Analysis of Underground Coal Miner Heat Exposure in a Refuge Chamber

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Outline of Presentation

Introduction

- A refuge chamber is a prefabricated barricade used as a last resort in the event of a mine emergency
- Isolate miners from harmful gases and sustain life until miners can be rescued
- Two basic types: stationary and portable
- Collectively referred to as “refuge alternatives”

Introduction

- Have been required in underground metal/nonmetal mines since 1977
- U.S. coal mines have been a late adopter of refuge alternatives
- Sago Mine Disaster resulted in significant regulatory changes
- Must be located within 1,000 feet of the face and one hour's travel distance apart in outby areas

Refuge Chamber (Longwall USA, http://flic.kr/p/9Wr21S)

Introduction

- Refuge alternatives must meet performance standards per 30 CFR Part 7
- Some pertinent requirements:
  - Internal apparent temperature must not exceed 35°C (95°F)
  - Provide a source of breathable air for 96 hours
  - Maintain average CO_2 concentrations below 1% vol.
  - All external electrical components must be intrinsically safe
  - Minimum requirements for floor space and unrestricted volume

Previous Work

- Heat exposure is a safety hazard that must be considered in a small, enclosed space
- NIOSH has performed in-mine testing at Lake Lynn Laboratory
- Have tested a variety of refuge alternative types
- Experimental set up consisting of light bulbs, humidifiers, O_2 source, CO_2 scrubber

Previous Work

- Sensible heat output from light bulbs equivalent to 117 W per occupant (NASA standard)
- Used soda lime and lithium hydroxide CO_2 scrubbers
- 42.8 W/person for soda lime
- 52.2 W/person for lithium hydroxide
- Average external temperature of approximately 17°C (62°F)

Previous Work

- A steady state temperature was reached after 4-15 hours
- At steady state, air became saturated and moisture condensed on refuge alternative walls
- Some refuge alternatives exceeded the apparent temperature standard

Model Design

- In-mine testing has a number of deficiencies
- A 96-hour test using human occupants could be psychologically damaging
- Time consuming and expensive
- Each new refuge alternative design requires a series of new tests
- Simulation is a viable alternative to in-mine testing

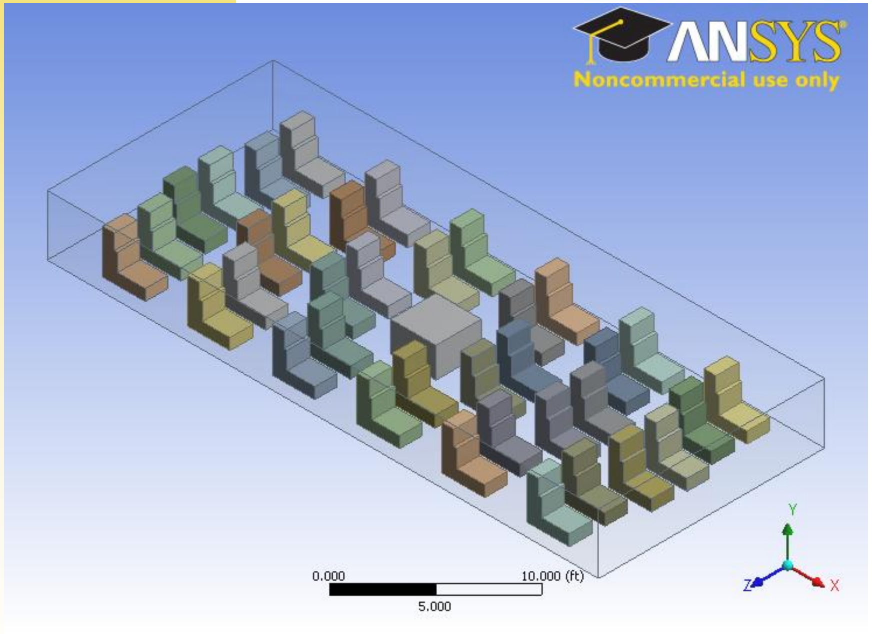
Model Design

- Performed modeling in ANSYS Fluent of the temperature inside refuge chambers
- ANSYS Fluent is a computational fluid dynamics (CFD) program
- Generic chamber designed around minimum MSHA requirements for floor space and unrestricted volume
- Not based on any commercially available refuge chamber in service

