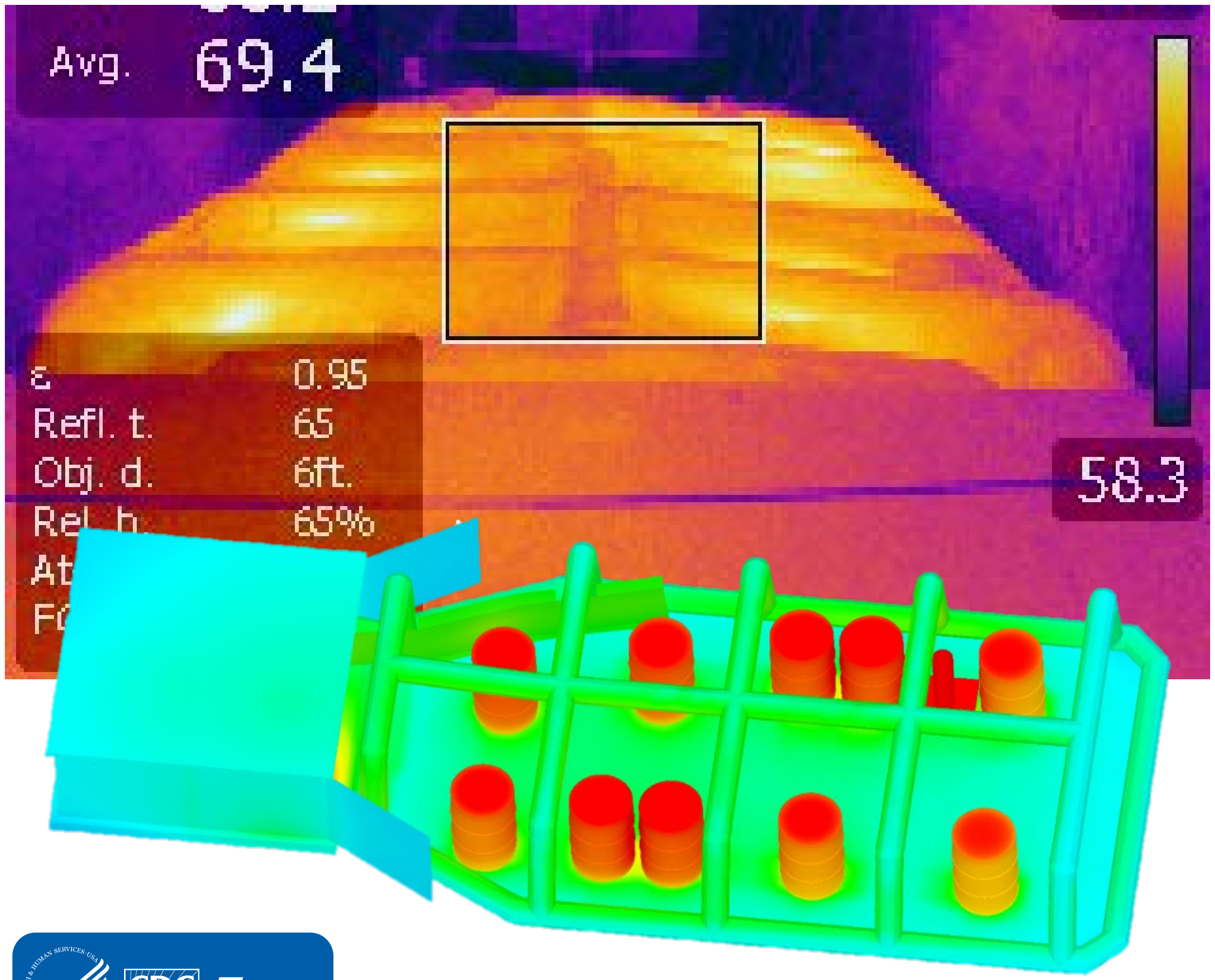
Refuge Alternative Heat/Humidity Testing, Thermal Simulation Model Development, and Effect of Mine Parameters on Resulting Apparent Temperature



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RA Partnership

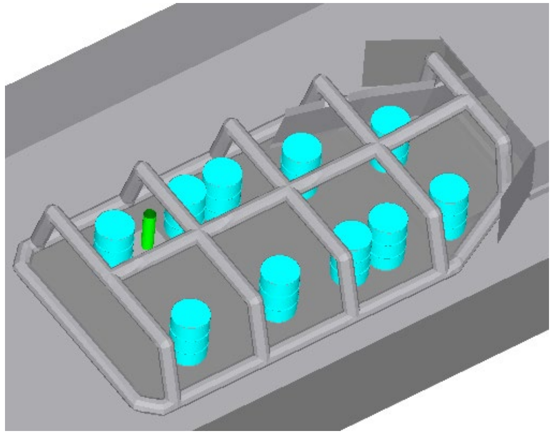
November 17-18, 2021

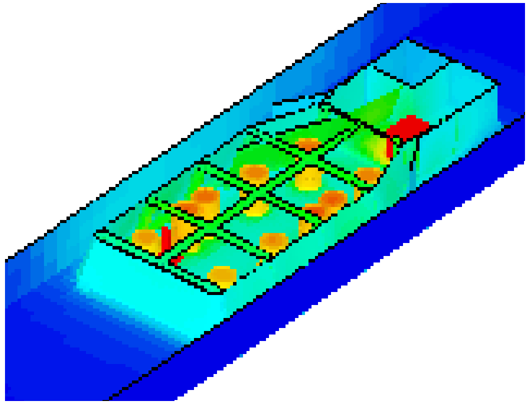
CDC NIOSH

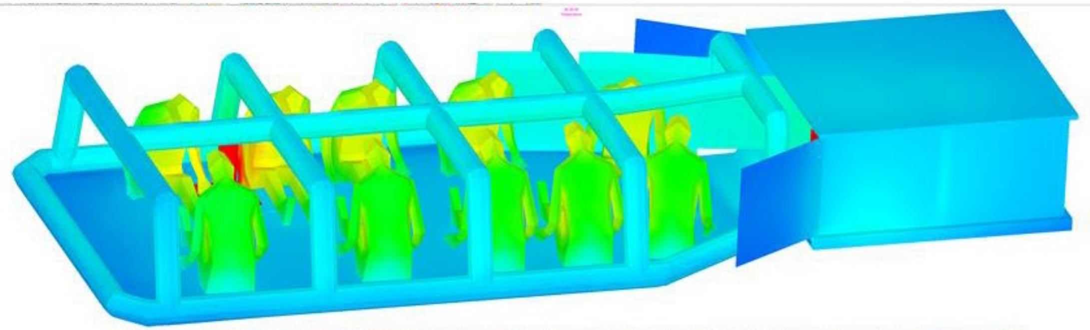
NIOSH Mining Program

Outline

- Challenges associated with testing/modeling of RA thermal environment
- In-mine heat/humidity testing of RAs
- Development of RA thermal simulation models
- Use of thermal simulation models to examine effects of mine parameters on RA thermal environment







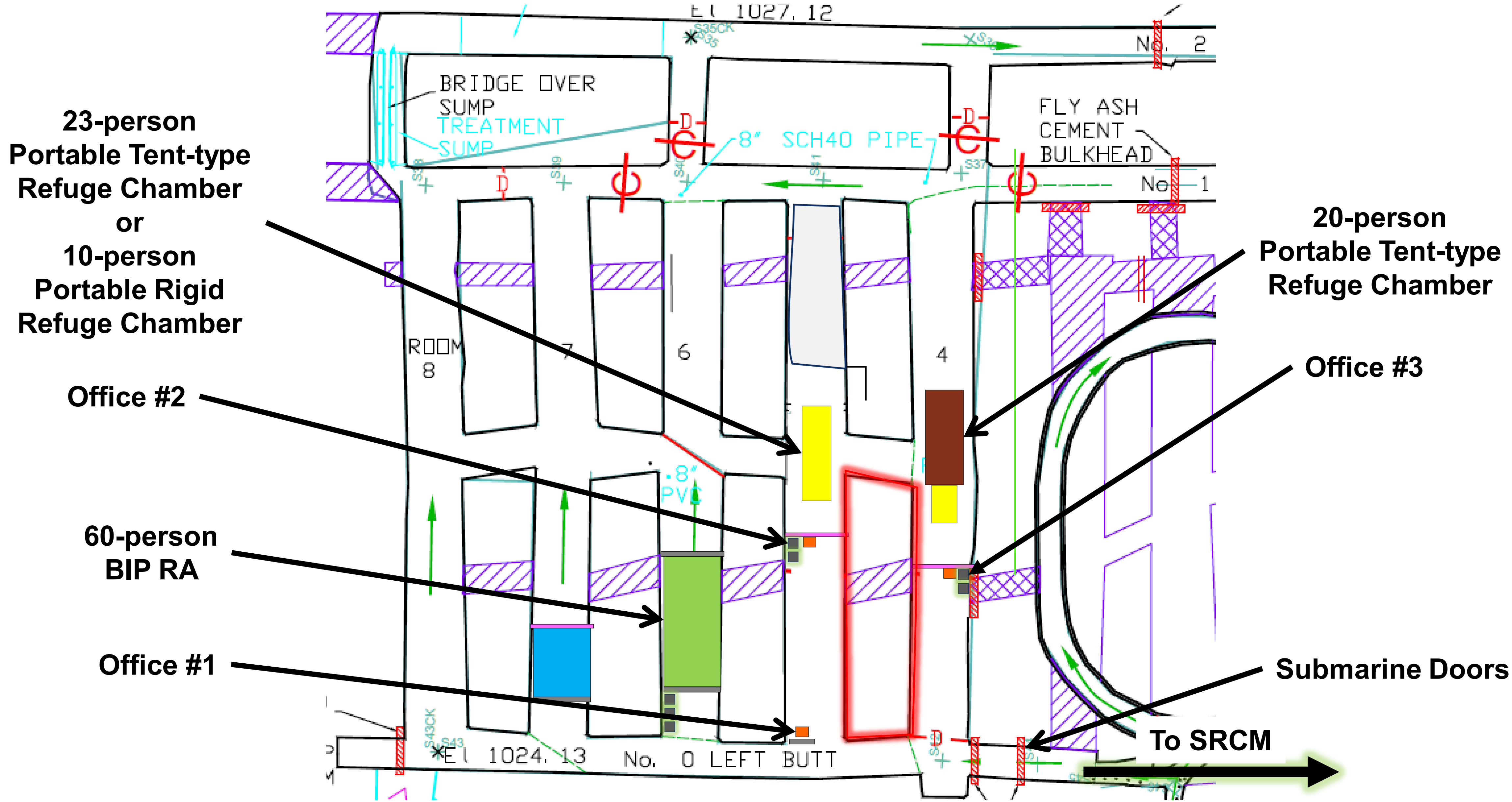
Testing/modeling the thermal environment of an occupied RA presents numerous challenges.

- Heat transfer from RA occupants to the RA includes
  - Convective heat transfer from occupants to RA air
  - Conductive heat transfer from occupants to RA floor
  - Radiation heat transfer from occupants to RA surfaces
  - Evaporation of sweat from occupants w/ subsequent condensation on RA surfaces
    - In “hot” environments evaporation of sweat is the body’s primary means of eliminating heat
- Heat transfer from the RA to the mine also includes
  - Convective heat transfer from RA surfaces to mine air
  - Conductive heat transfer from RA floor to mine floor
  - Radiation heat transfer from RA outer surface to mine surfaces

Testing/modeling the thermal environment of an occupied RA presents numerous challenges.

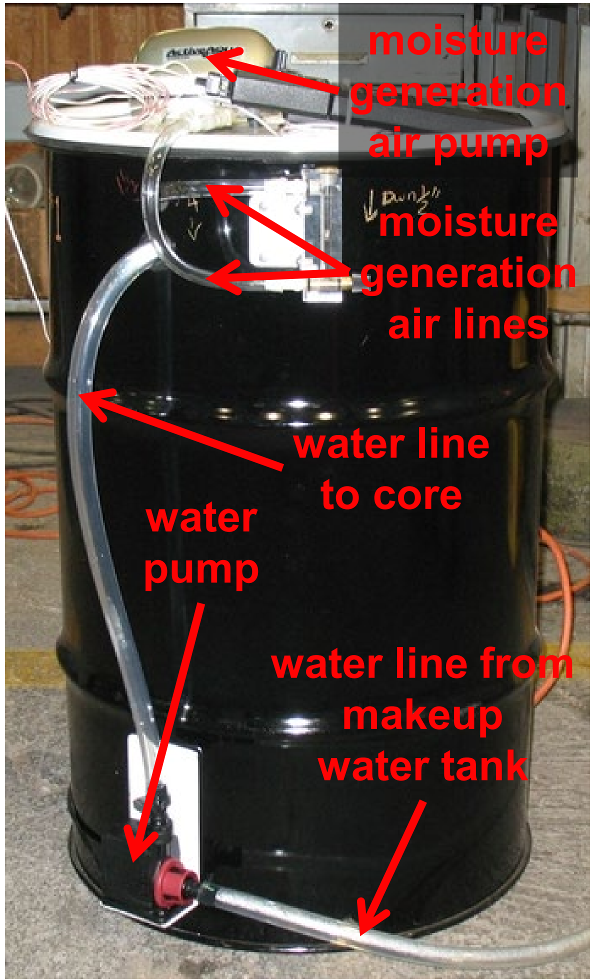
- Mine strata thermal properties play an important role in an occupied RA's thermal environment
  - A high bay is not a good representation of a mine
- Over 96 hours, steady state conditions may not be reached
  - This is a transient heat transfer problem
- Heat sources within an RA include the metabolic heat input of miners and its carbon dioxide scrubber system (portable RAs)
- Heat sources include both sensible (dry) and latent (moist) heat, and the apparent temperature depends on %RH
  - Cannot use light bulbs or electric resistance heaters without adding latent heat
- How do we input the heat of miners for 96 continuous hours?
  - Using real people is not an option
- How do we input the heat of a carbon dioxide scrubber system?
  - Injecting carbon dioxide and using carbon dioxide scrubbing curtains would add complexity

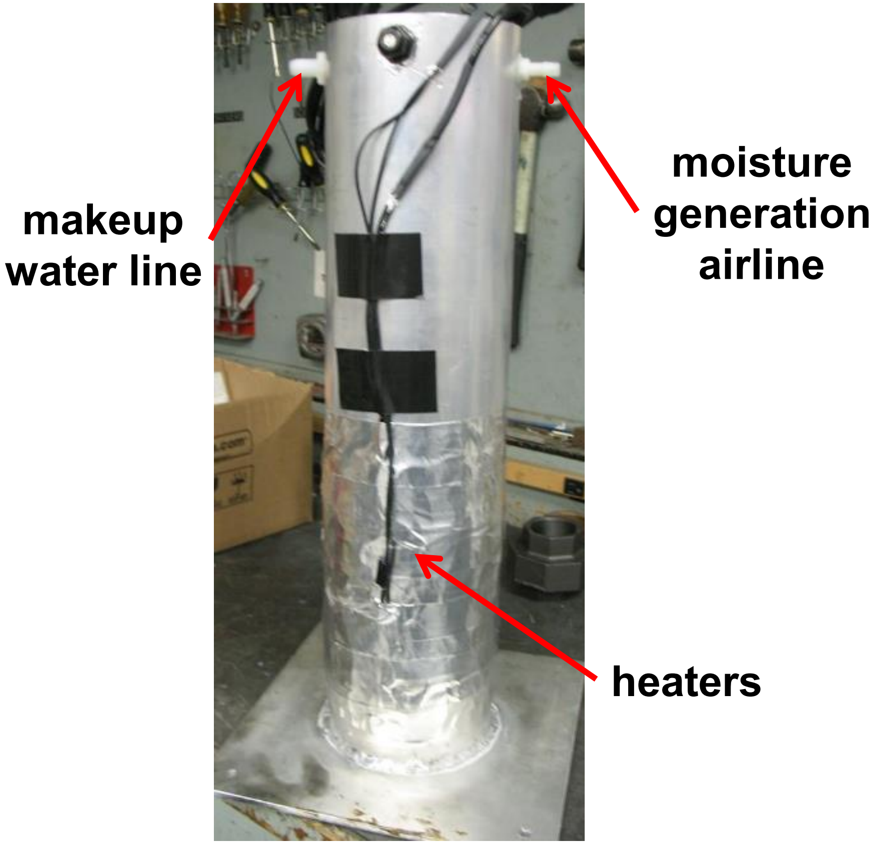
Multiple RA test areas were set up in the NIOSH Experimental Mine.

