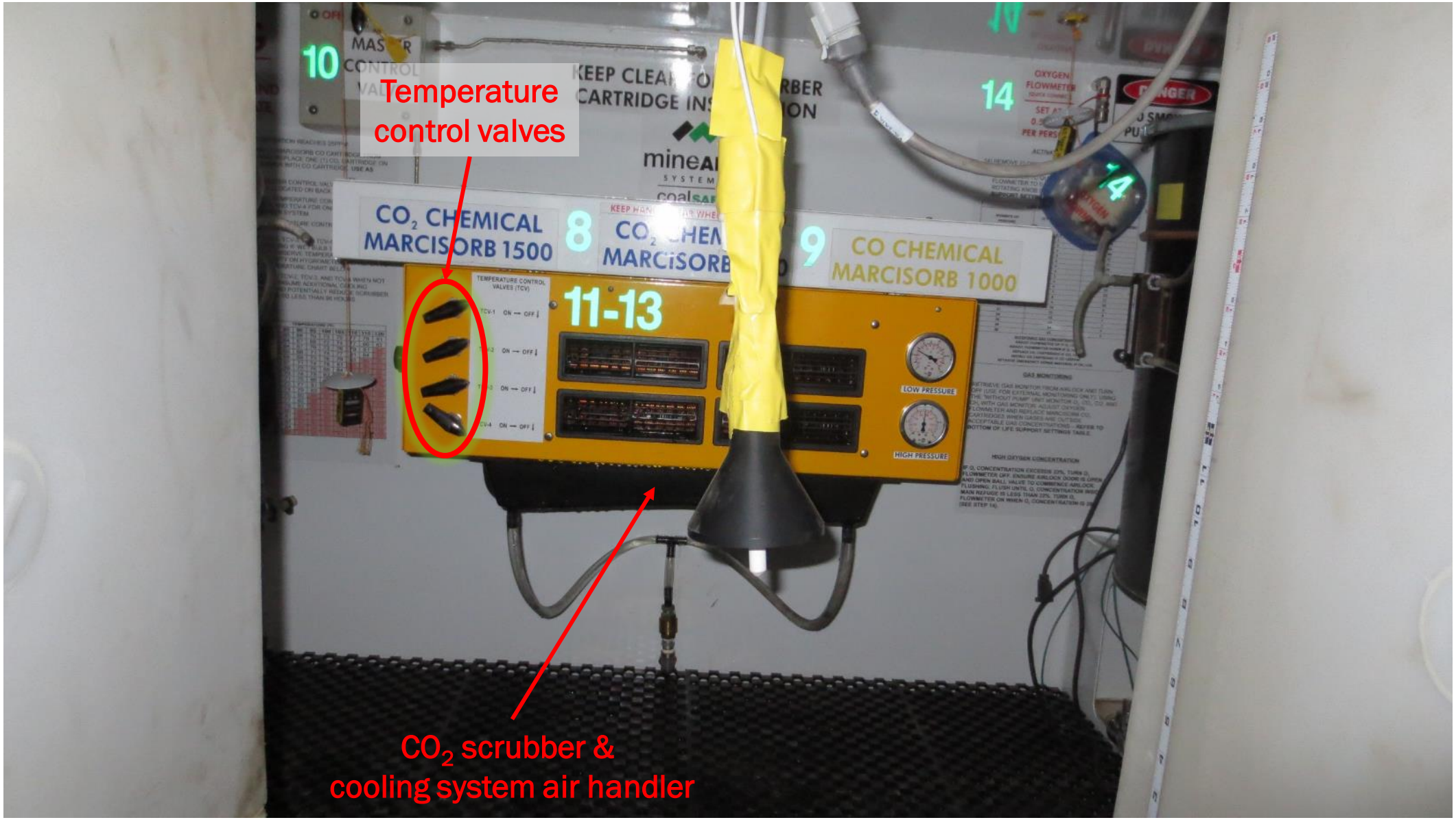
We followed the same test procedures that we used in our research mines.

Within the RA “living space”, eight SMs were positioned on the benches and two heated water tanks were placed on stands. Four SMs were placed on the floor in the air lock.

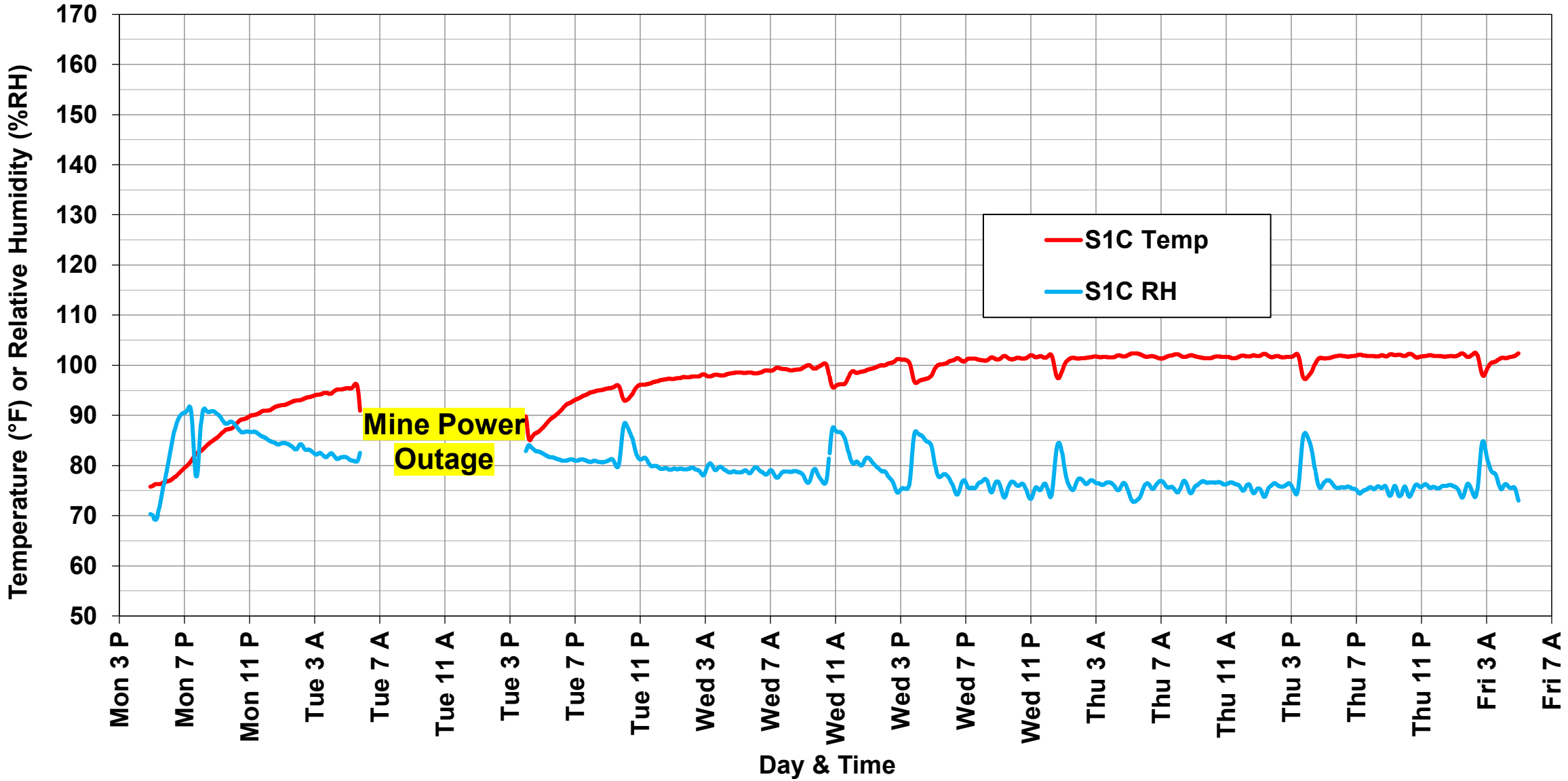




During the test with the cooling system operating, the temperature control valves were adjusted periodically to maximize operating time.



Without the carbon-dioxide-based cooling system, the 95°F apparent temperature limit was exceeded within 4 hours.