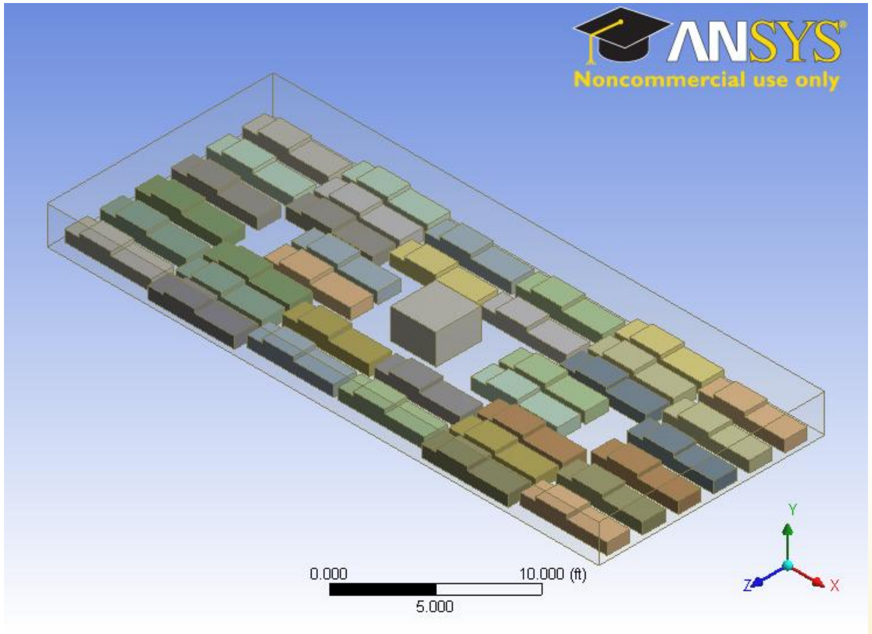
Model Design

Four steps in CFD modeling:

1) Create the Geometry
2) Mesh the Geometry
3) Fluid Dynamics/Heat Transfer Modeling
4) Post-process the Results