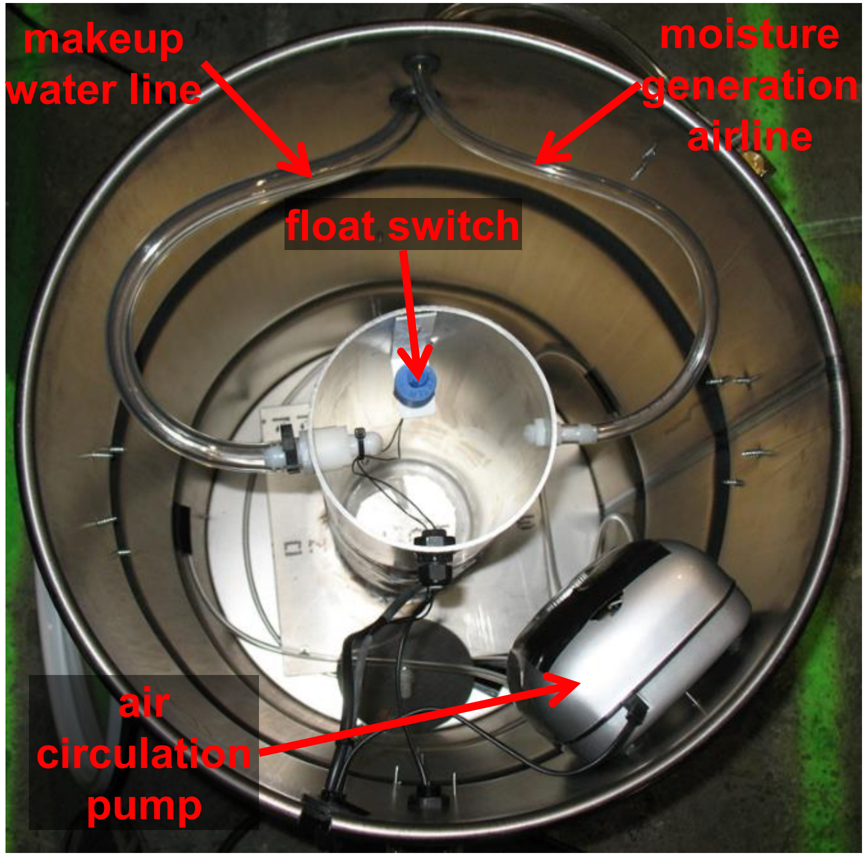


NIOSH developed "simulated miners" (SMs) to input representative sensible and latent heat of actual miners.

- "Gen 1" SMs were built using a 30-gallon steel drum, a water-filled aluminum "core", electrical resistance heaters, air pumps, a water pump, and a float switch

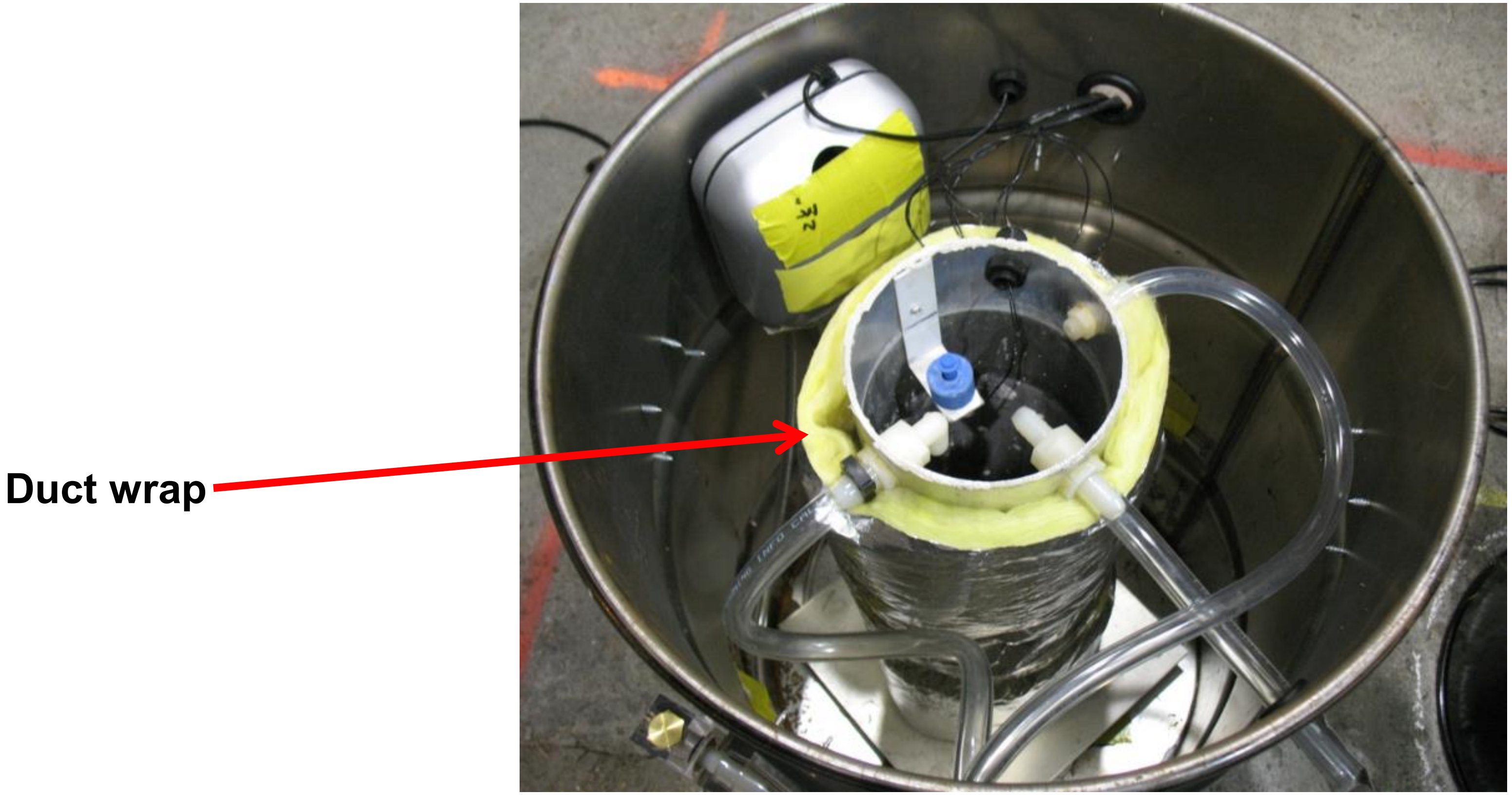






NIOSH developed "simulated miners" (SMs) to input representative sensible and latent heat of actual miners.

- "Gen 1" SMs were built using a 30-gallon steel drum, a water-filled aluminum "core", electrical resistance heaters, air pumps, a water pump, and a float switch
- Duct wrap was added to the water-filled core to increase moisture input
  - 1.8 L/day in conditions of 80°F and 80 to 85 %RH



We used quilted fiberglass insulation blankets and Styrofoam lids to decrease the time to bring the 1st generation SMs up to "operating temperature".

NIOSH developed 2nd generation SMs to address some operational challenges with using 1st generation SMs.

- "Gen 2" SMs were built using a 30-gallon plastic drum, galvanized duct, electrical resistance heaters, a stepper-motor-based water pump, and soaker hose
  - Eliminated the need to use quilted fiberglass blankets and Styrofoam lids during SM preheat
  - Improved control of latent heat input via adjusting "sweat rate"; adjusted water output to 1.5 L/day

heaters

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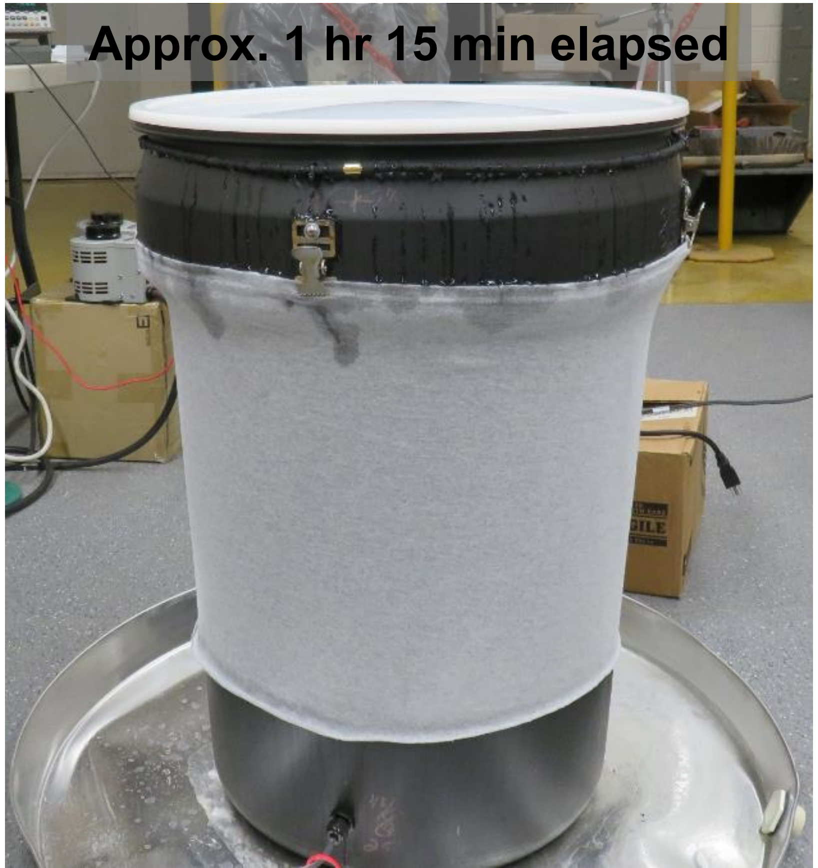
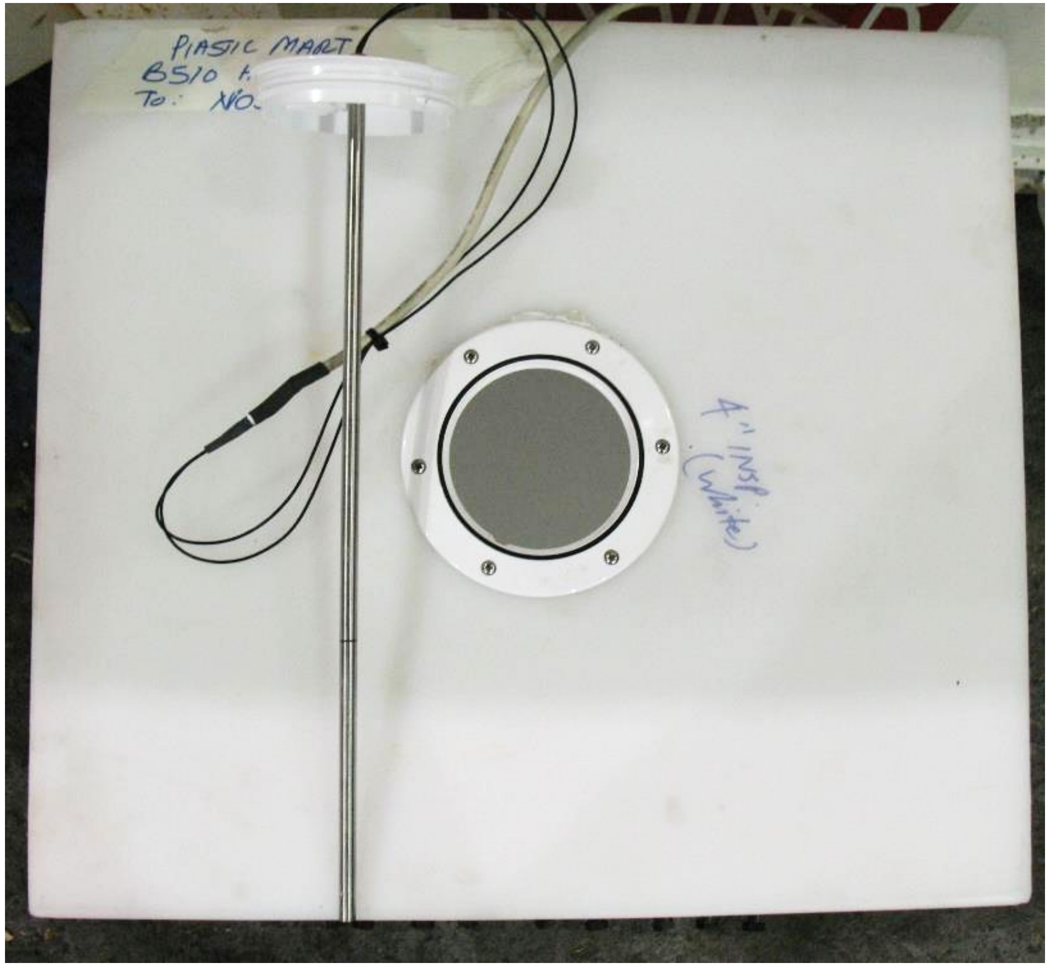