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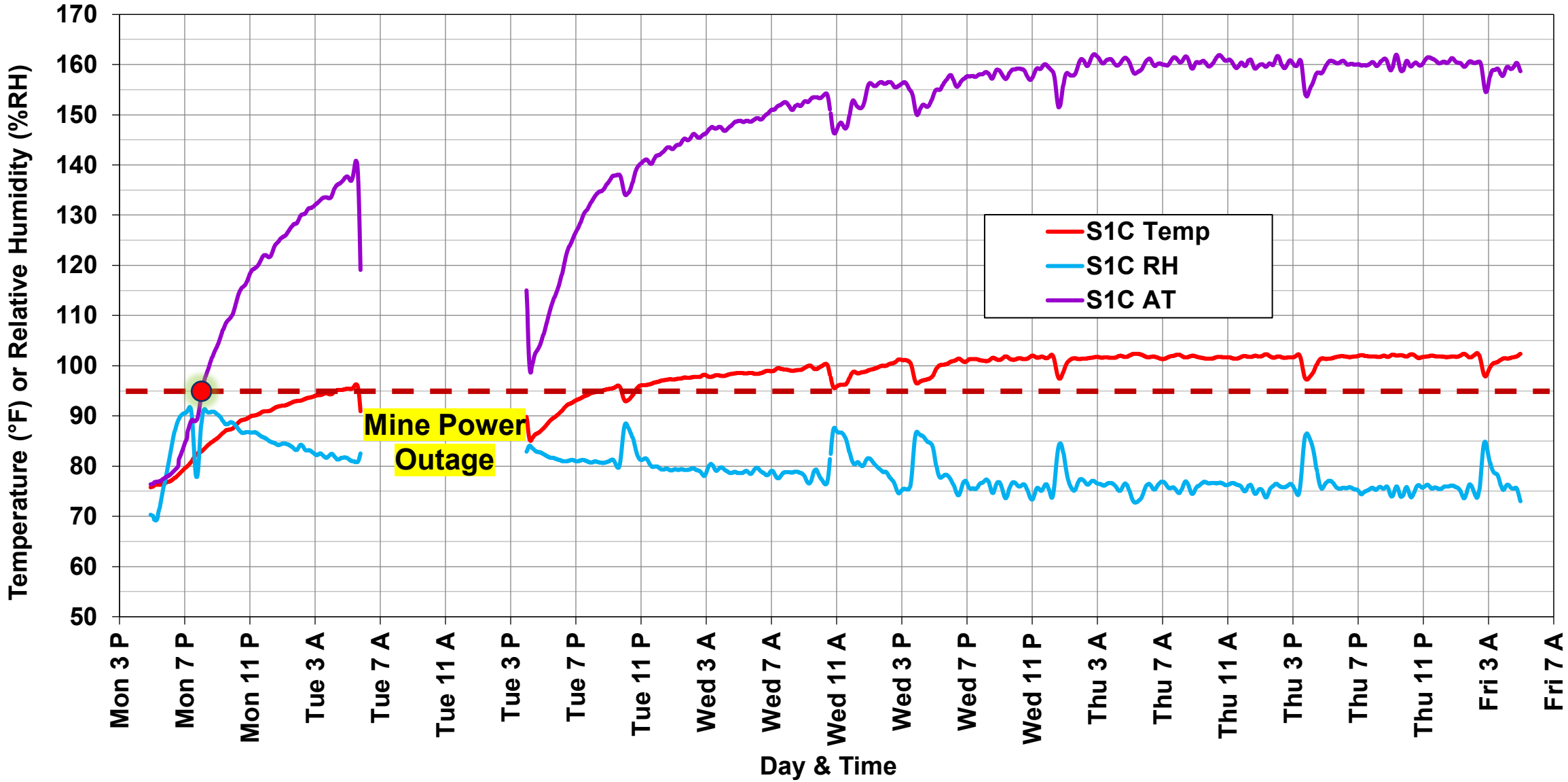

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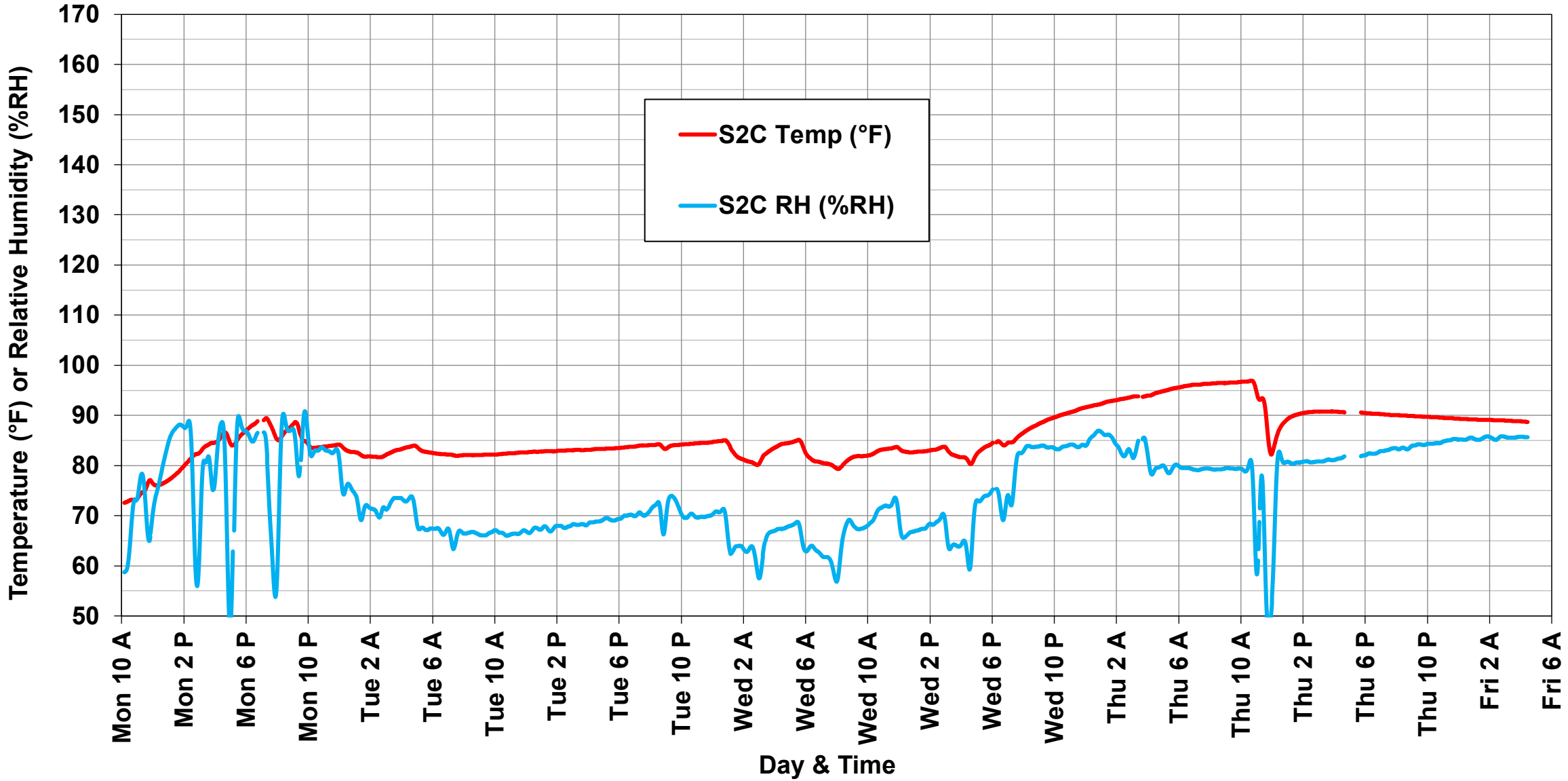
With the cooling system operating, the RA was below the apparent temperature limit until the system ran out of carbon dioxide.



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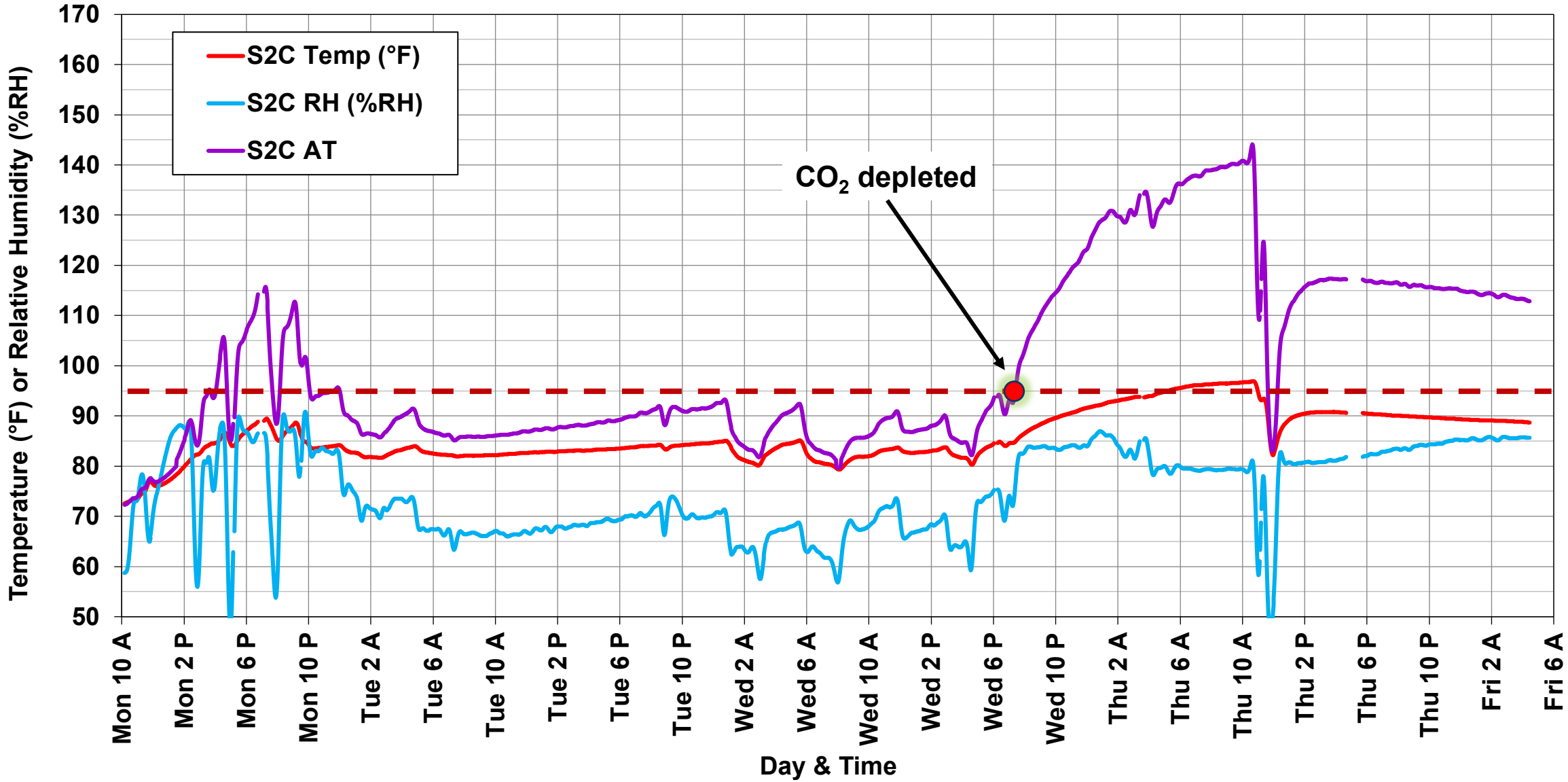

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We tested two heat mitigation systems that were part of Broad Agency Announcement (BAA) contracts.