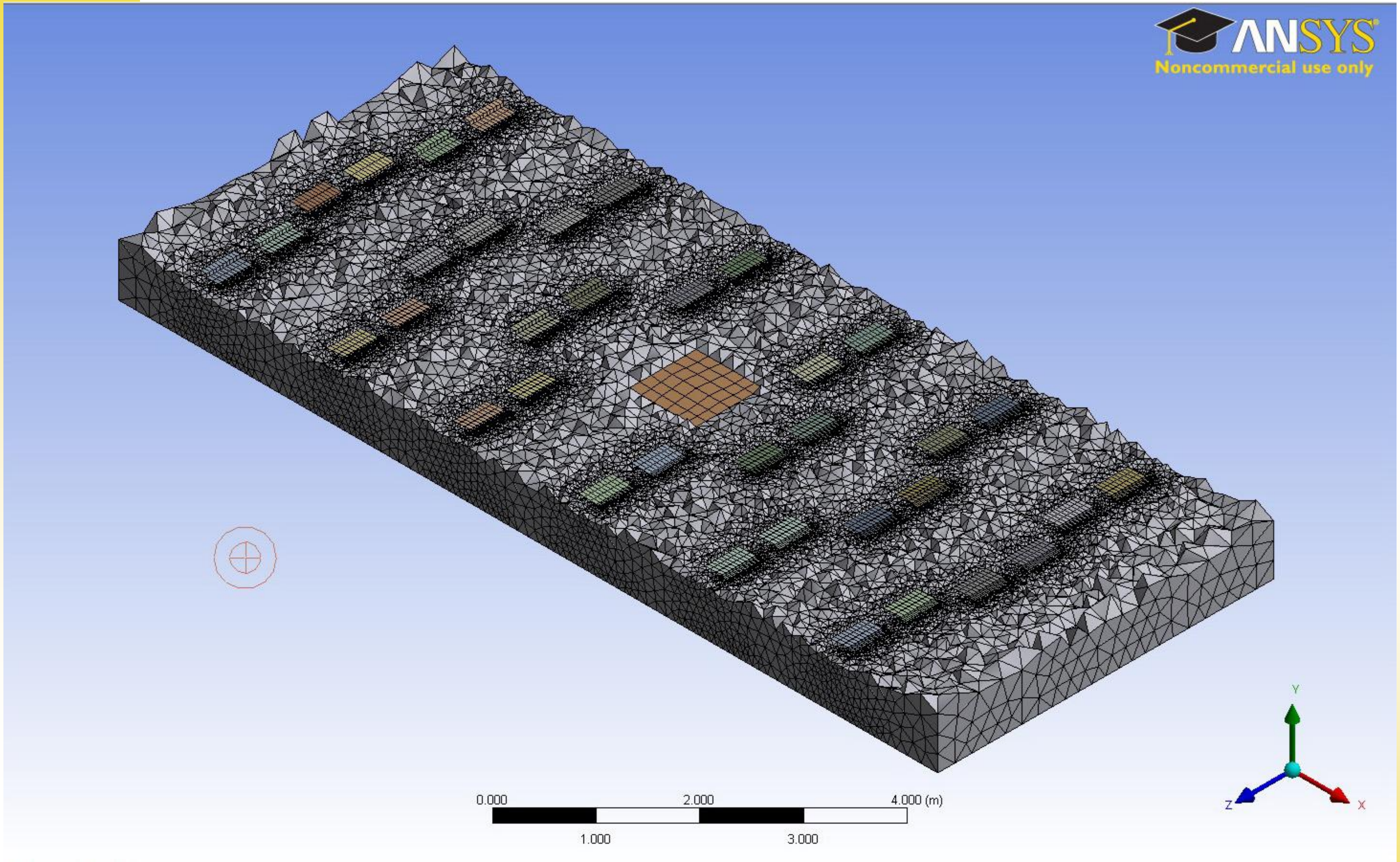
High Seam Refuge Chamber Geometry



Low Seam Refuge Chamber Geometry

Model Design

	High Seam Refuge Chamber	Low Seam Refuge Chamber
Length	11.2 m	11.2 m
Width	4.6 m	4.6 m
Height	1.2 m	0.8 m
Number of Occupants	36	36
Floor Space per Occupant	1.4 m^2	1.4 m^2
Volume per Occupant	1.7 m^3	1.1 m^3
Heat Production per Occupant	117 W	117 W
Heat From Scrubber (per Occupant)	52 W	52 W