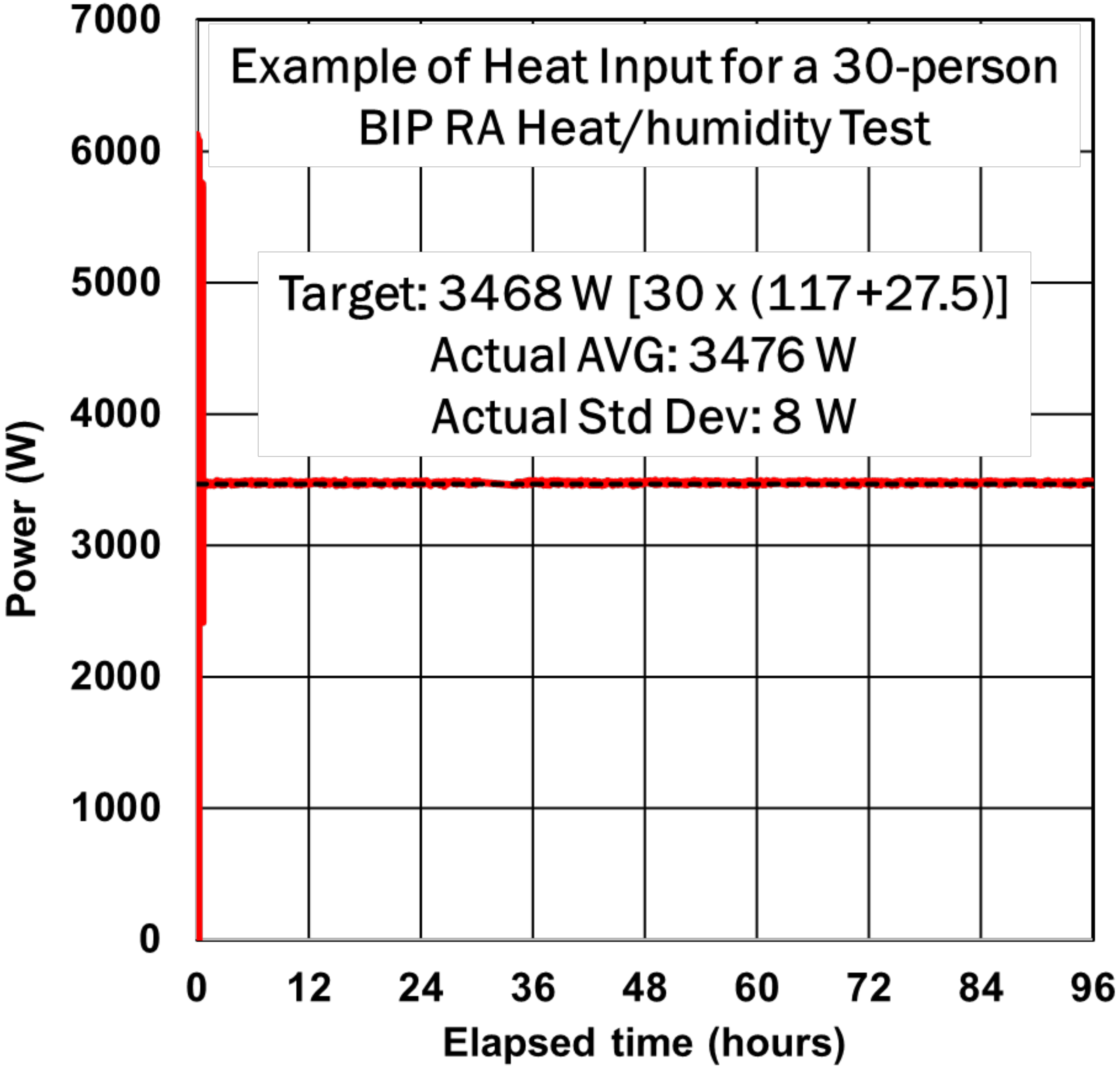
Heated water tanks were used to input the heat due to an RA's carbon dioxide scrubbers.

- Immersion-style heaters were used to heat the water
- Water tanks were positioned within the RA during testing



NIOSH used programmable automatic VARIACs to control the input heat during testing.

- SM heat input set to 117 W per SM
- Water tank heat input set to 27 W per SM



Test preparation for testing of a 23-person portable tent-type RA in our Experimental Mine

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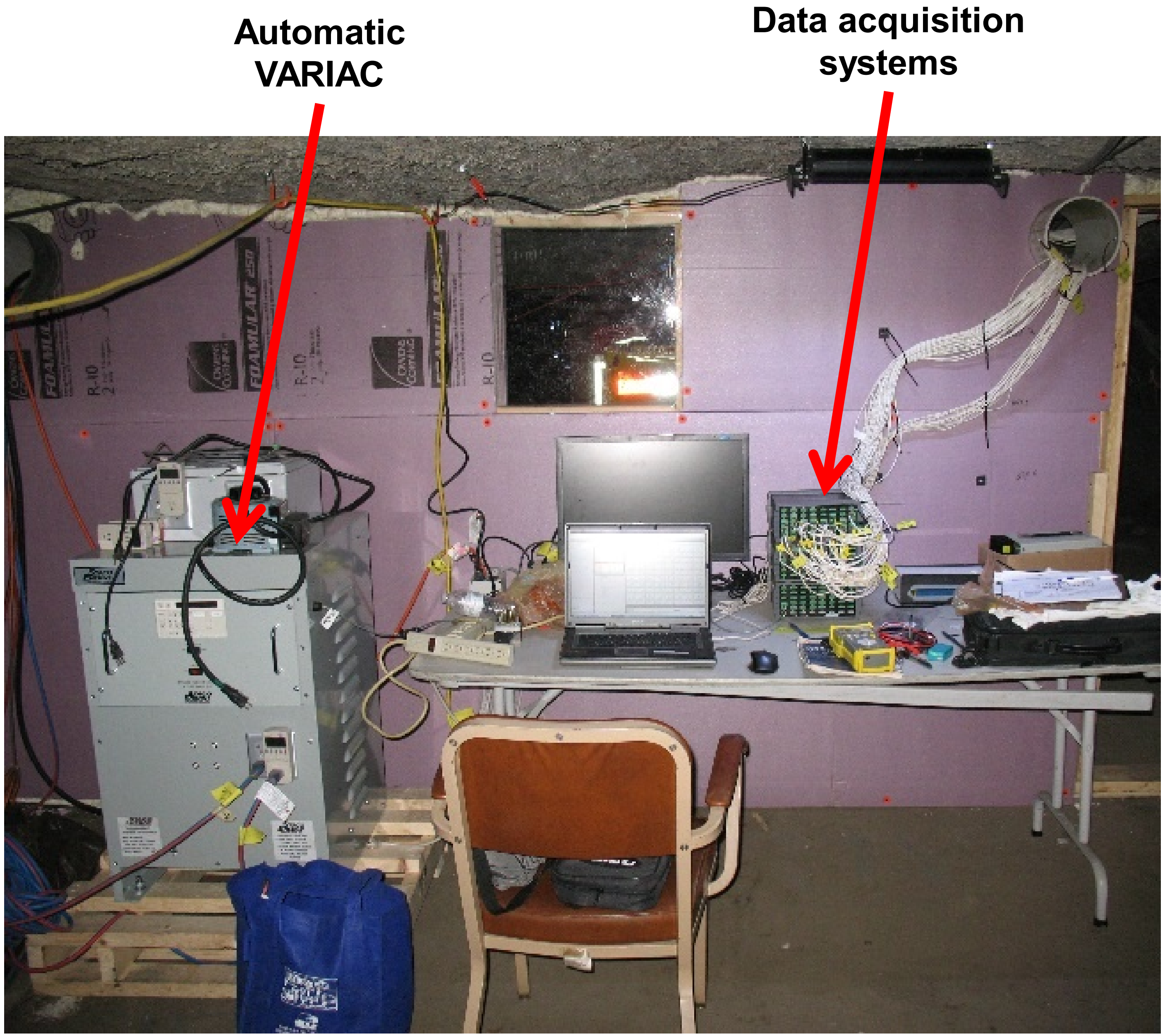
During testing, up to 128 channels of data were recorded.

- Heat input by each VARIAC
- Water level for each water tank
- SM surface temps
- RA air temperature
- RA air %RH
- RA surface temps
- Mine air temps
- Mine air %RH
- Mine strata temps at multiple depths



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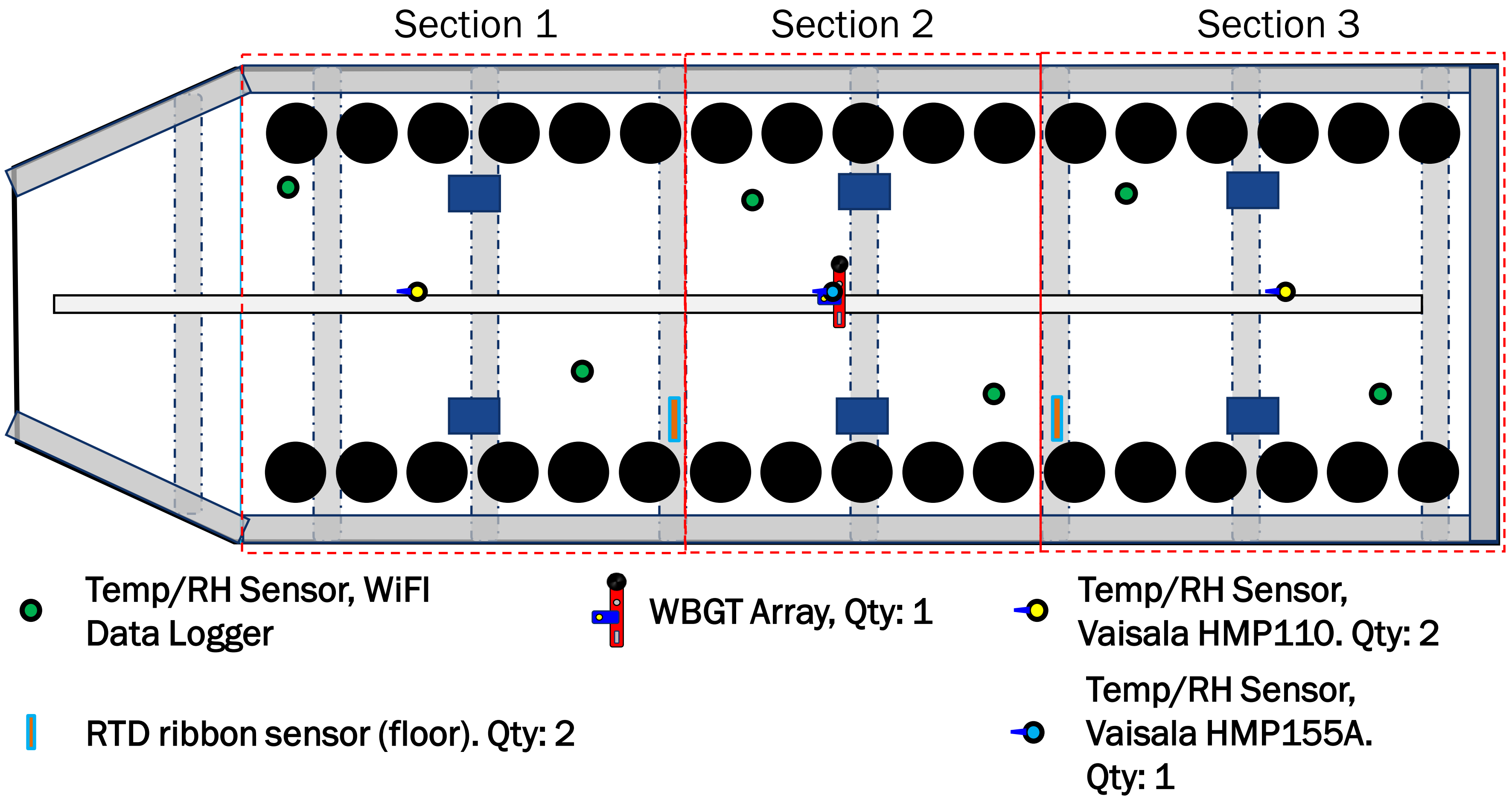

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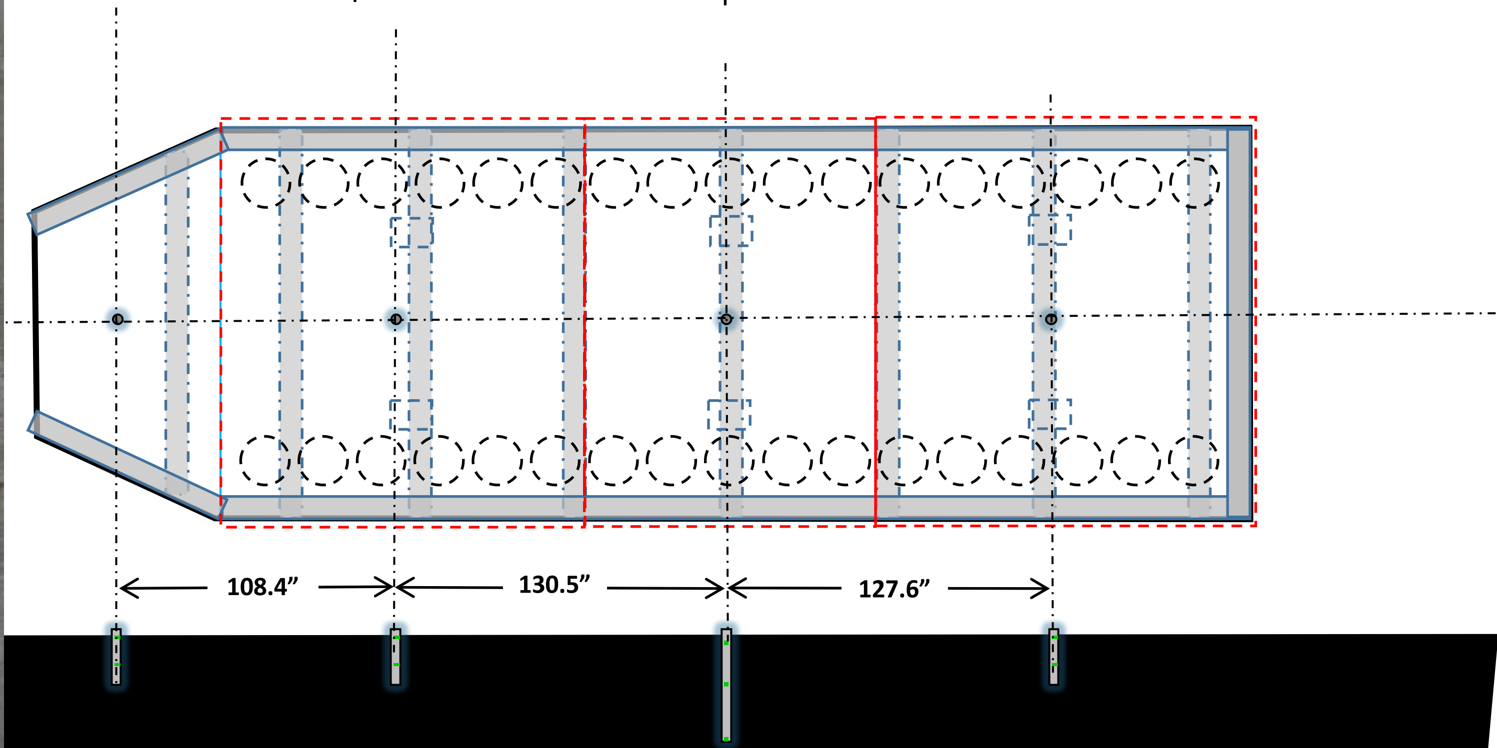

Strata temperature probe, side view

Strata temperature probe, overhead view

During testing, up to 128 channels of data were recorded.