Contract No. 200-2016-91901
HDT Global (formerly DRS Environmental Systems)
“Refuge Alternative Environmental Control System”

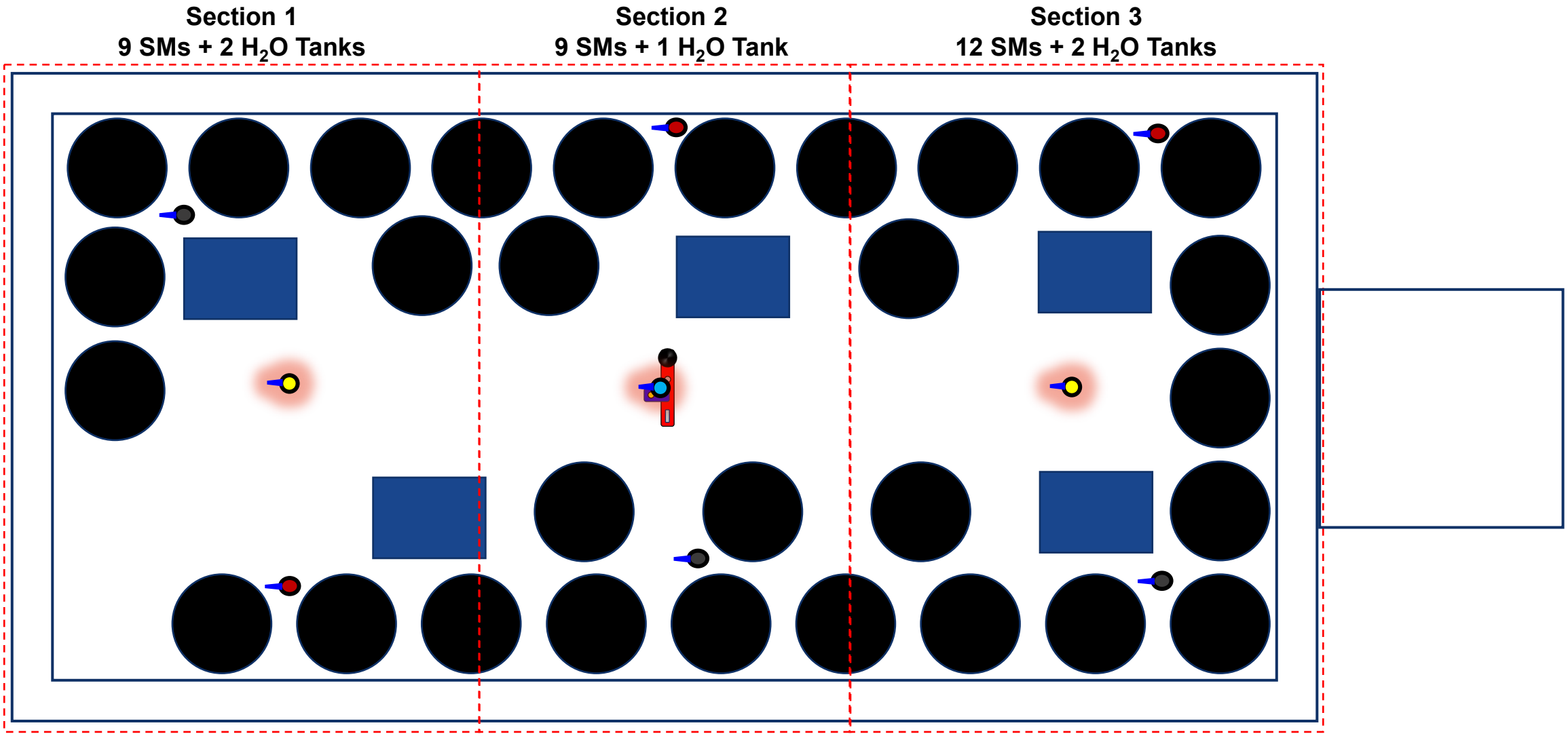
battery-powered A/C system

Contract No. 200-2016-91194
Cryo Life Support Systems, LLC
“Refuge Alternative Heat Mitigation System Utilizing Advanced Liquid Air Technologies”

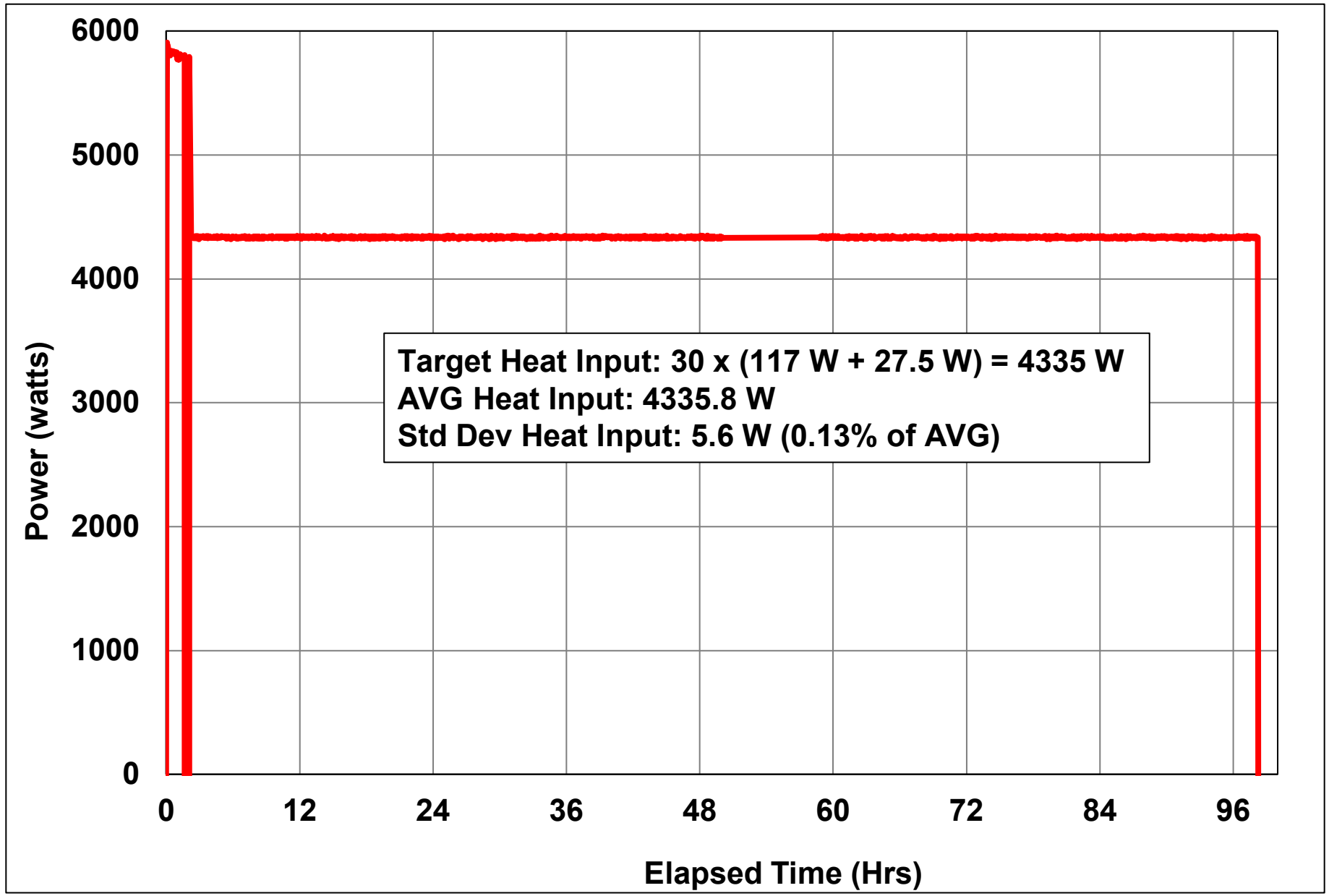
cryogenic air supply

We used a 20-person tent-type RA as a “test mule” for the evaluations.