Mesh for the High Seam Refuge Chamber

Model Design

- **Heat flux from a wall to the adjacent fluid cell calculated as:**

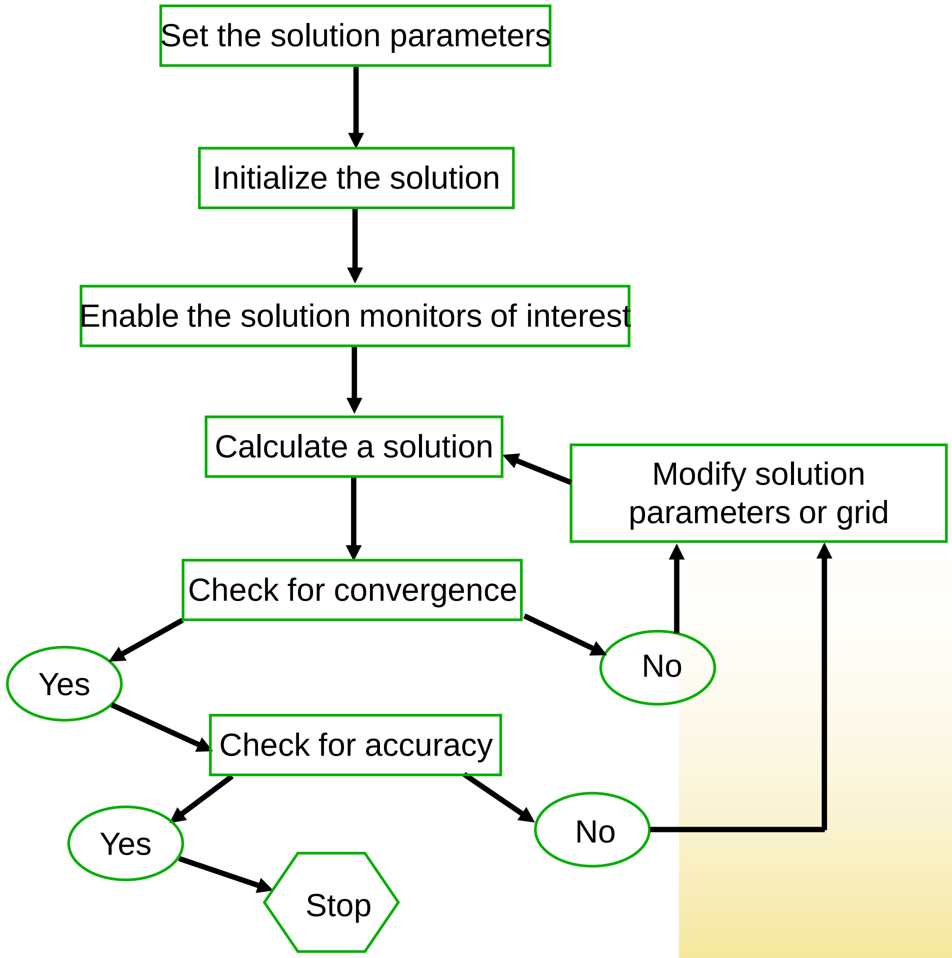
  $$q = h_f(T_w - T_f) + q_{rad}$$

- **Fluid side heat transfer coefficient (h_f) determined based on the local flow properties**

Model Design

- For realistic heat transfer coefficients, model must correctly resolve buoyancy driven flow
- Realizable kappa-epsilon (κ-ε) model used for turbulence closure
- Incompressible ideal gas law used to model density variation:

$$\rho = \frac{P_{op}}{\frac{R}{M_w} T}$$


Set the solution parameters
Initialize the solution
Enable the solution monitors of interest
Calculate a solution
Modify solution parameters or grid
Check for convergence
Yes
No
Check for accuracy
Yes
No
Stop

Model Design

Three different structural materials were modeled

1) Steel
2) Rubber
3) Aluminum

Six different external temperatures were considered

1) 16° C (60° F)
2) 16.7° C (62.1° F)
3) 21° C (70° F)
4) 27° C (80° F)
5) 32° C (90° F)
6) 38° C (100° F)

Model Design

	Steel Refuge Chamber	Aluminum Refuge Chamber	Rubber Refuge Chamber
Density	7,833 kg/m^3	2,739 kg/m^3	1,100 kg/m^3
Thickness	6.4 mm	6.4 mm	1.8 mm
Specific Heat	502 J/kg●K	896 J/kg●K	2,010 J/kg●K
Thermal Conductivity	45.3 W/m●K	222 W/m●K	0.13 W/m●K
Emissivity	0.90	0.90	0.86