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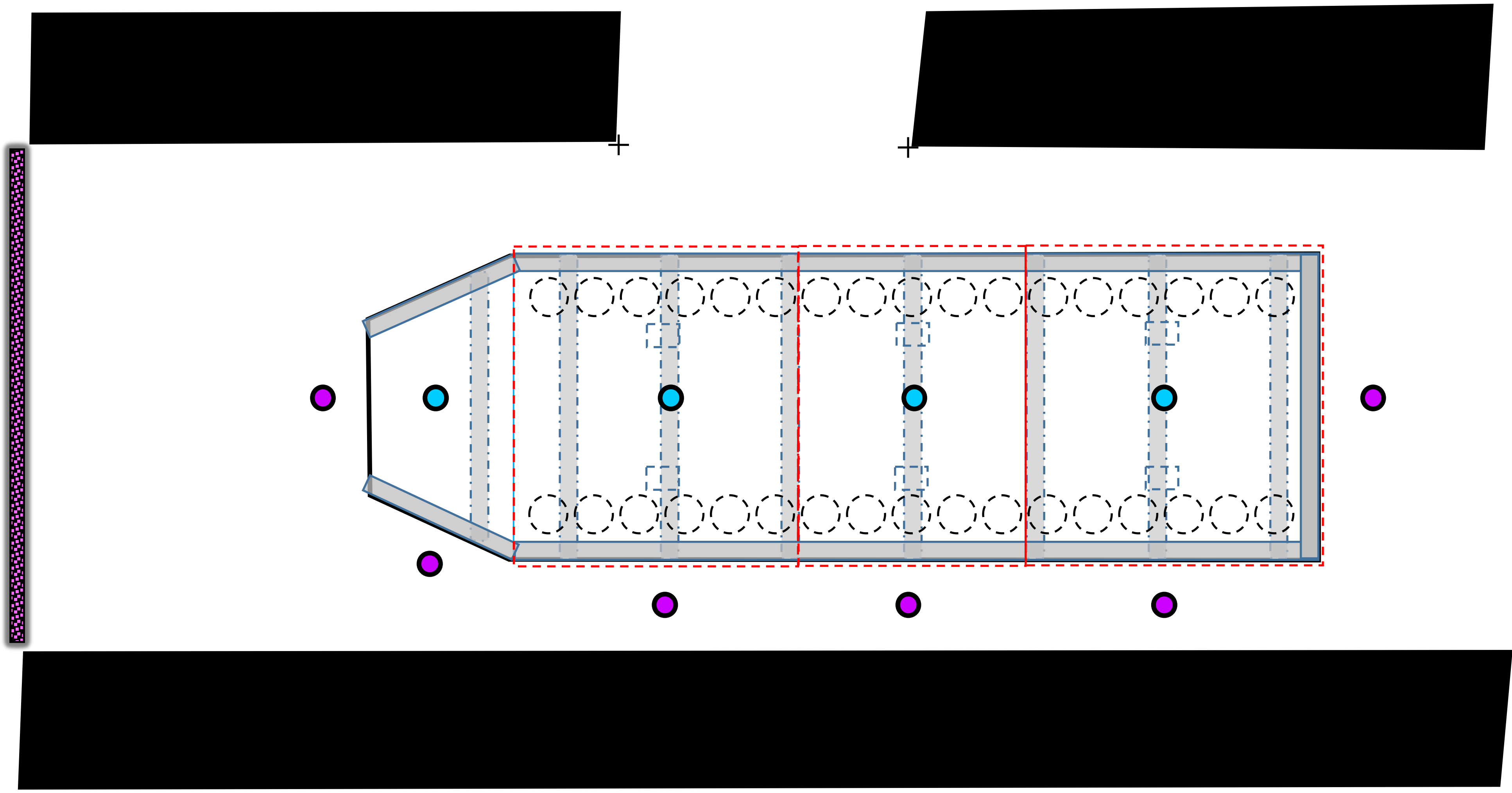


From 2013 to 2018, NIOSH conducted more than 30 in-mine, 96-hour-long heat/humidity tests on 7 different RAs: 3 portable tent-type RAs, 2 portable metal RAs, and 2 BIP RAs.

10-person portable
tent-type RA training unit – SRCM

23-person portable
tent-type RA – EM

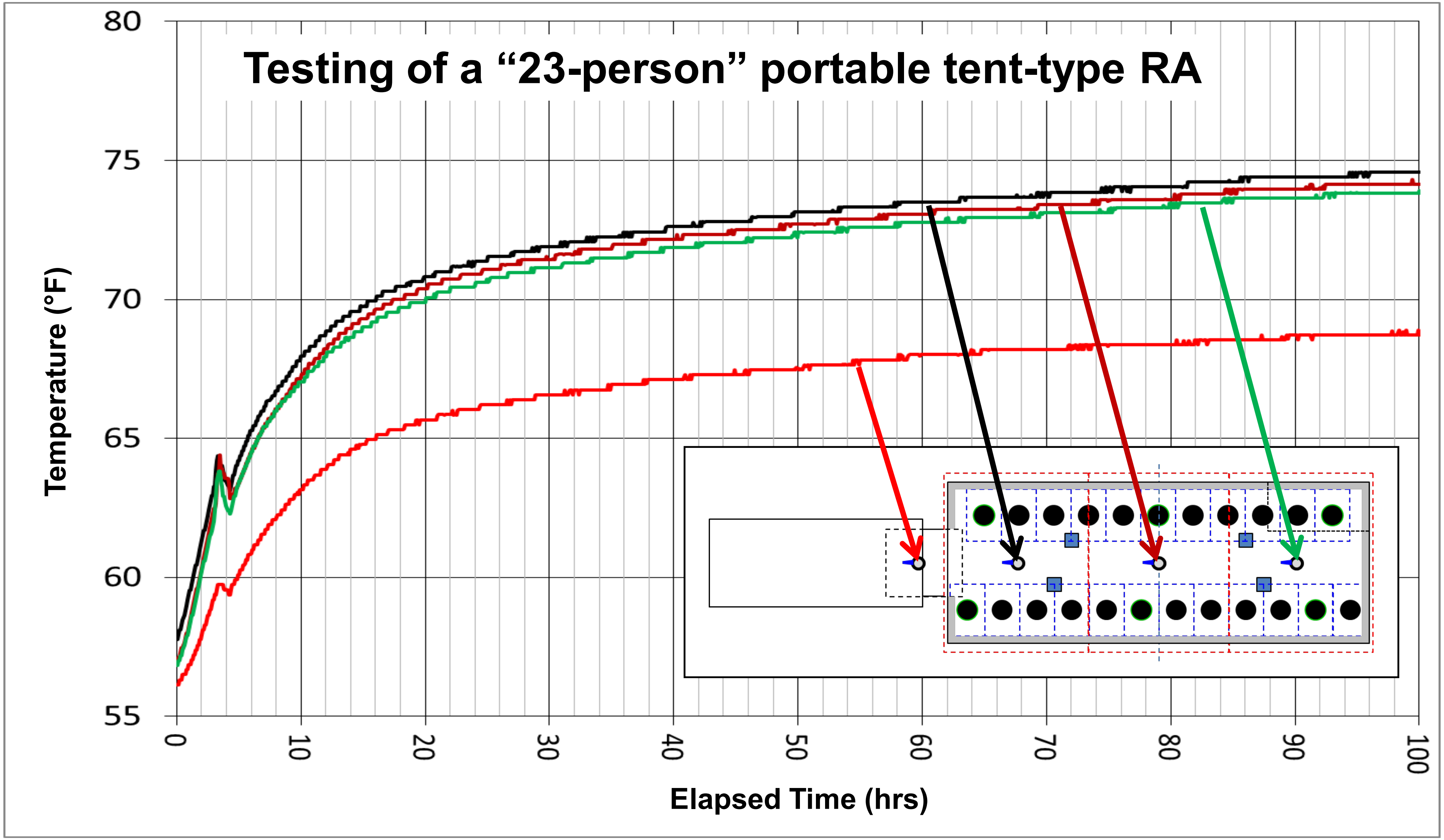
60-person/30-person
built-in-place RA – EM

6-person portable
rigid RA – EM

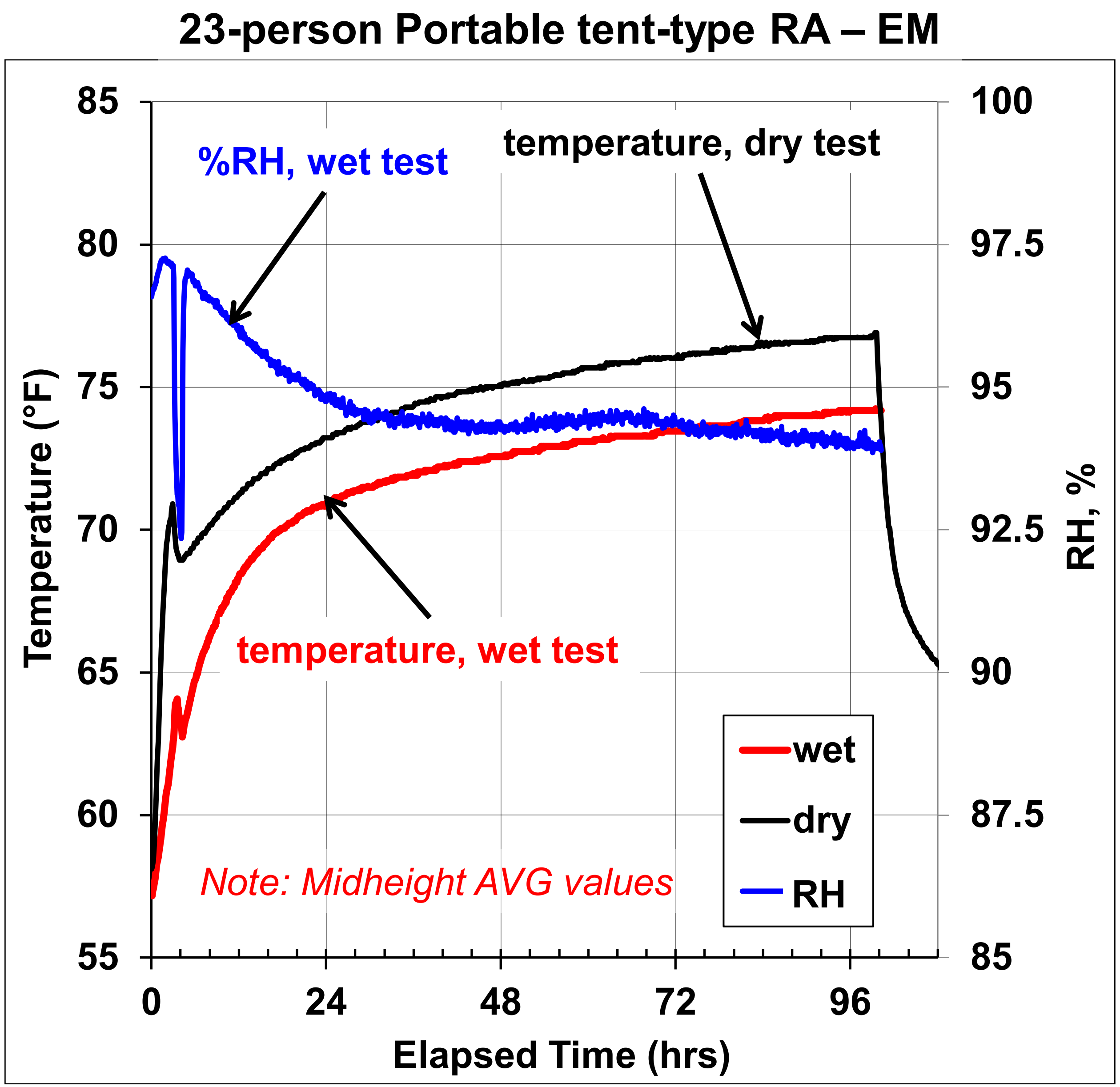
6-person
(sold as 12-person)
portable
rigid RA – field site

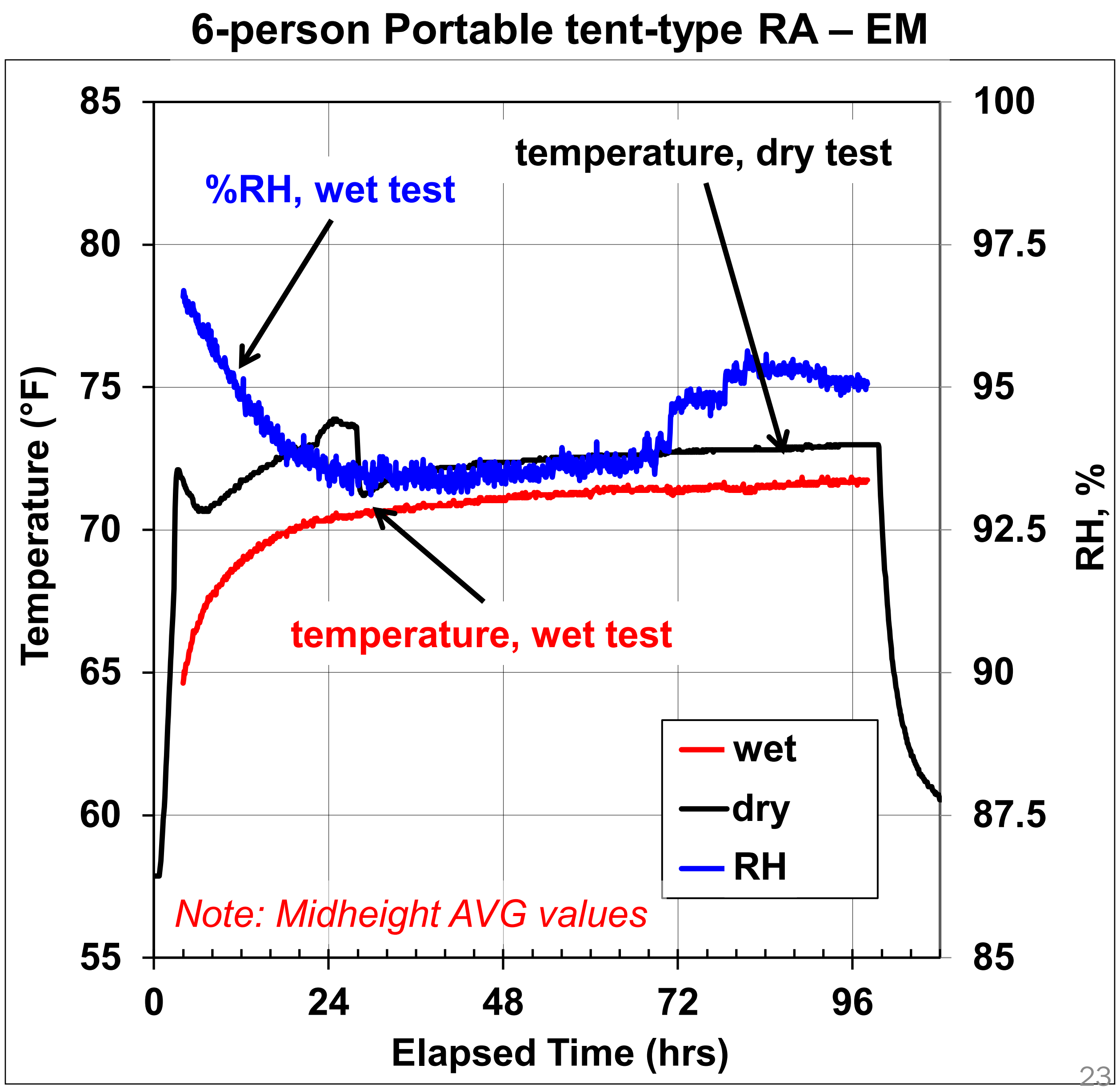
20-person portable
tent-type RA – EM

For all the tests, the RA internal temperature did not reach steady state within 96 hours.