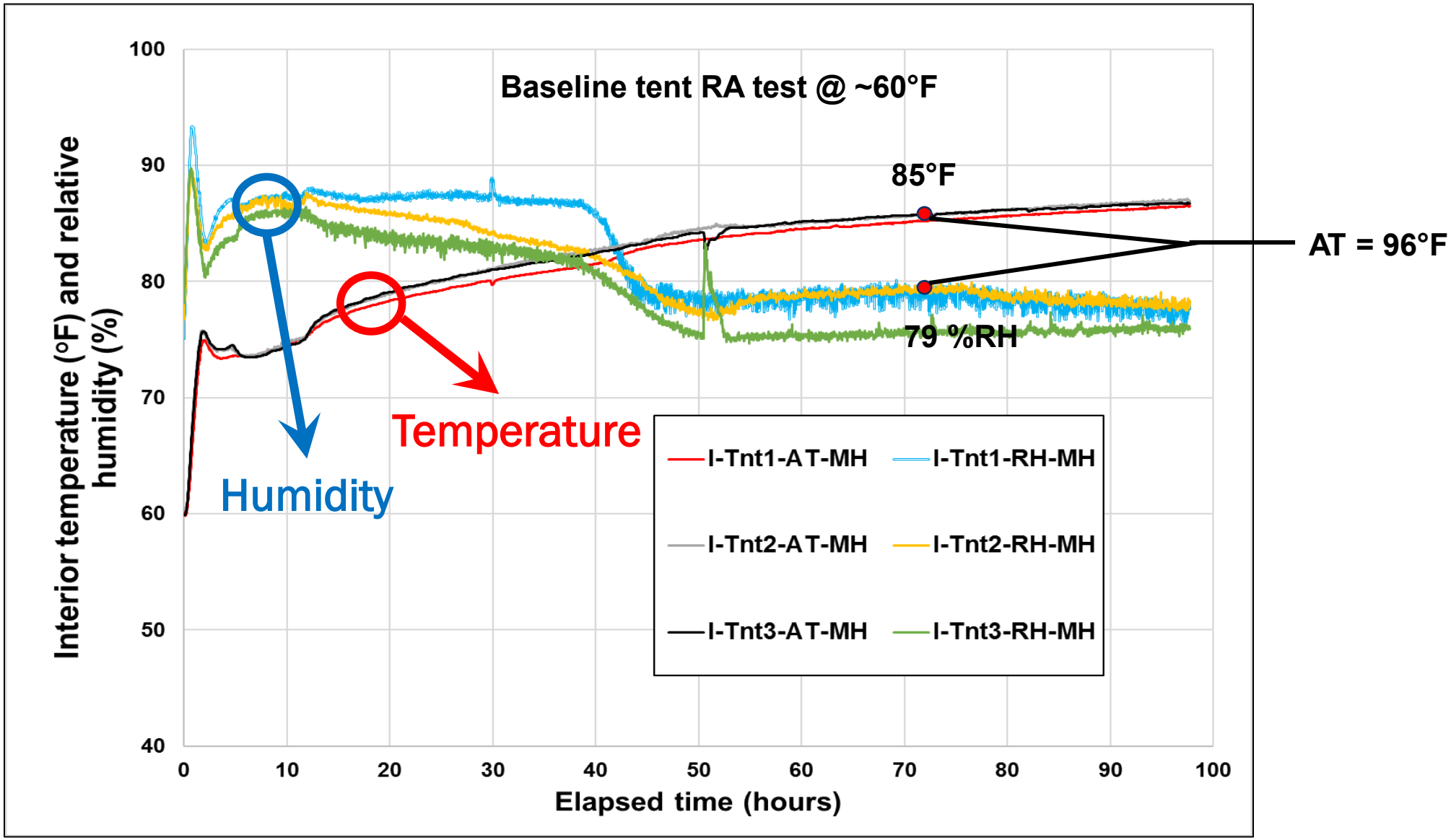
In order to provide a higher than ordinary heat load, we used 30 SMs in the 20-person tent-type RA test mule.



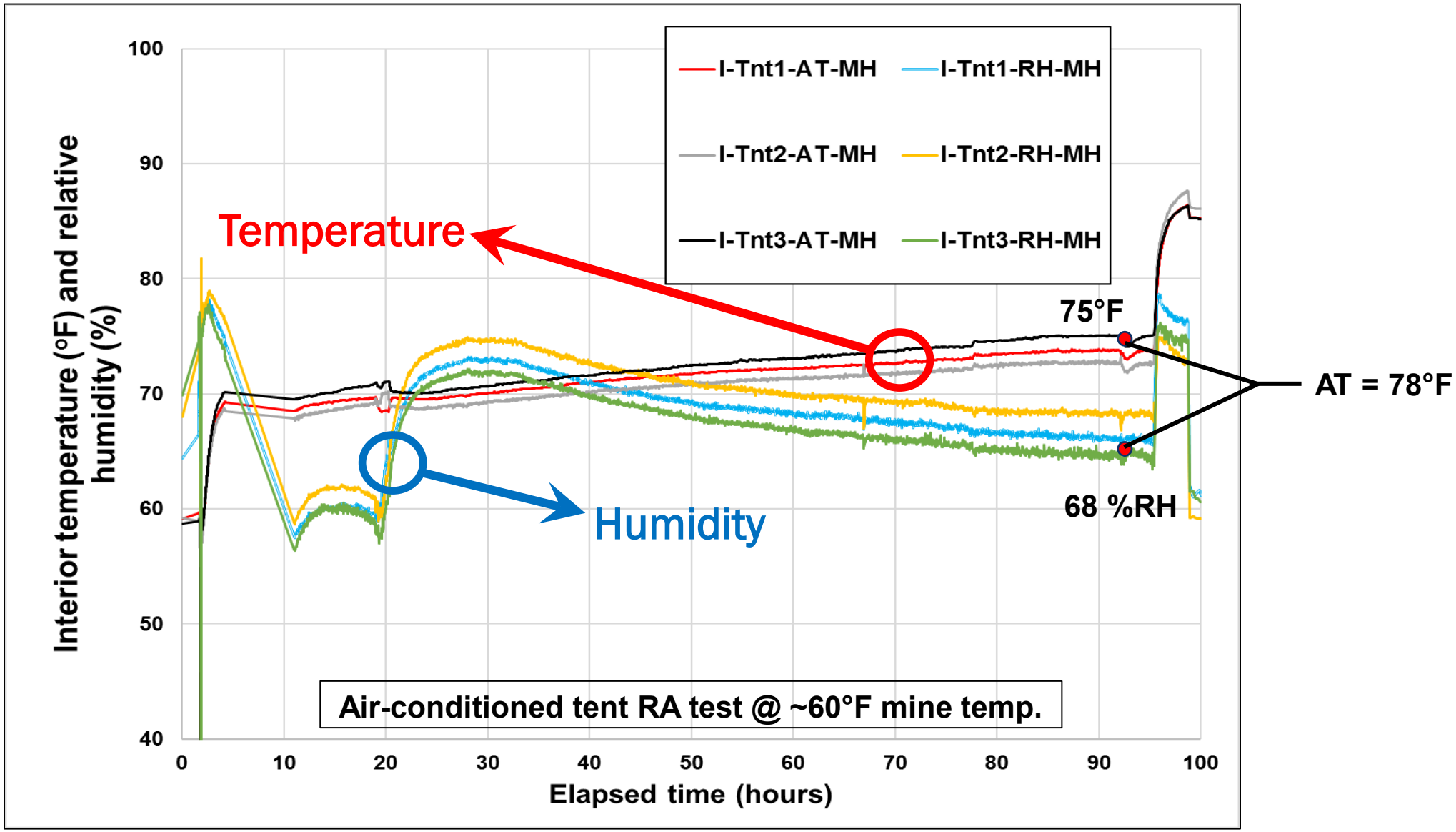
The heat input was very stable during the tests.



For baseline tests conducted with the mine at its “natural temperature”, the apparent temperature exceeded 95°F after about 70 hours.



When the battery-powered A/C unit was tested with the mine at its “natural temperature”, it kept the apparent temperature under 95°F.



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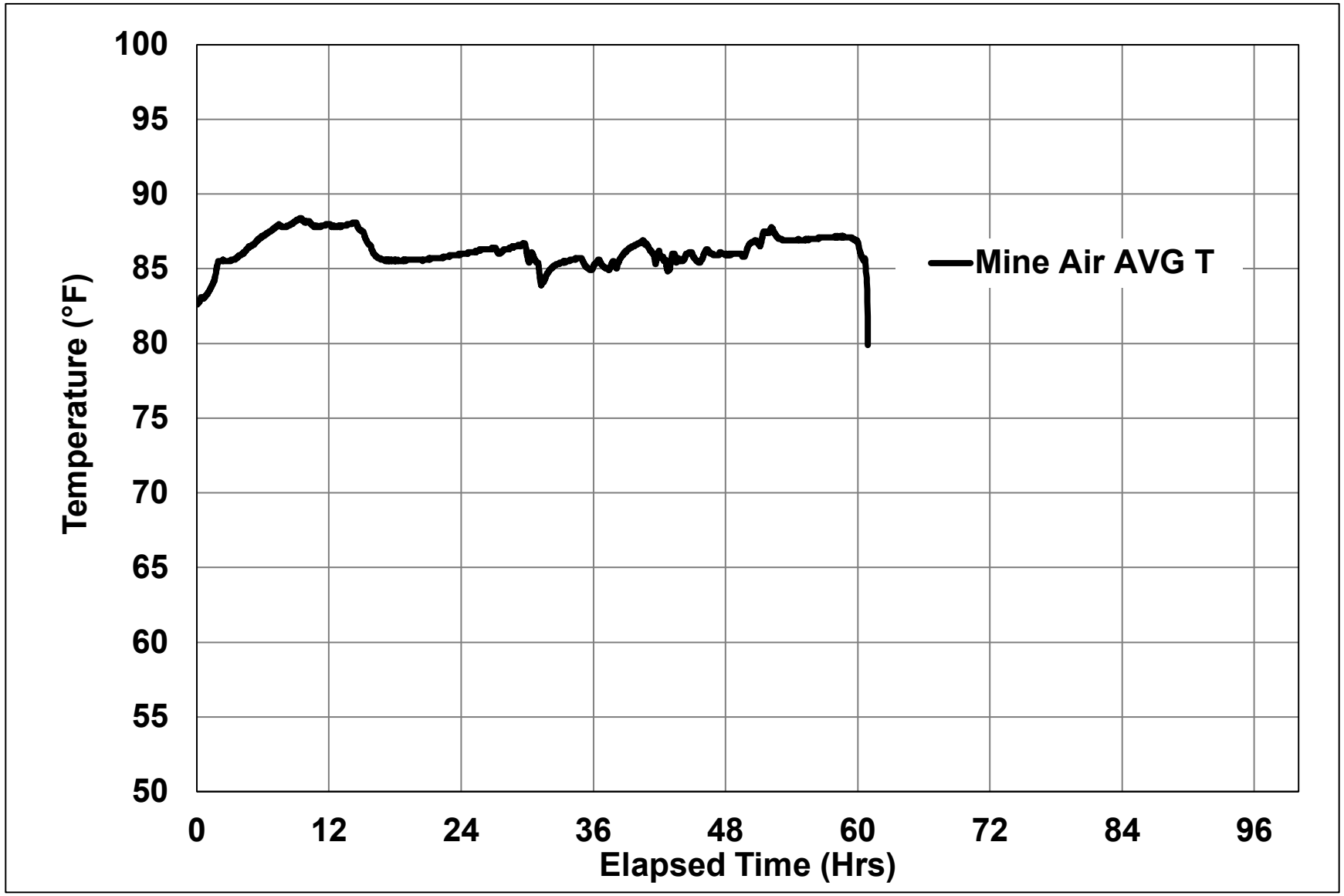
The mine air temperature around the RA was elevated to ~85°F to evaluate the battery-powered A/C unit in hot mine conditions.