**The emissivity value for the steel and aluminum chambers assumes a painted surface*

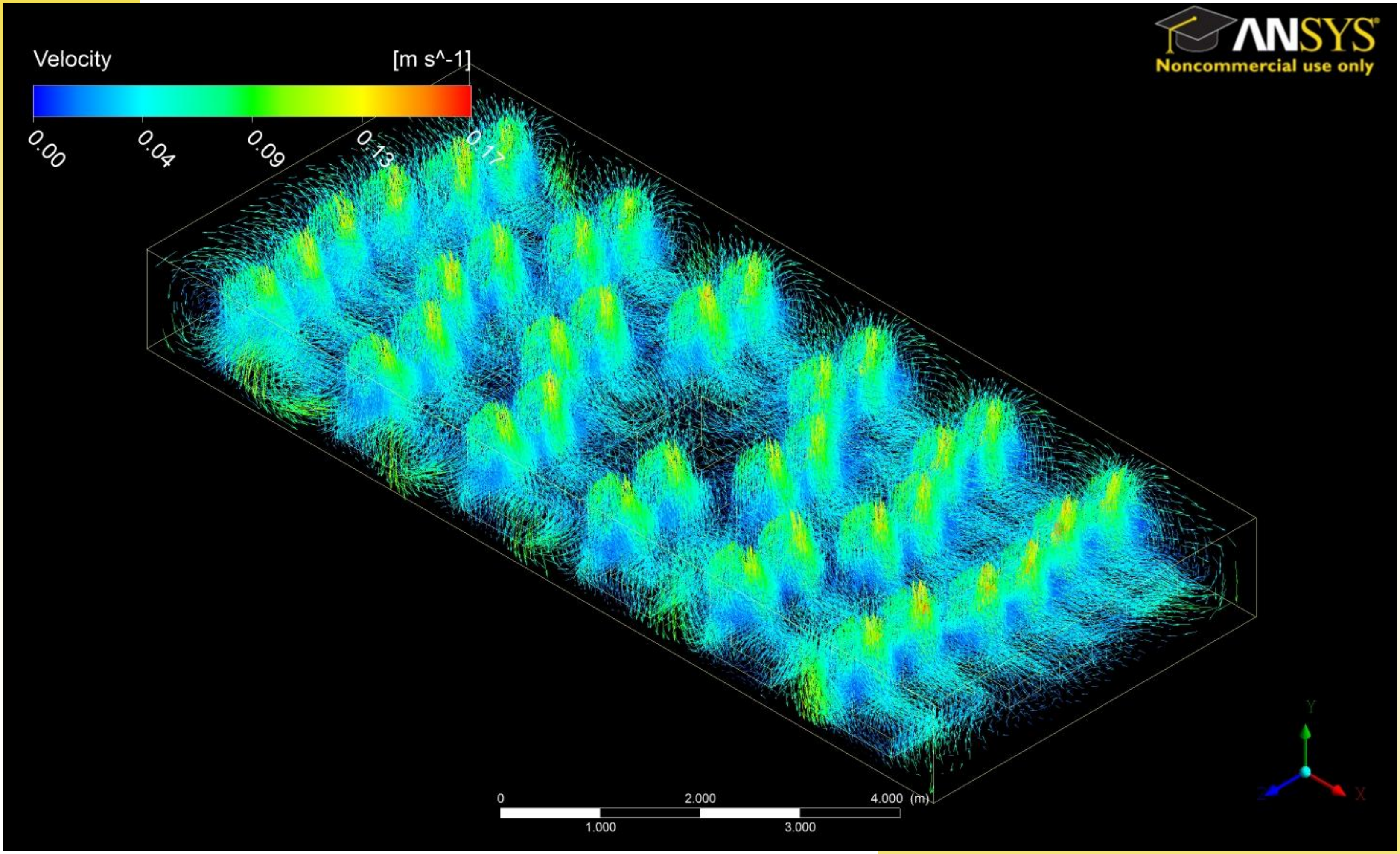
Model Design

Assumptions:

1) Temperature outside the chamber was assumed to be constant
2) No cross air flow over the chamber
3) Convective heat transfer coefficient of 5 $W/m^2 \cdot K$ for the outside of the chamber
4) The mine floor was assumed to be at a constant temperature
5) Perfect thermal contact between chamber bottom and the mine floor