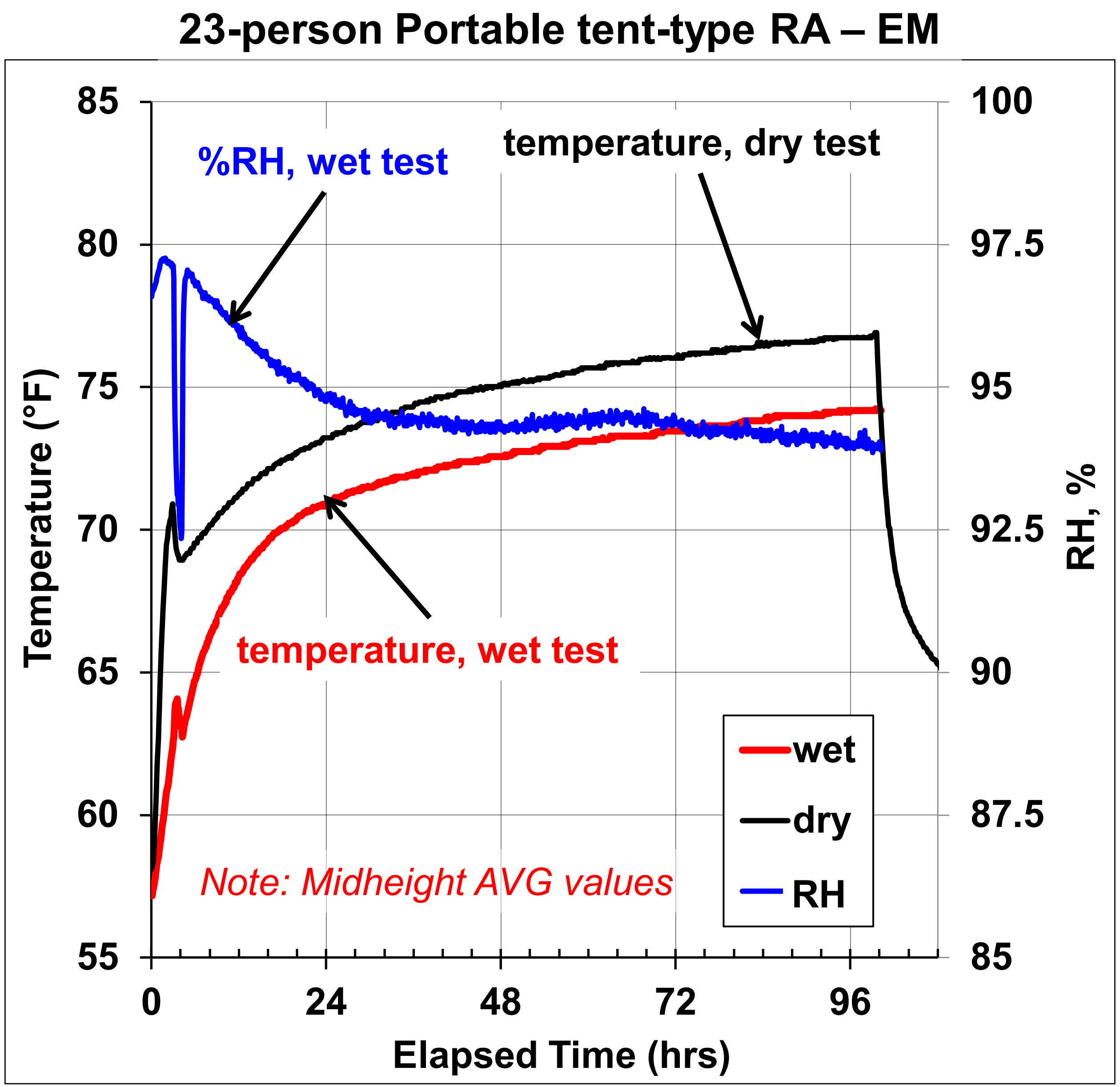


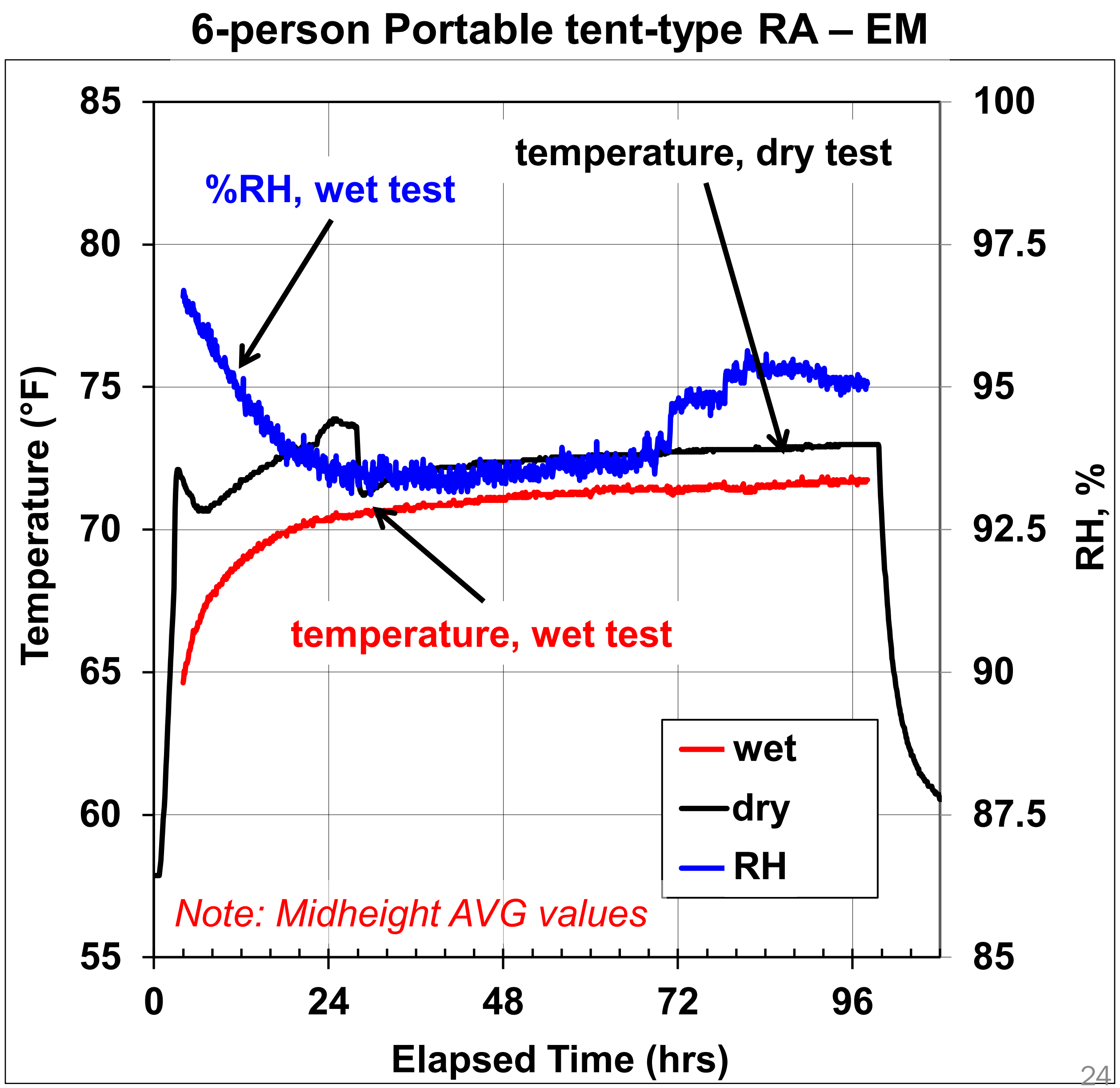
For all tests of portable RAs, “dry” tests resulted in a higher final dry-bulb temperature than “wet” tests.





For all tests of portable RAs, the internal %RH was reasonably steady after 1–2 days and the final %RH was above 90 %RH.





After testing, the interior of the RAs would be covered in condensation.

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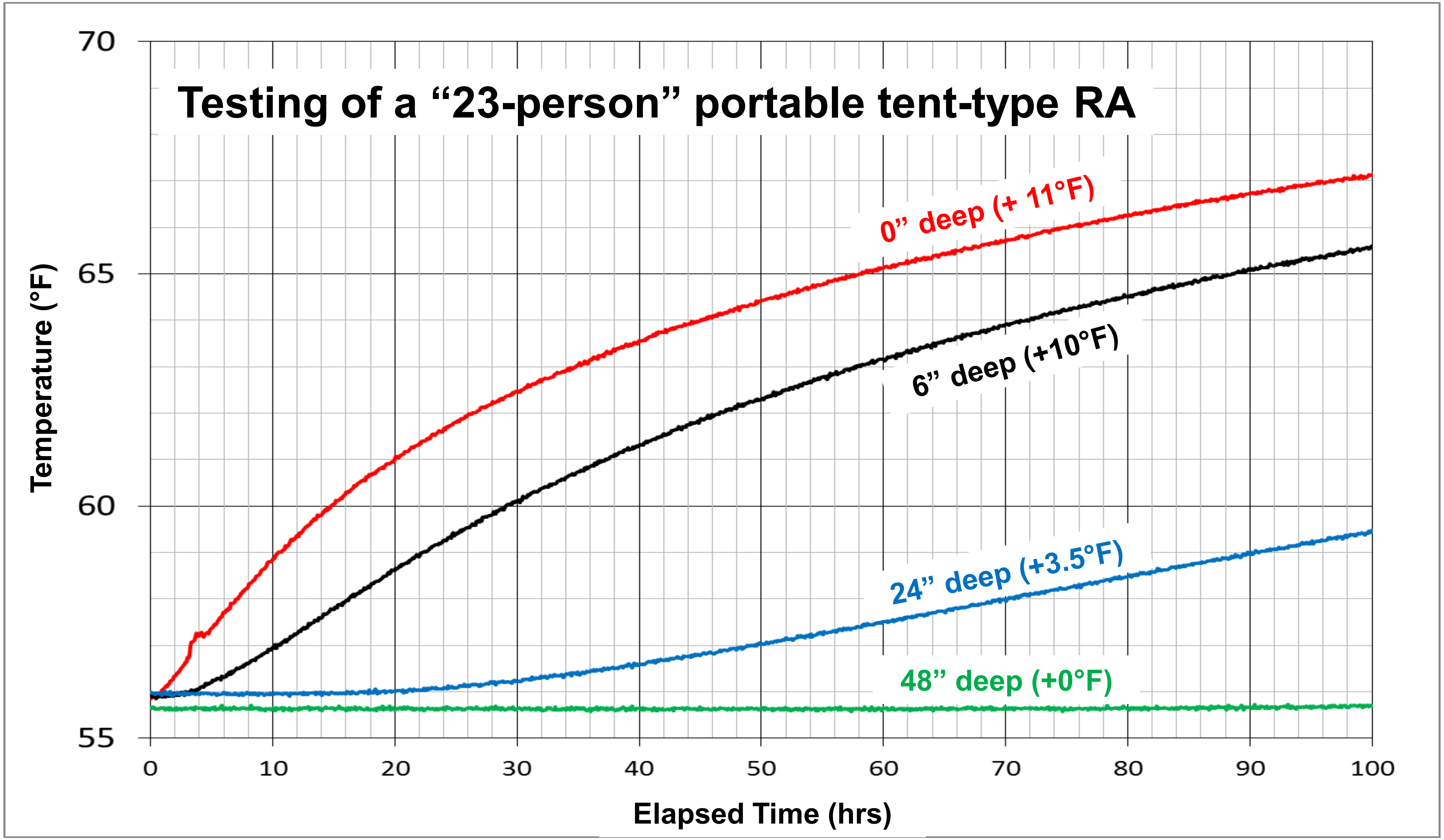
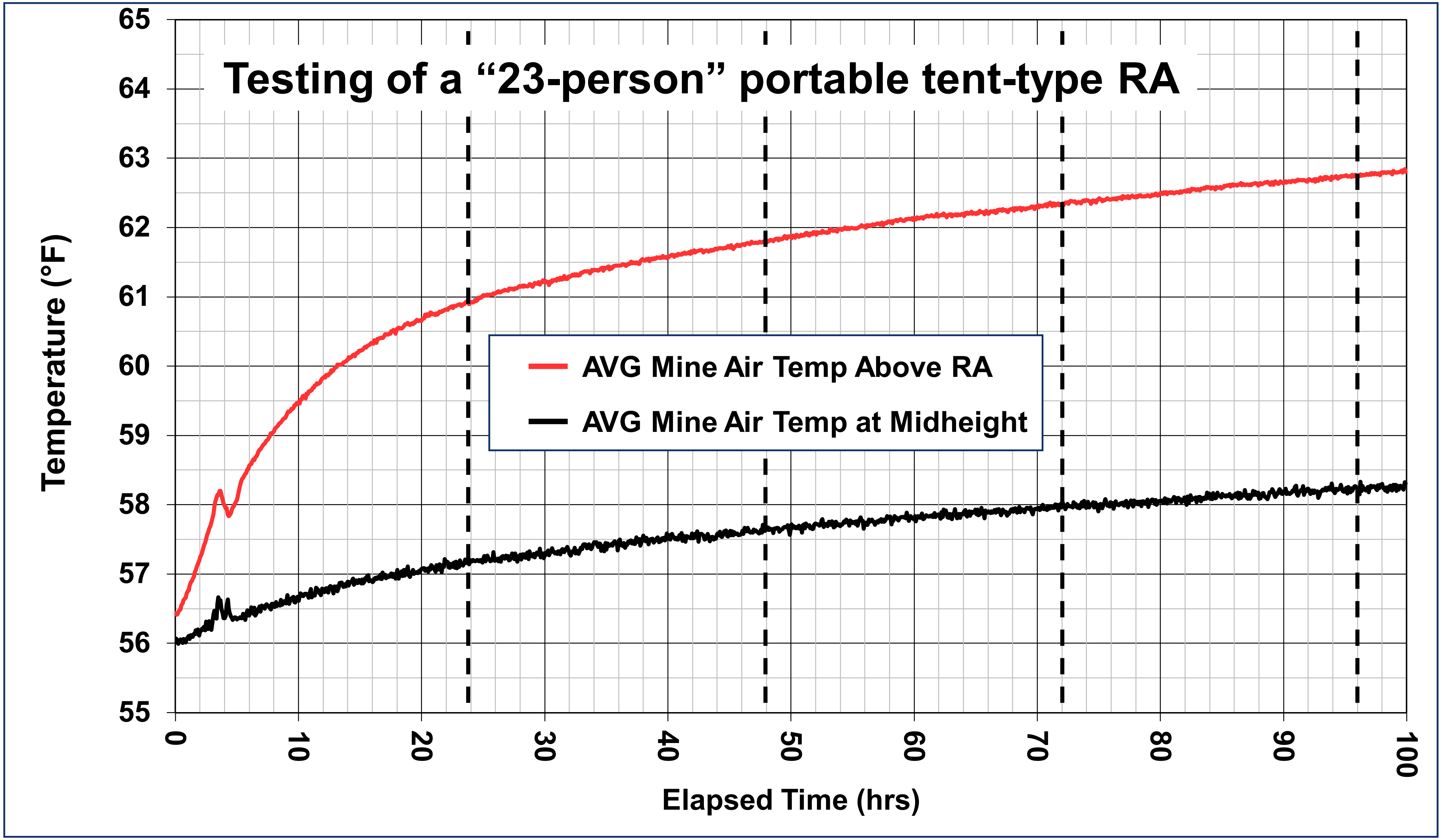
For all tests, the mine strata temperature under the RA did not reach steady state in 96 hours and the temperature at 4 ft deep was roughly constant.