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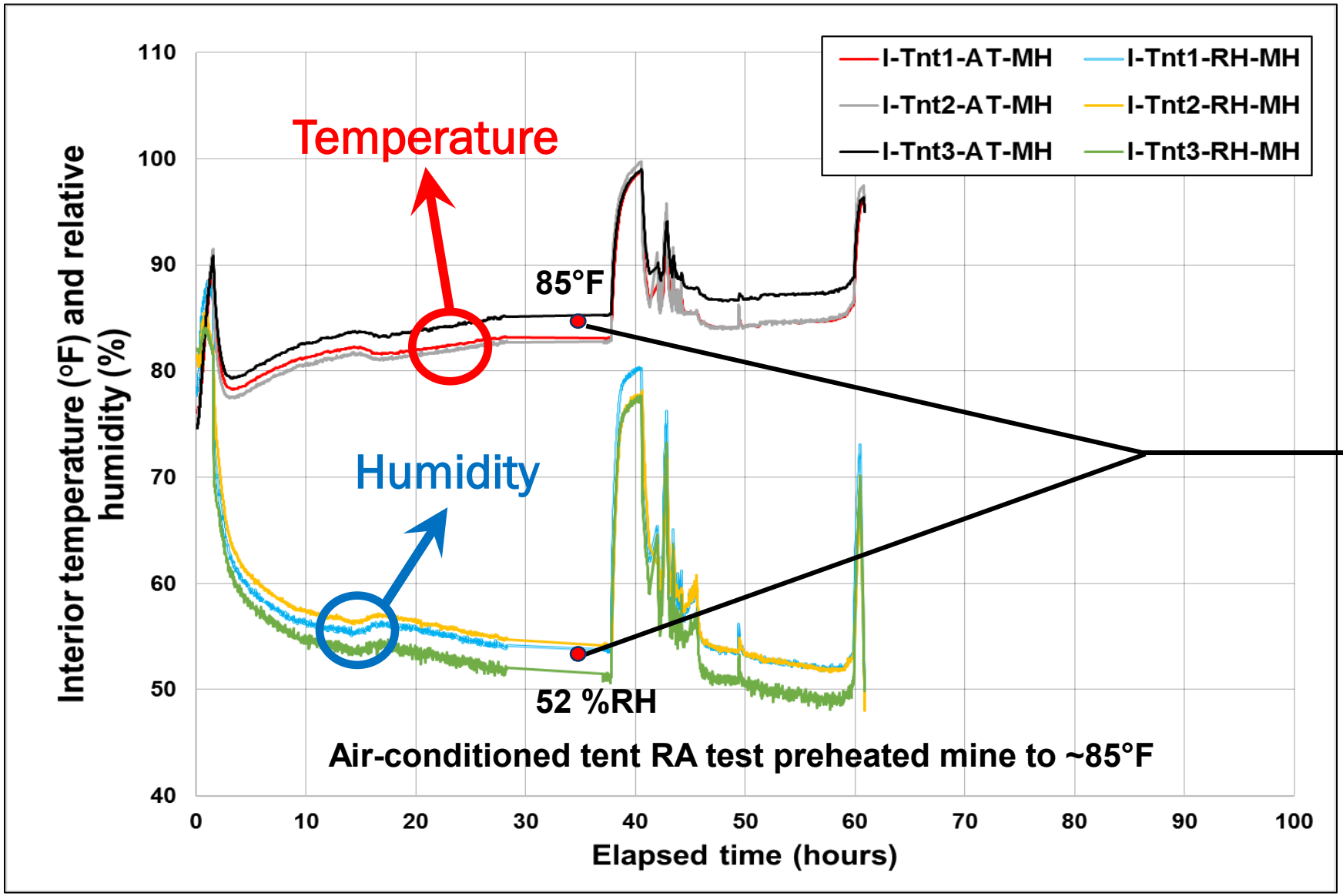
With the mine air at 85°F, the battery-powered A/C unit was able to keep the apparent temperature below 95°F until battery issues occurred at ~40 hours.



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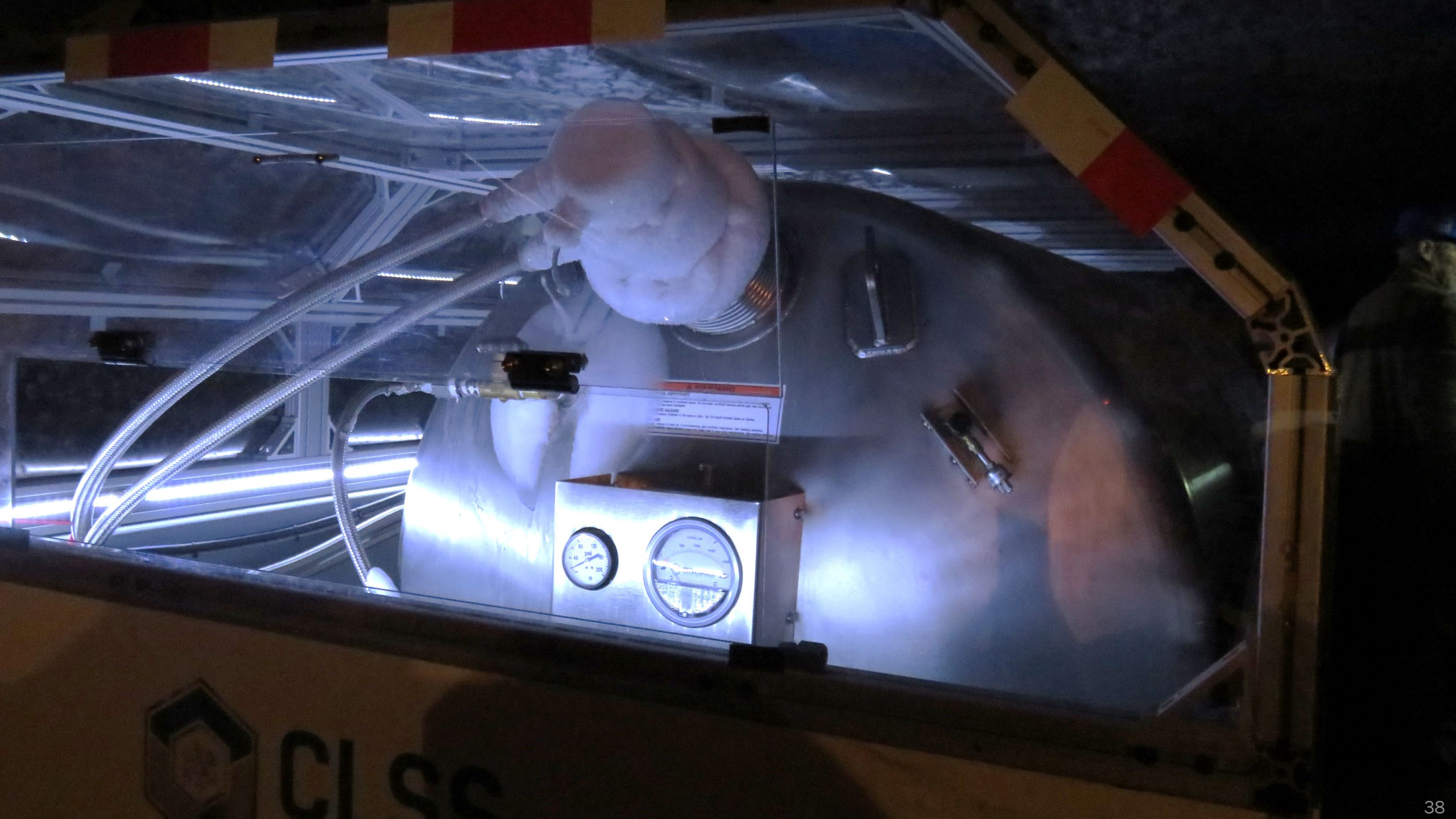
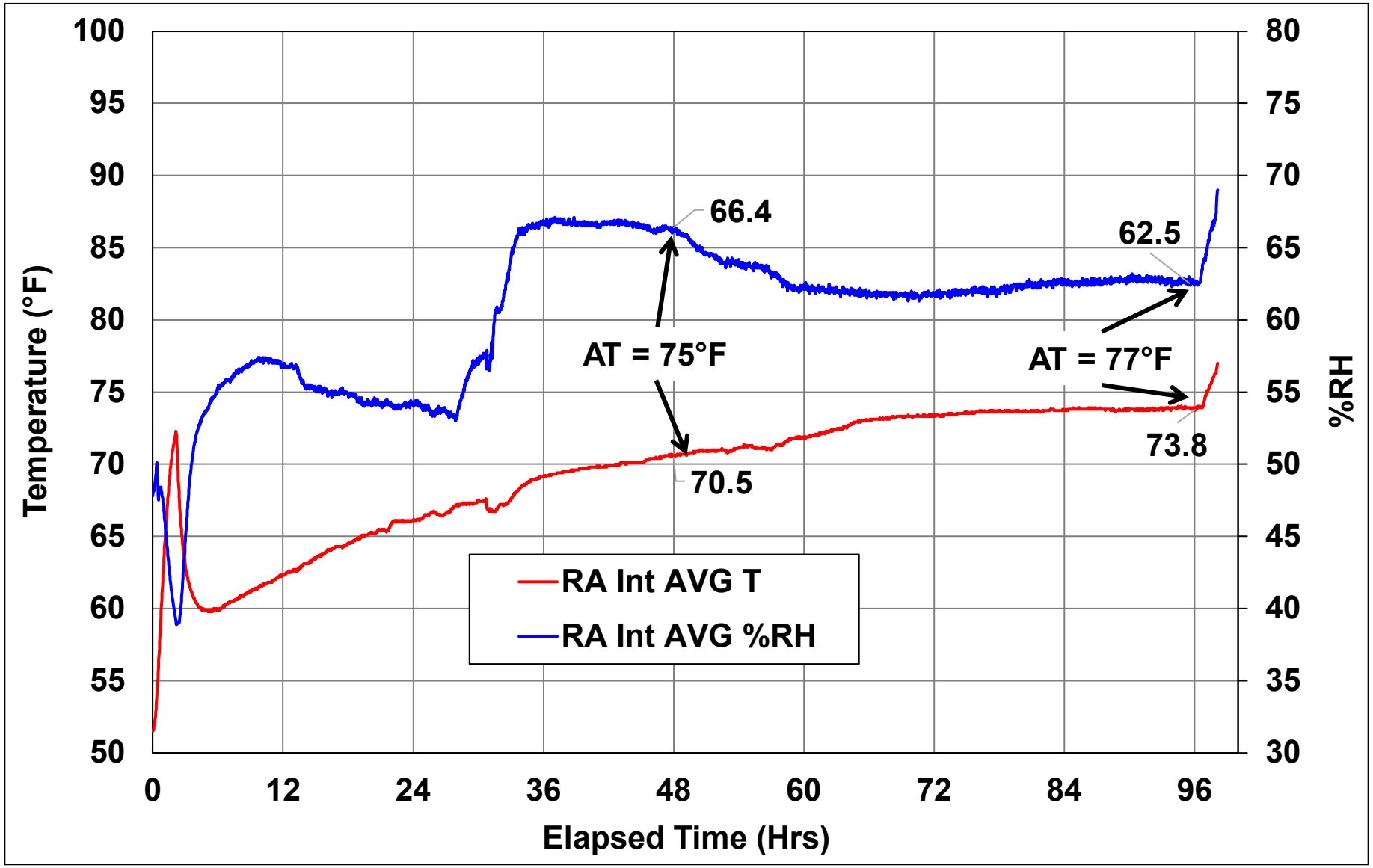


When the cryogenic air supply was tested with the mine at its “natural temperature”, it kept the apparent temperature under 95°F.



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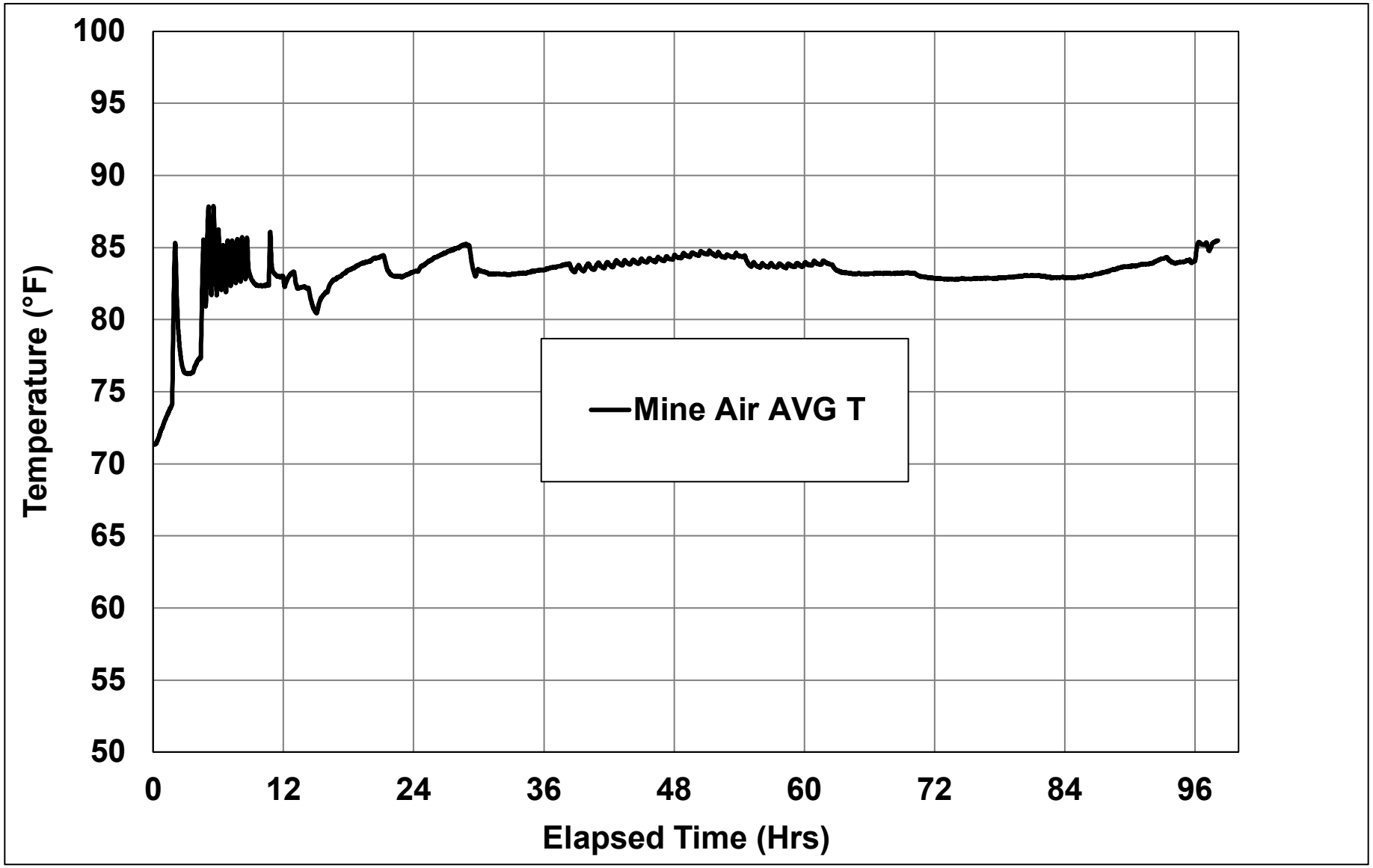

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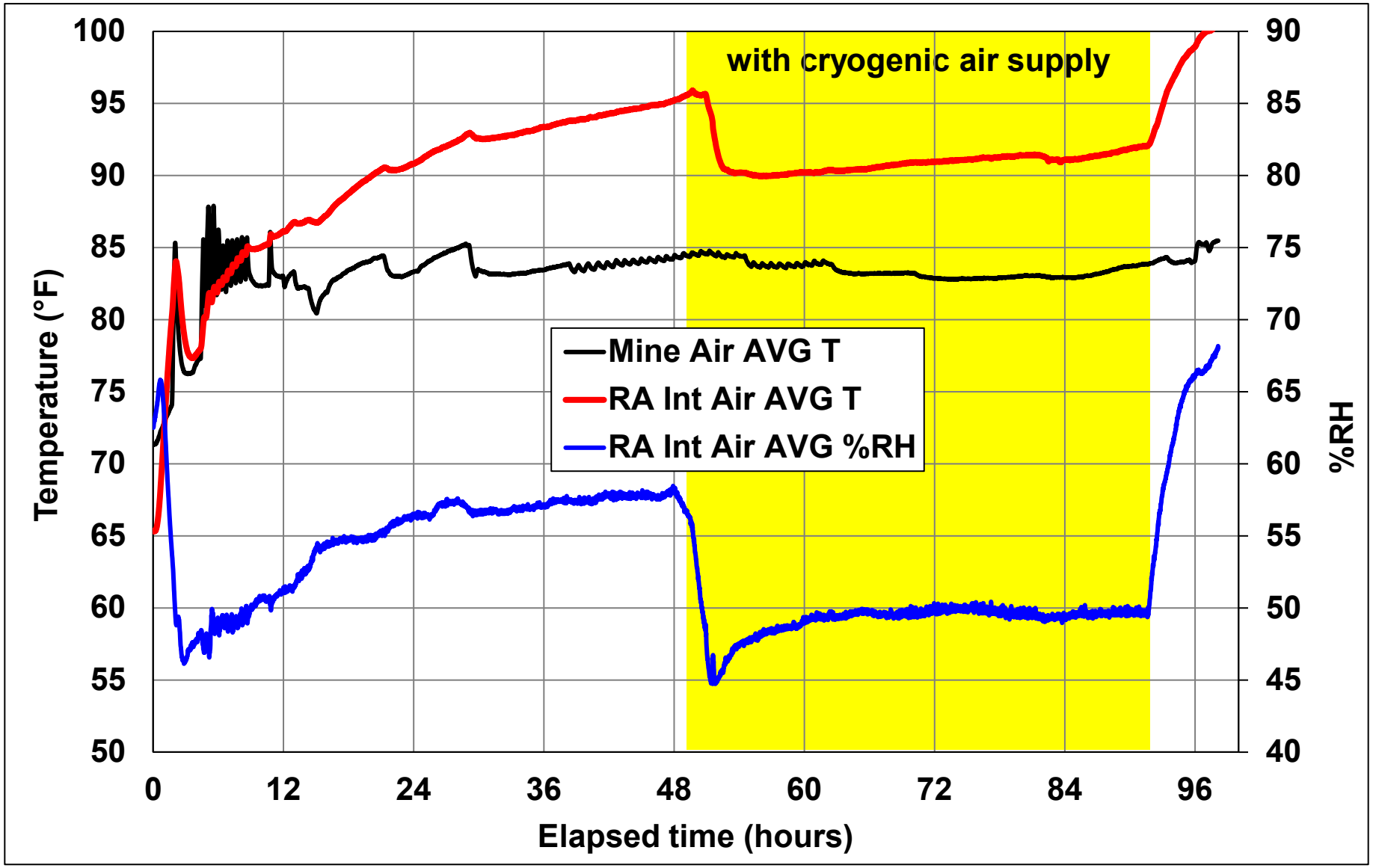
Due to time limitations, we had to conduct a combined test to get baseline data and test data with the cryogenic air supply.