For all tests of portable RAs, the mine air temperature near the RA continued to increase throughout the tests.



For the 23-person tent-type RA and the 6-person rigid RA, the final temperature rise for the wet tests were ~90%of the temperature rise for the dry tests.

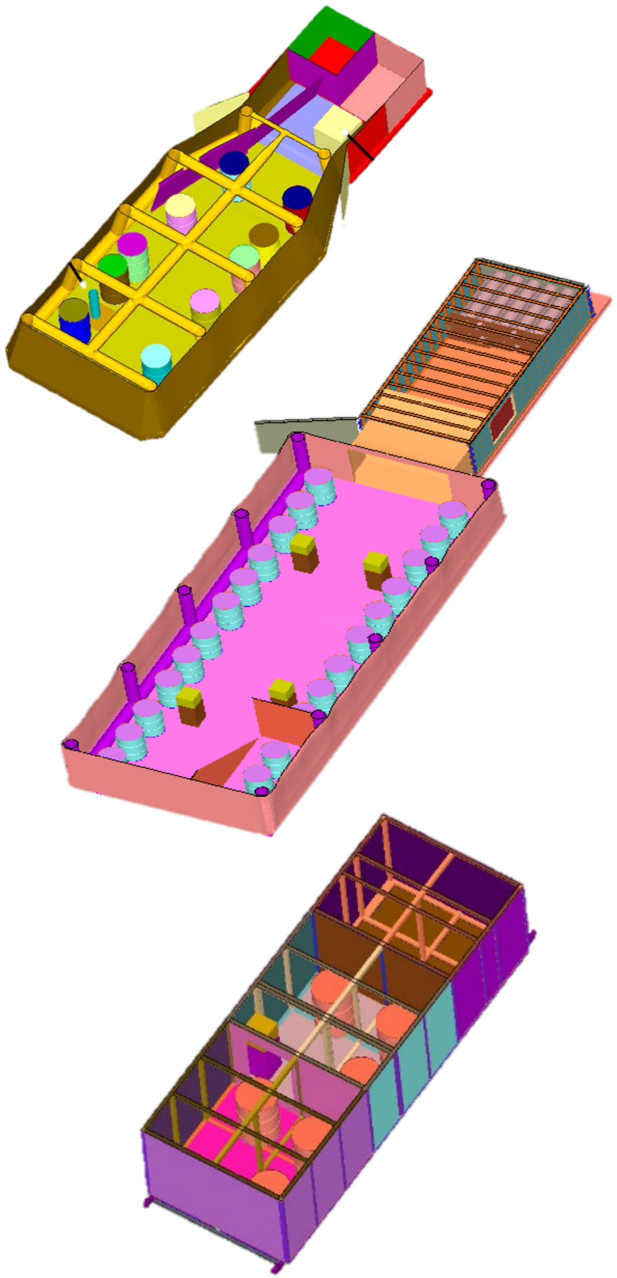
Tested RA	Test condition	Final ΔT (°F)	Final RH (%)	Final ΔT, wet / Final ΔT, dry
23-p tent, EM	dry	+18.6	--	91%
	wet	+17.0	94	
6-p metal, EM	dry	+15.0	--	93%
	wet	+14.0	94	

For the 23-person tent-type RA and the 6-person rigid RA, the ratio of the temperature rise for each day to the final temperature rise were similar.

Tested RA	Test condition	$\Delta T_{day\ 1}/\Delta T_{day\ 4}$ (%)	$\Delta T_{day\ 2}/\Delta T_{day\ 4}$ (%)	$\Delta T_{day\ 3}/\Delta T_{day\ 4}$ (%)
23-p tent, EM	dry	81	91	96
	wet	82	91	96
6-p metal, EM	dry	NA	96	98
	wet	91	95	98

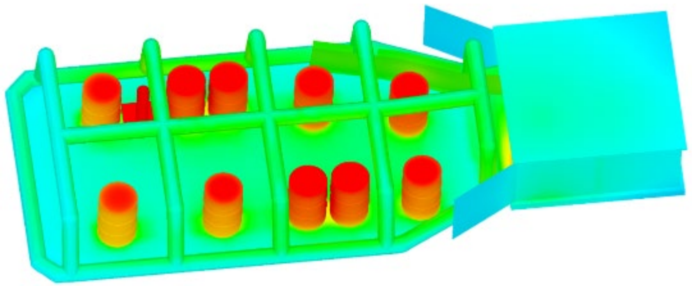
NIOSH contracted ThermoAnalytics, Inc. to develop thermal simulation models of three portable RAs.

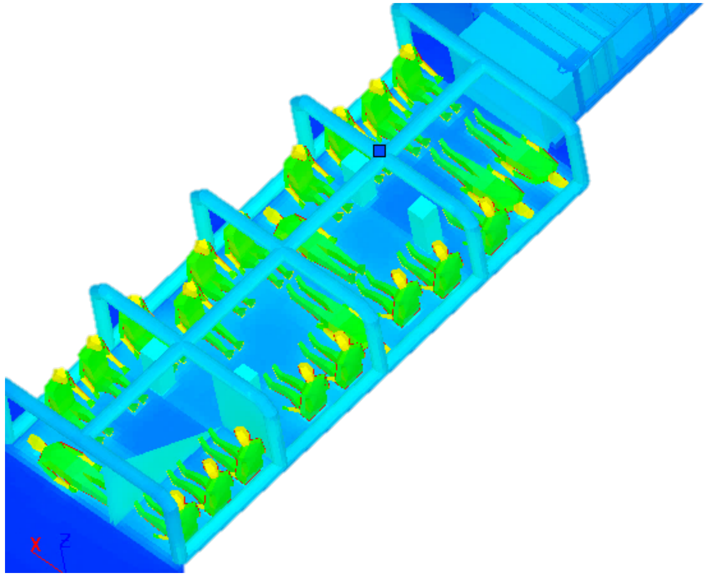
- 10-person tent-type RA training unit in Safety Research Coal Mine
- 23-person tent-type RA and 6-person rigid RA in Experimental Mine
- Mine strata modeled in layers up to a depth of 6 feet
  - 23-person tent-type RA and 6-person rigid RA models used mine strata parameters determined from measurements
    - Ground penetrating radar used to examine thickness of the concrete floor in the EM
    - Core samples to determine strata properties
- Models ignore air stratification
- Mine strata temperature at 6’ depth is treated as constant

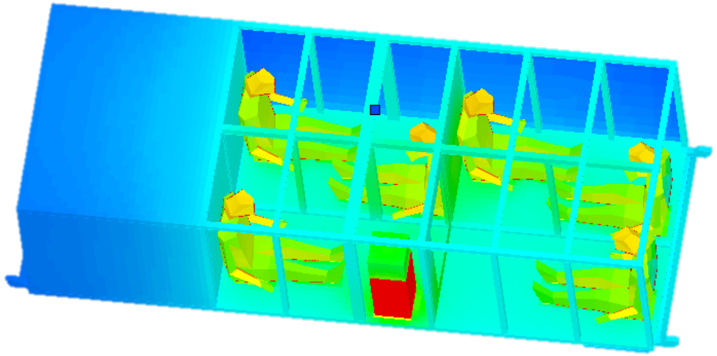


NIOSH contracted ThermoAnalytics, Inc. to develop thermal simulation models of three portable RAs.

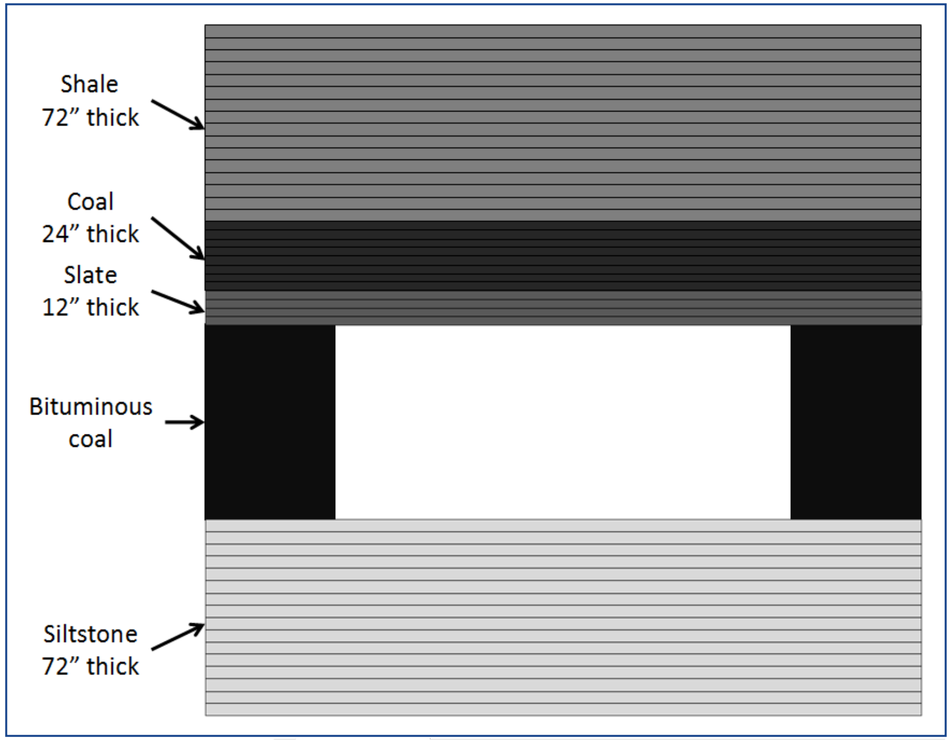
- Models account for heat input from simulated miners and carbon dioxide scrubber heat (water tanks)
    - 23-person tent-type RA and 6-person rigid RA models include moisture input
- Mine air/strata and RA air/structure temperatures, and RA %RH are initial conditions
- All models predict temperatures of RA air, RA structure, mine air, and mine strata
- 23-person tent-type RA and 6-person rigid RA also predict internal %RH

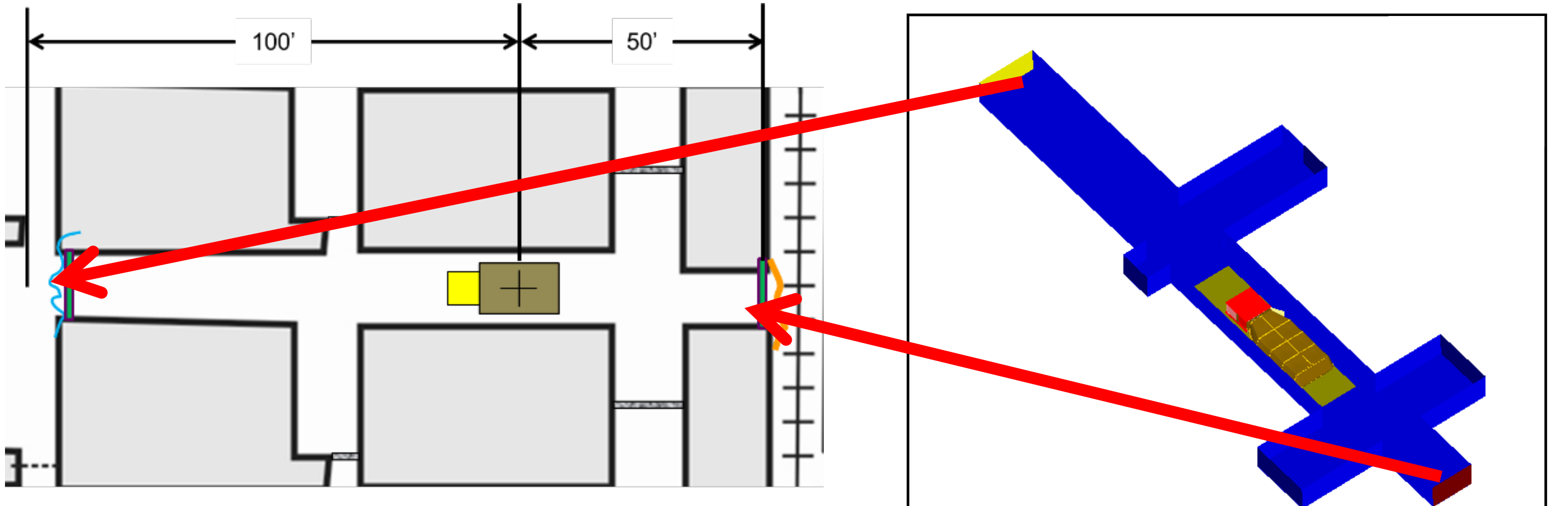


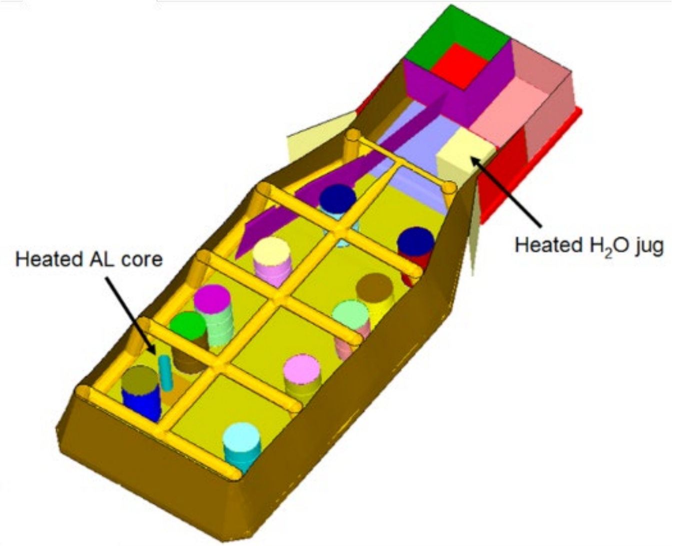




The model of the 10-person tent-type RA training unit was used to examine the effects of several parameters.