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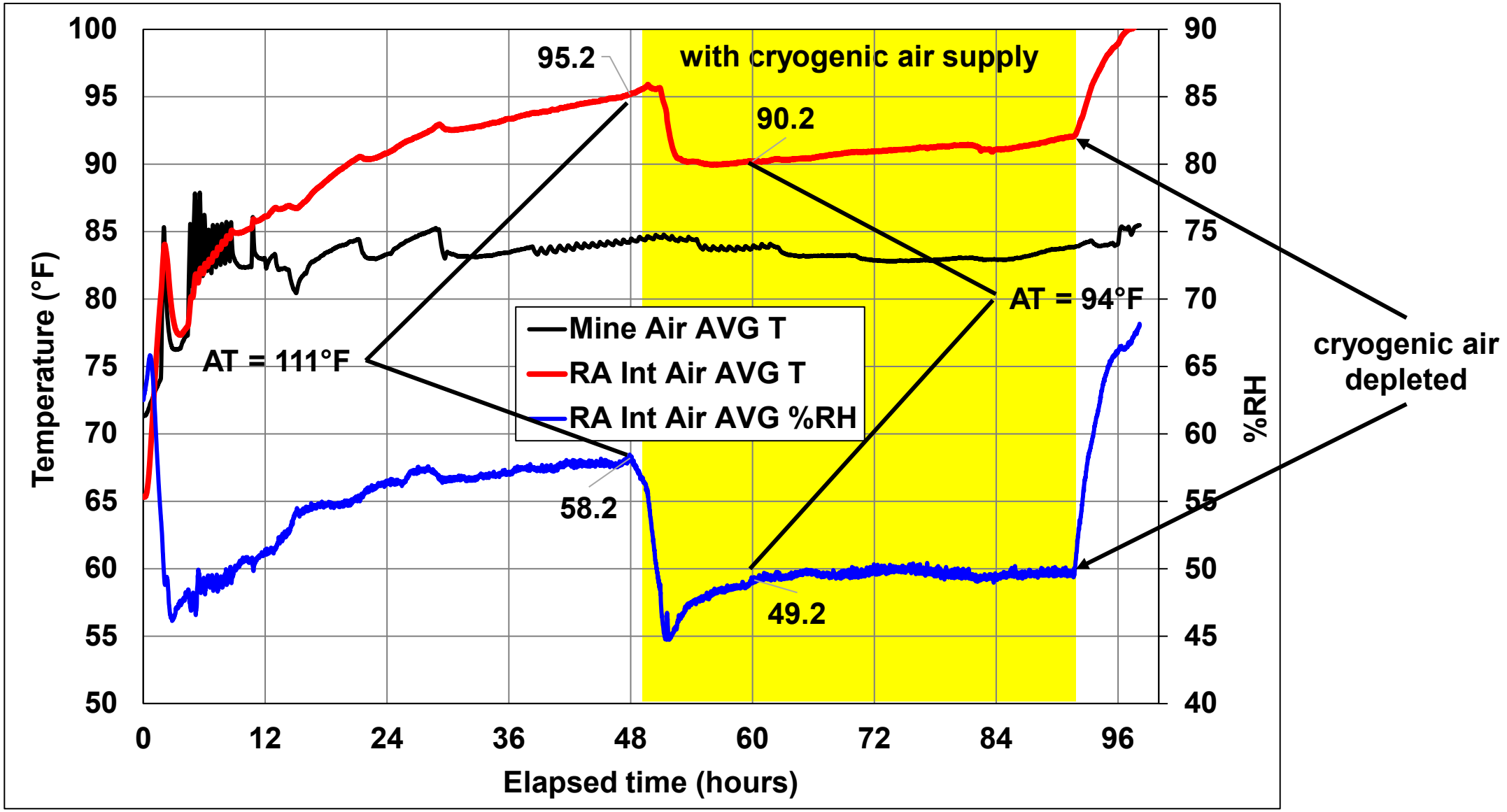
When the cryogenic air supply was running, the apparent temperature was below the 95°F apparent temperature limit.



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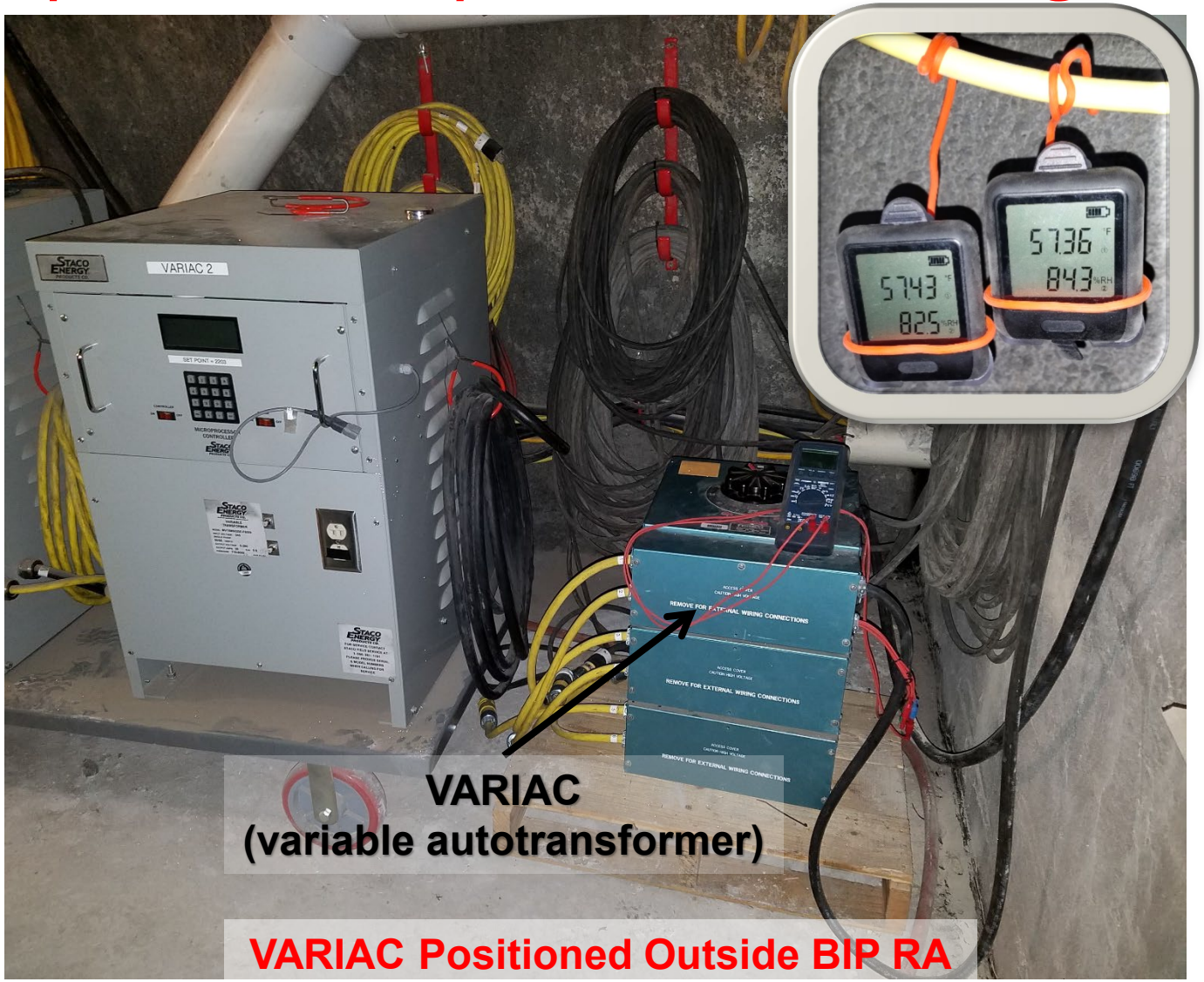
Additional testing was conducted on a 30-person BIP RA with the interior preheated to represent an 85°F mine.