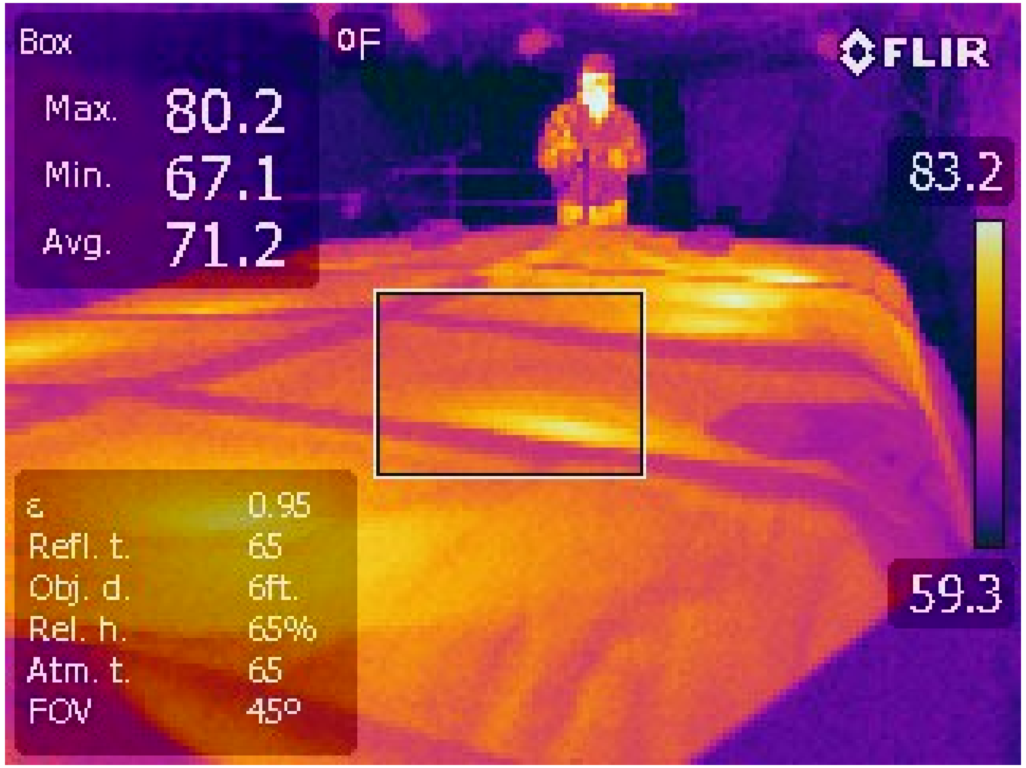


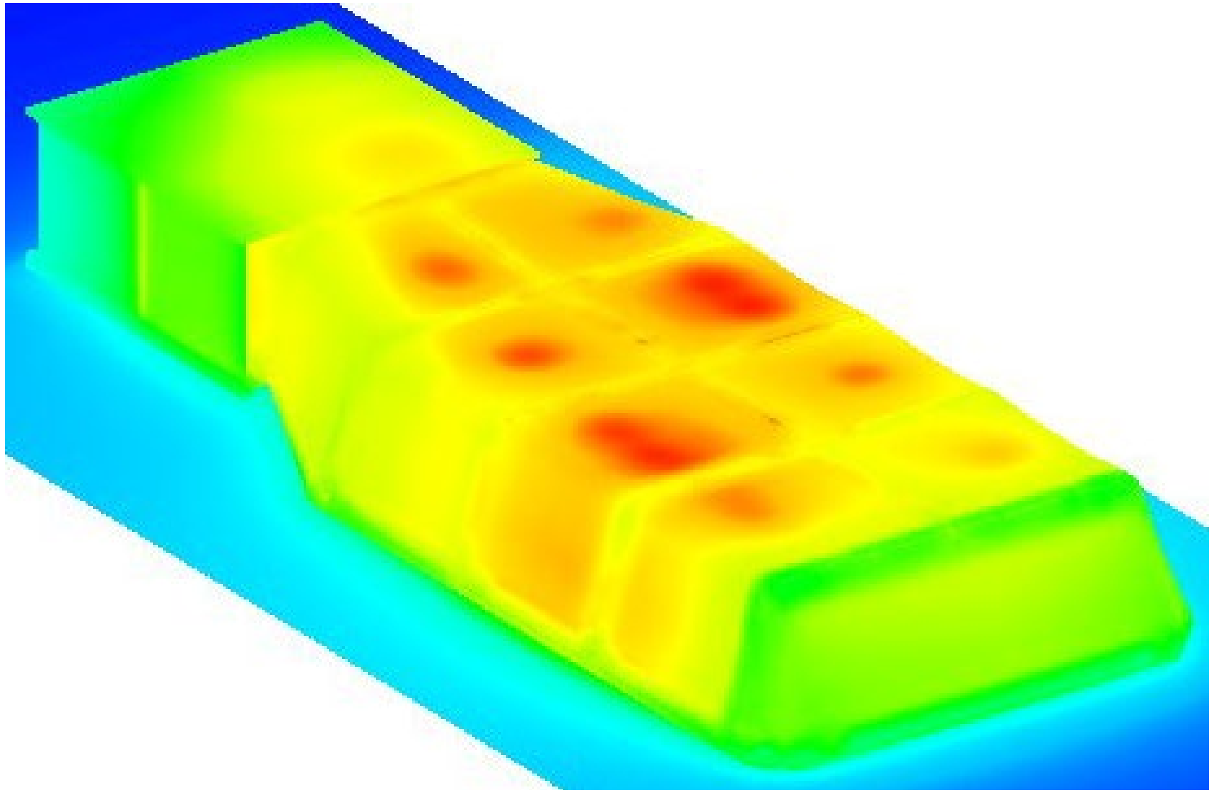




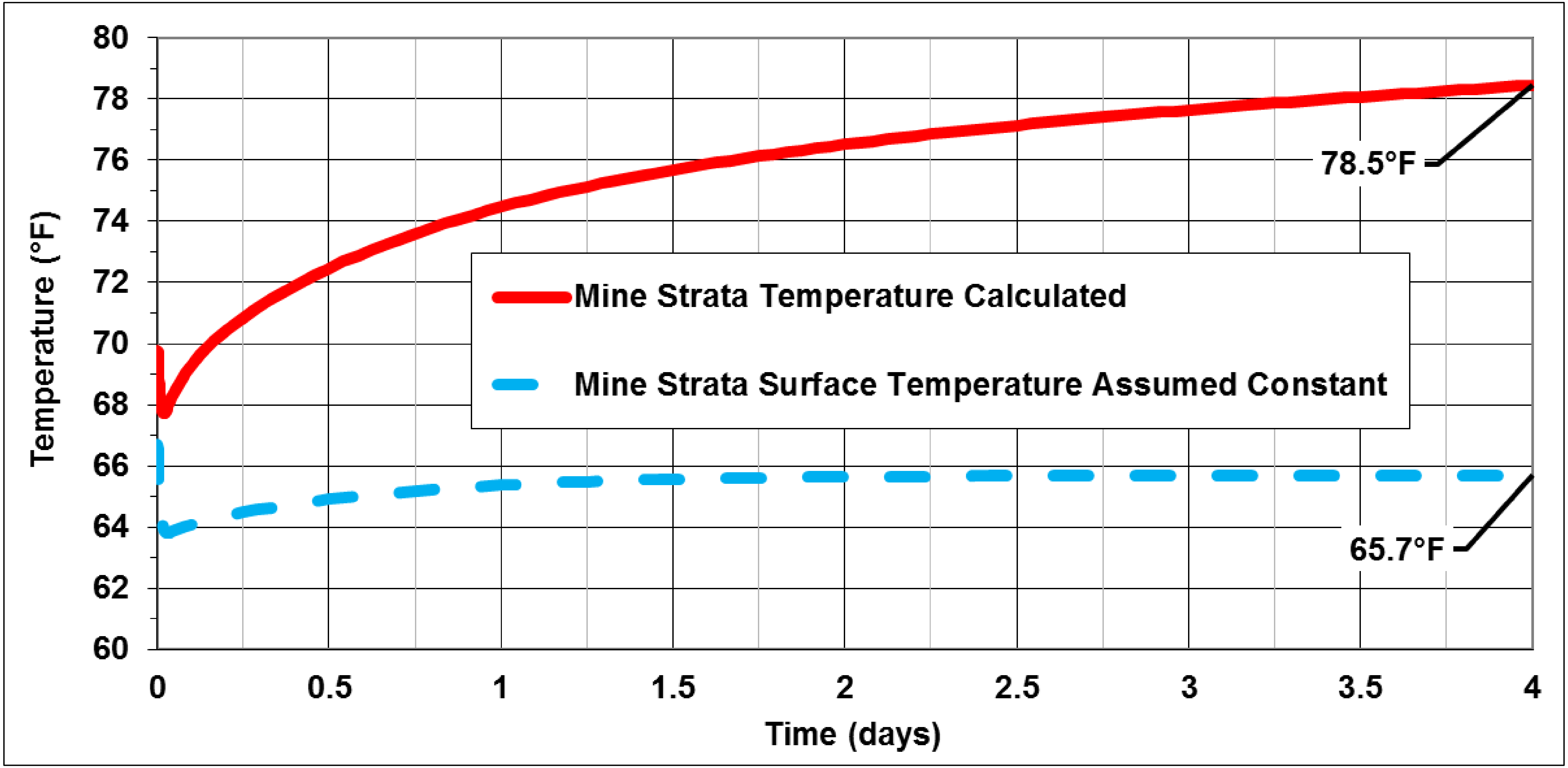
The model of the 10-person tent-type RA training unit was used to examine the effects of several parameters.

- Mine strata thermal behavior, constant or variable
- Initial temperatures of mine air, strata surface, and strata at depth
- Mine entry size (clearance)
- Mine strata composition





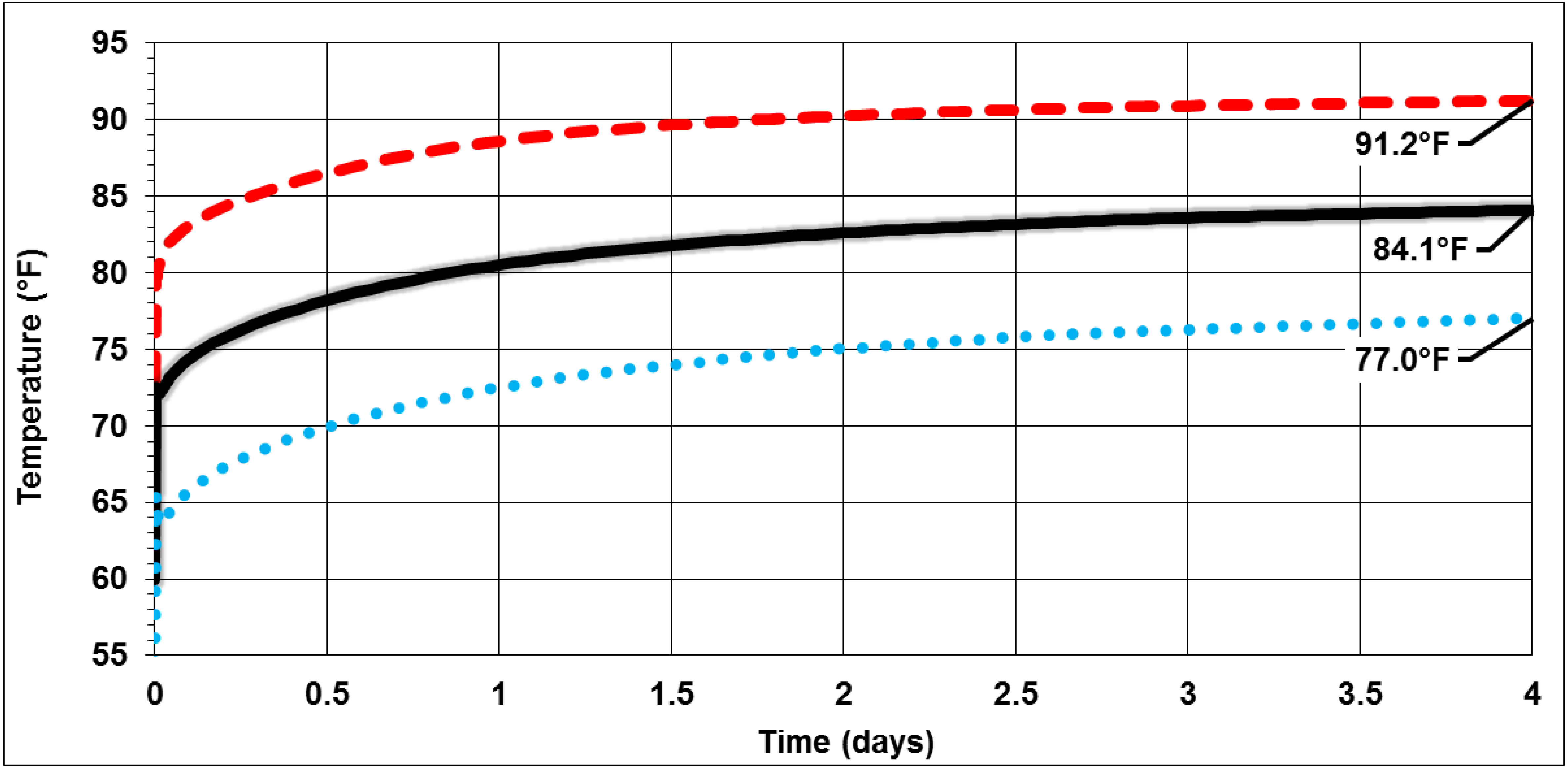
The predicted average RA internal air temperature was *13 °F higher* when the mine strata temperature increase was included in the computations.



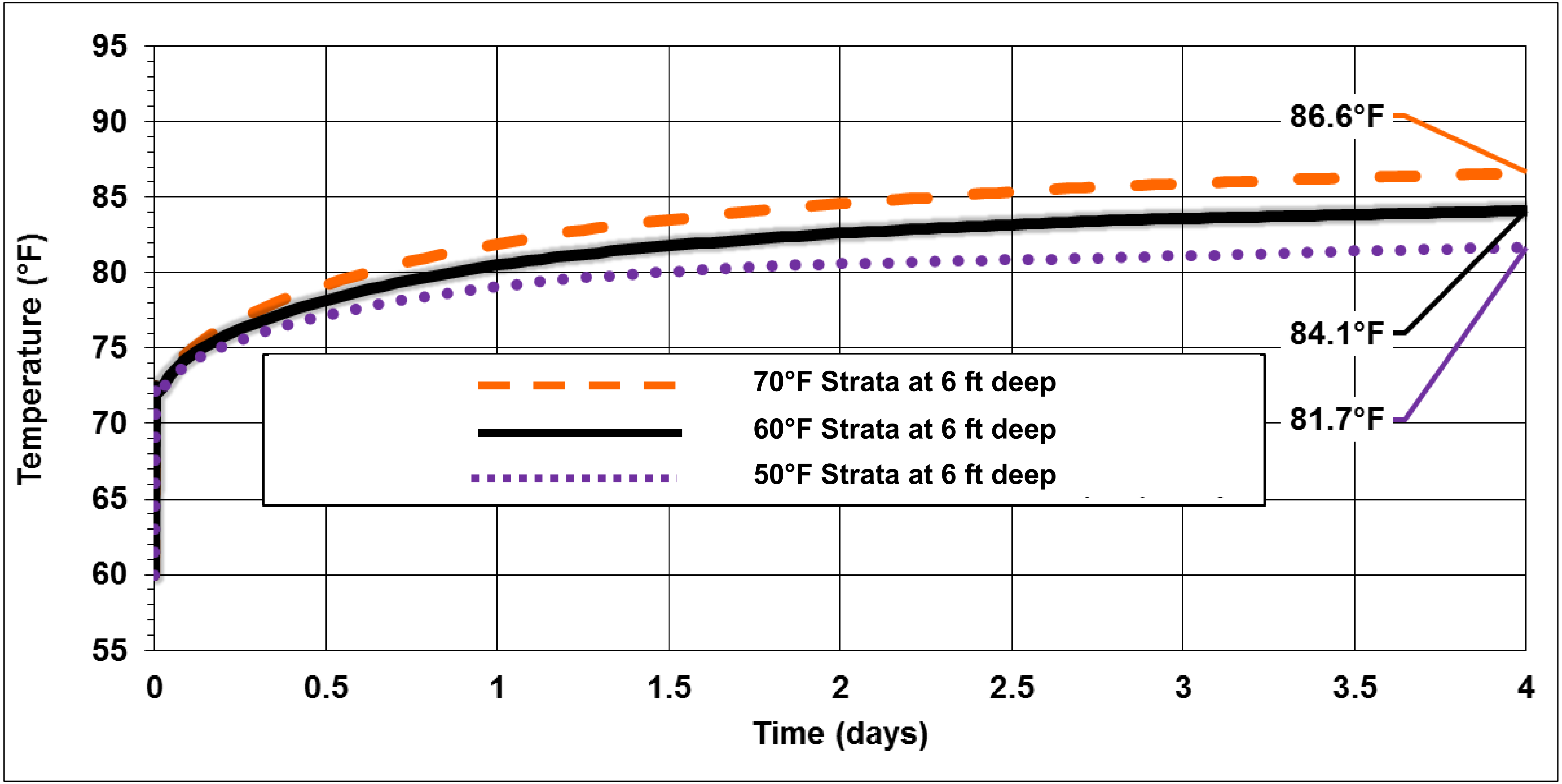
A *10 °F difference in initial mine air temperature* changed the predicted RA air temperature after 96 hours by only *0.03 °F*.

Parameter	Case A	Case B
Initial temp of simulated miner surfaces	95°F (35.0°C)	
Initial temp of mine strata surface	60°F (15.6°C)	
Initial temp of mine air, RA "body", RA internal air	70°F (21.1°C)	60°F (15.6°C)
Final temp of RA internal air	**80.09°F (26.72°C)**	**80.06°F (26.70°C)**

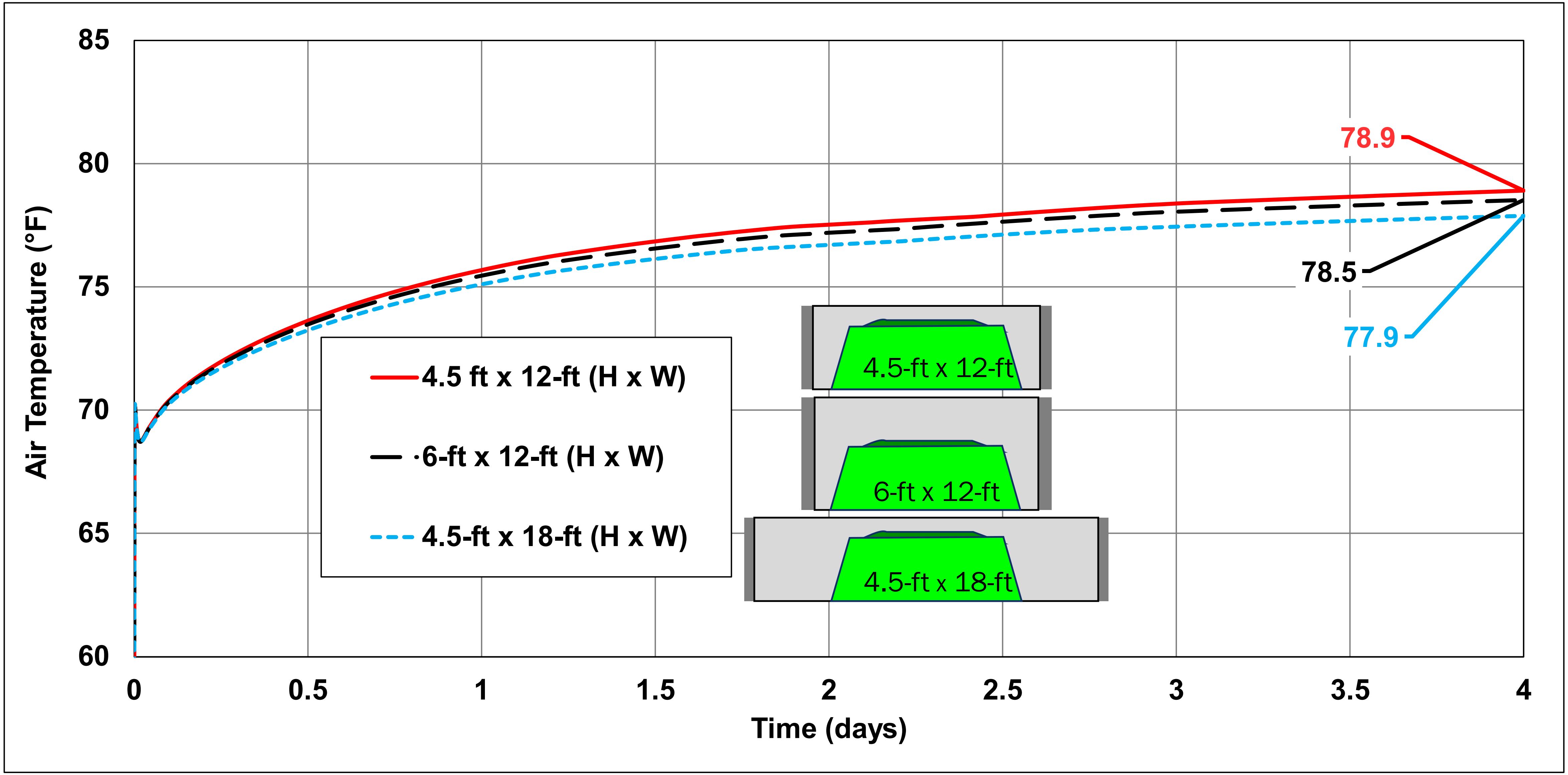
A *10°F difference in initial strata surface temperature* changed the predicted RA air temperature after 96 hours by *7°F*.



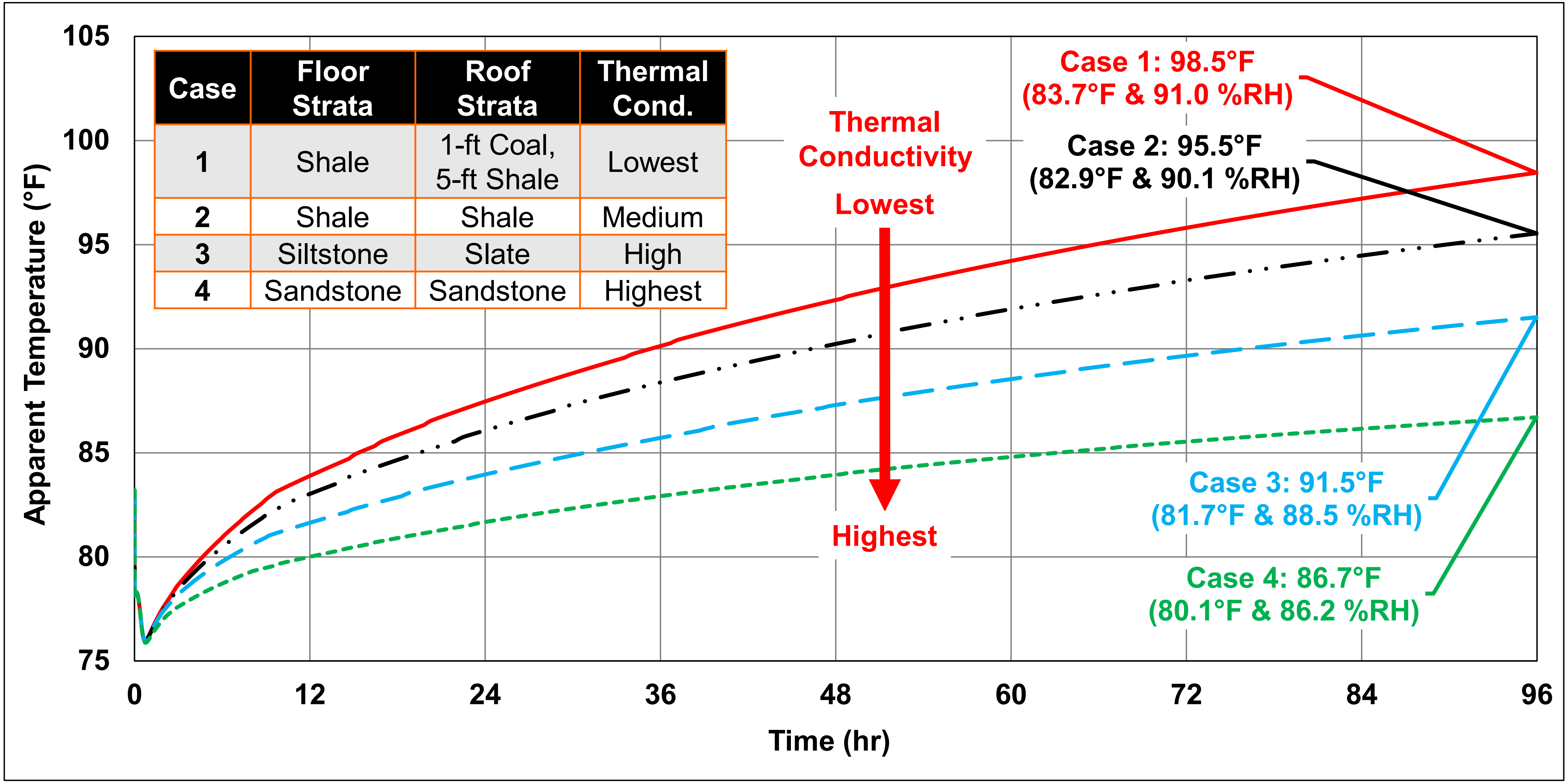
A *10 °F difference in initial strata temperature at 6 feet* changed the predicted RA air temperature after 96 hours by *~2.5 °F.*



Clearance around the RA had very little effect on final internal RA temperatures.



The predicted internal RA temperature, % RH, and apparent temperature increased as thermal conductivity decreased.

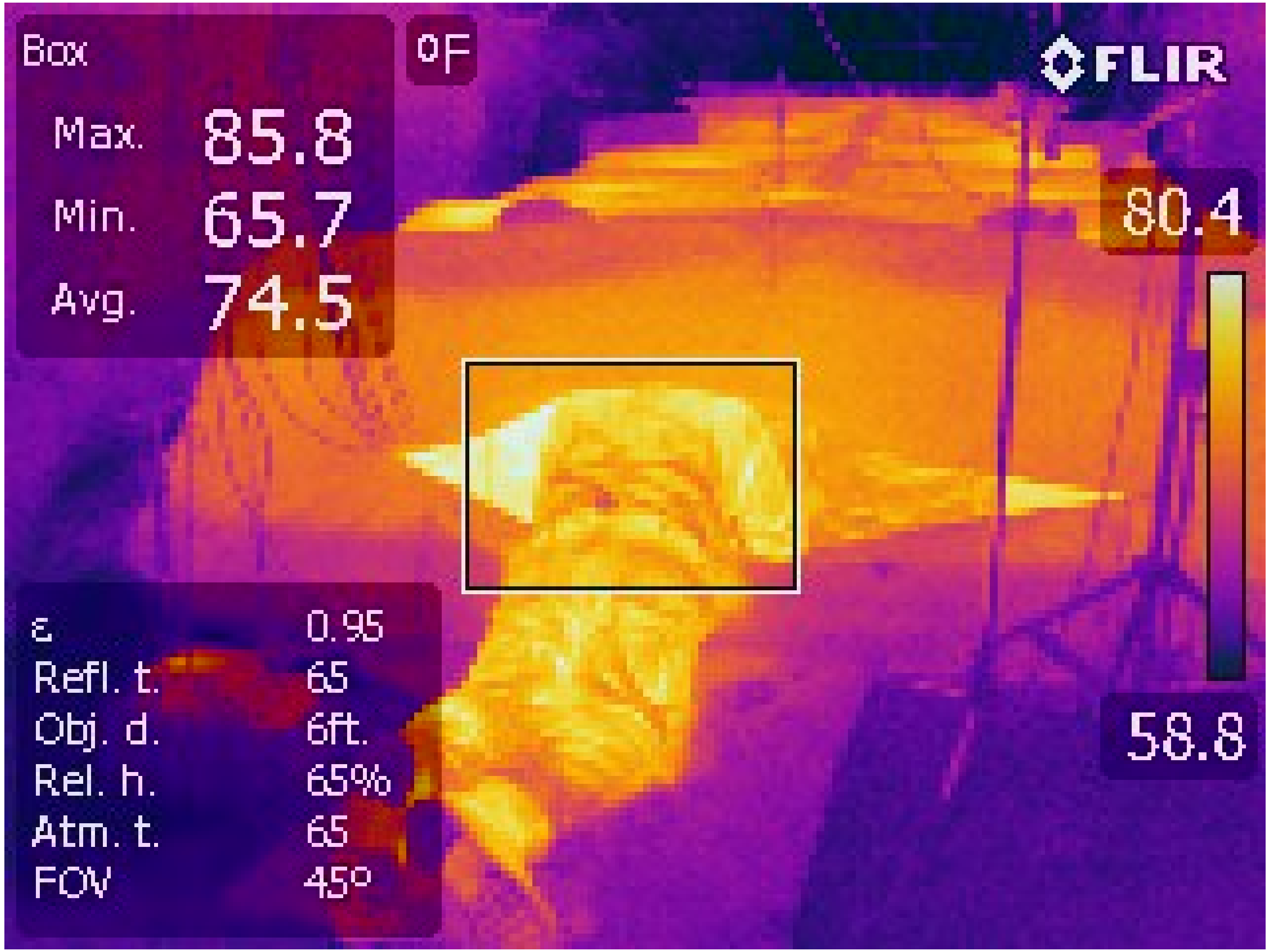


Case	Floor Strata	Roof Strata	Thermal Cond.
1	Shale	1-ft Coal, 5-ft Shale	Lowest
2	Shale	Shale	Medium
3	Siltstone	Slate	High
4	Sandstone	Sandstone	Highest

Summary & Conclusions

- Portable RAs will not reach steady state thermal conditions in 96 hours
- The inside of a portable RA will be humid; all NIOSH portable RA tests in a ~55°F mine showed the %RH stabilized above 90 %RH
- Initial mine strata surface temperature appears to be the key initial condition
- Initial mine strata temperature at depth affects RA final temperature, but less than initial mine strata surface temperature
- Mine height and width (clearance) has a small affect on RA temperature
- Mine strata thermal conductivity affects RA temperature, %RH, and apparent temperature
- RA apparent temperature and max occupancy estimates should
  - Properly account for mine strata behavior (strata heating)
  - Use mine air temperature and mine strata temperature as initial conditions
  - Consider mine-specific strata composition

Thank you for your attention!



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