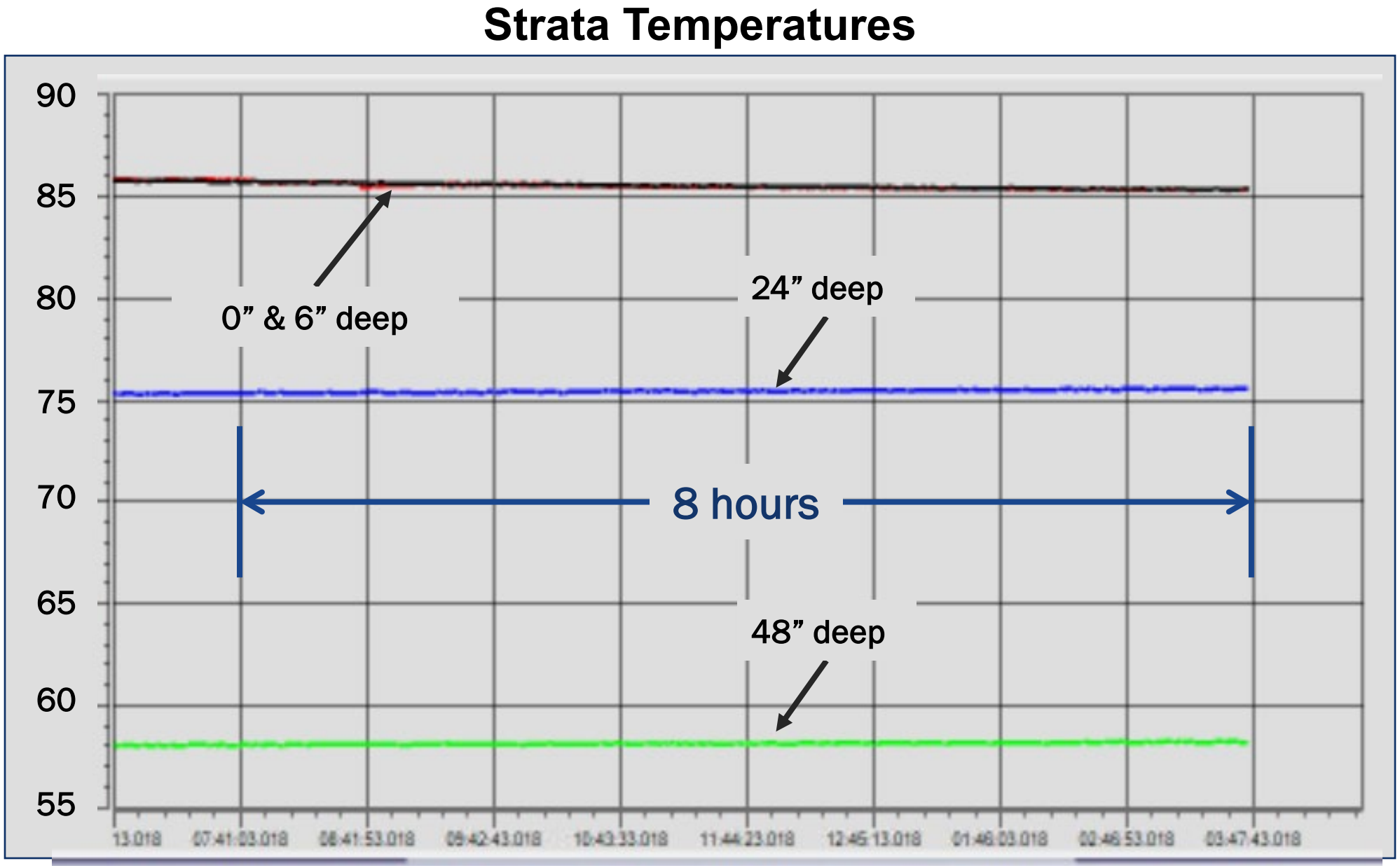
A stable 85°F air temperature was created in the BIP RA using manually controlled VARIACs to power baseboard heaters.

No thermostat was used, we set the power consumption at a fixed wattage!



A 30-kW heater was used to rapidly provide heat, then six manual-VARIAC-controlled baseboard heaters were used provide constant heat input.

The BIP RA strata surface temperature was stabilized at 85°F.



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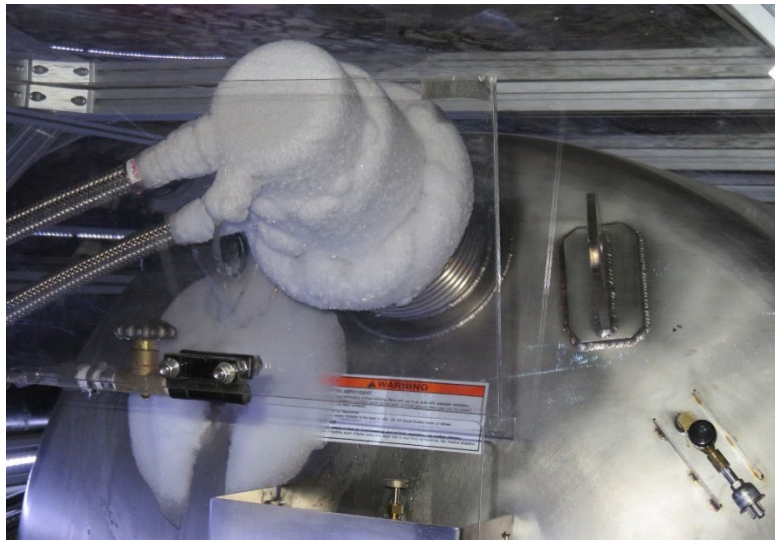
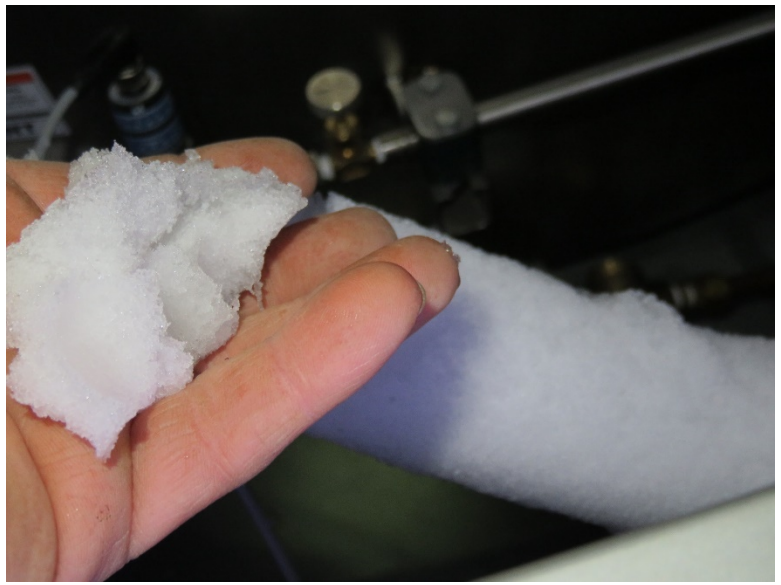
We conducted four heat/humidity tests to examine maximum occupancy of the 30-person BIP RA subject to the 95°F apparent temperature limit.

- Test #1: 24 SMs with cryogenic air supply
- Test #2: 16 SMs with cryogenic air supply
- Test #3: 12 SMs with cryogenic air supply
- Test #4: 12 SMs without cryogenic air supply

Note: The cryogenic air flow rate was adjusted in an attempt to achieve enough cooling to keep the apparent temperature below 95°F and to achieve 96 hours of operation.





The results indicated the cryogenic air supply provided enough cooling to allow for 12 SMs without exceeding the apparent temperature limit.

	Test 1	Test 2	Test 3	Test 4
# of SMs	24	16	12	12
Test hours	96	96	96	8
Cryo used	yes	yes	yes	no
Time when cryo air supply was depleted	91 hrs	96 hrs	91 hrs	NA
apparent temperature when cryo air supply was depleted	99.4°F	--	86.6°F	--
apparent temperature at end of the test	118.6°F	95.3°F	100.3°F	105.2°F

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Conclusions

- Fully occupied RAs may exceed the apparent temperature limit depending on mine air and strata temperature and mine strata composition
- Occupancy derating could be used to meet the apparent temperature limit
- Occupancy derating would be a function of the RA and mine environment
- Several heat mitigation strategies show promise for RAs as they were able to provide enough cooling to meet the apparent temperature limit
  - The borehole air supply operated successfully for 96 hours and was able to keep the conditions in a 60-person BIP RA below the apparent temperature limit
  - The battery-powered air supply would need extended battery life and MSHA electrical approval for use in underground coal mines
  - The carbon-dioxide-based cooling system would need improved flow control to maximize operation time; additional carbon dioxide cylinders would allow for more cooling and/or longer operation time
  - The cryogenic air supply would need flow control to maximize operation time; a larger tank would allow for more cooling and/or longer operation time

Thank you for your attention!

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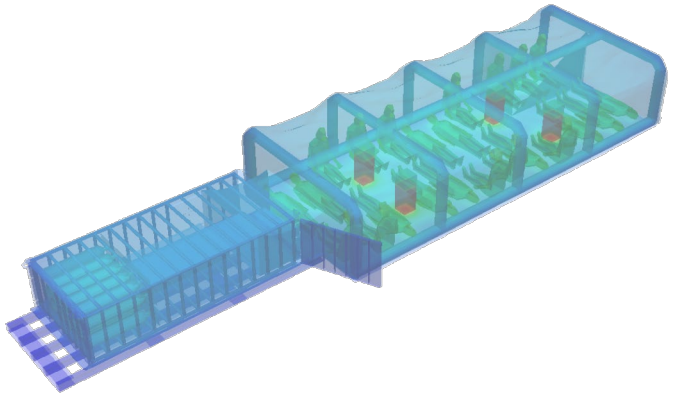

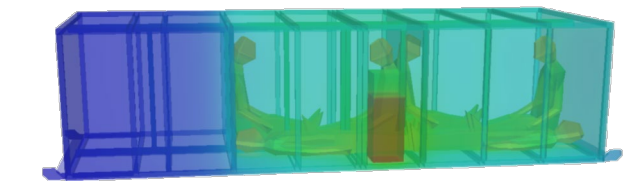

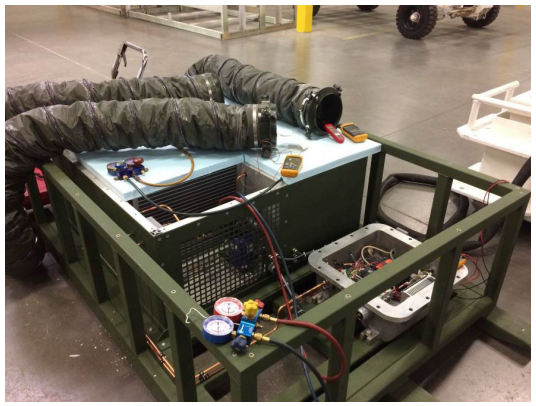

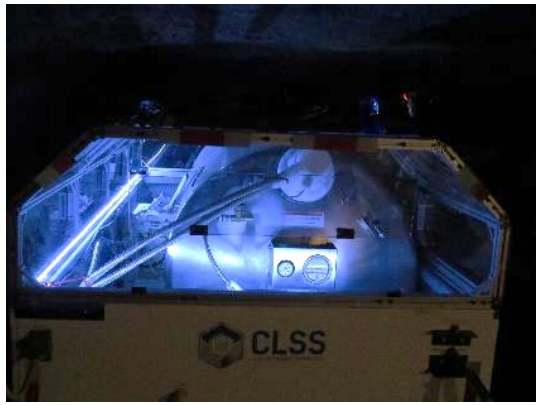

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