Results

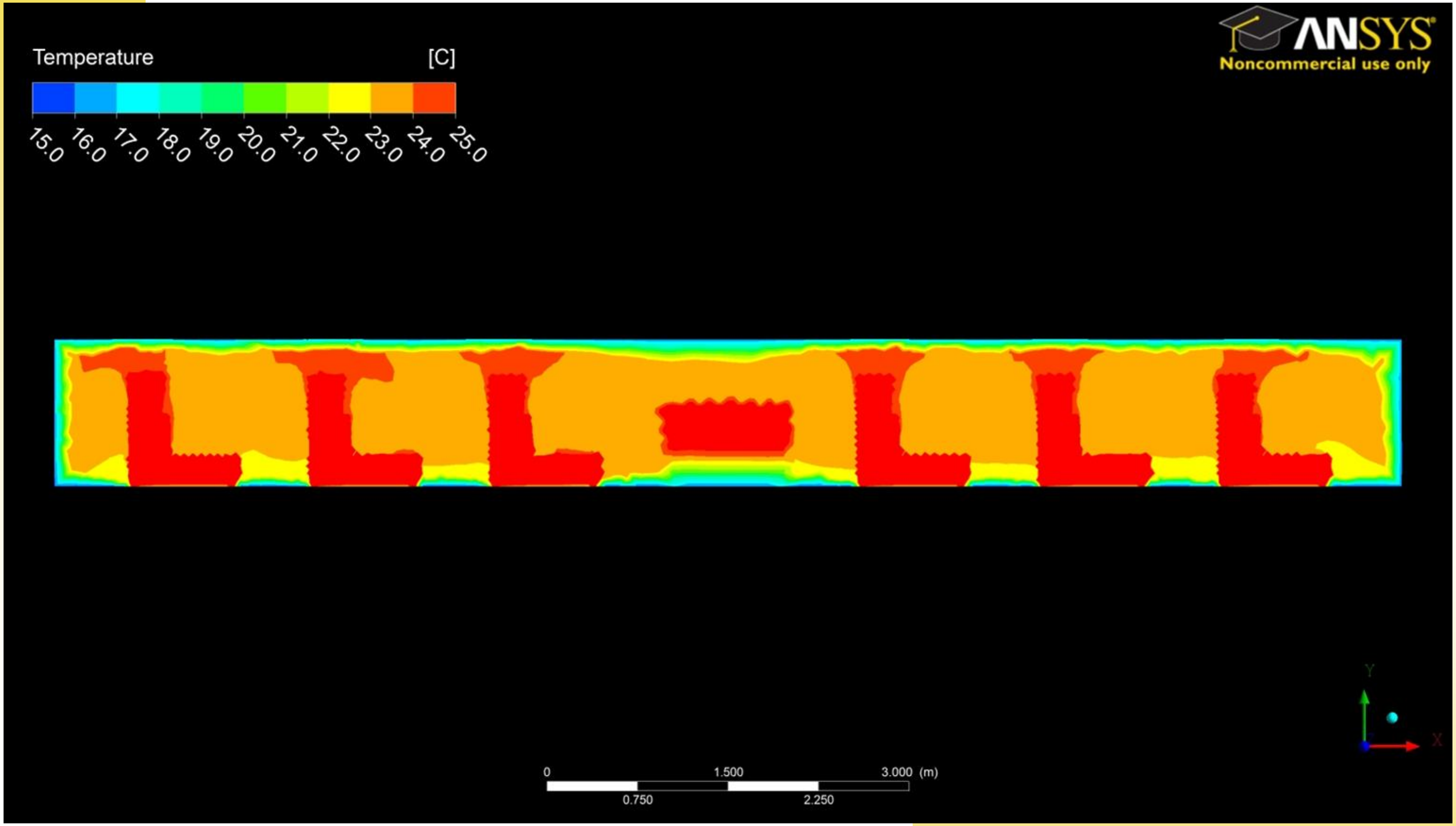
- NIOSH in-mine testing validates our simulation results
- Average internal temperature for our generic refuge chamber was 24.7° C (76.5° F)
- Average internal temperature for a refuge chamber of similar design in NIOSH testing was 25.3°C (77.5° F)
- Natural convection currents apparent in model results



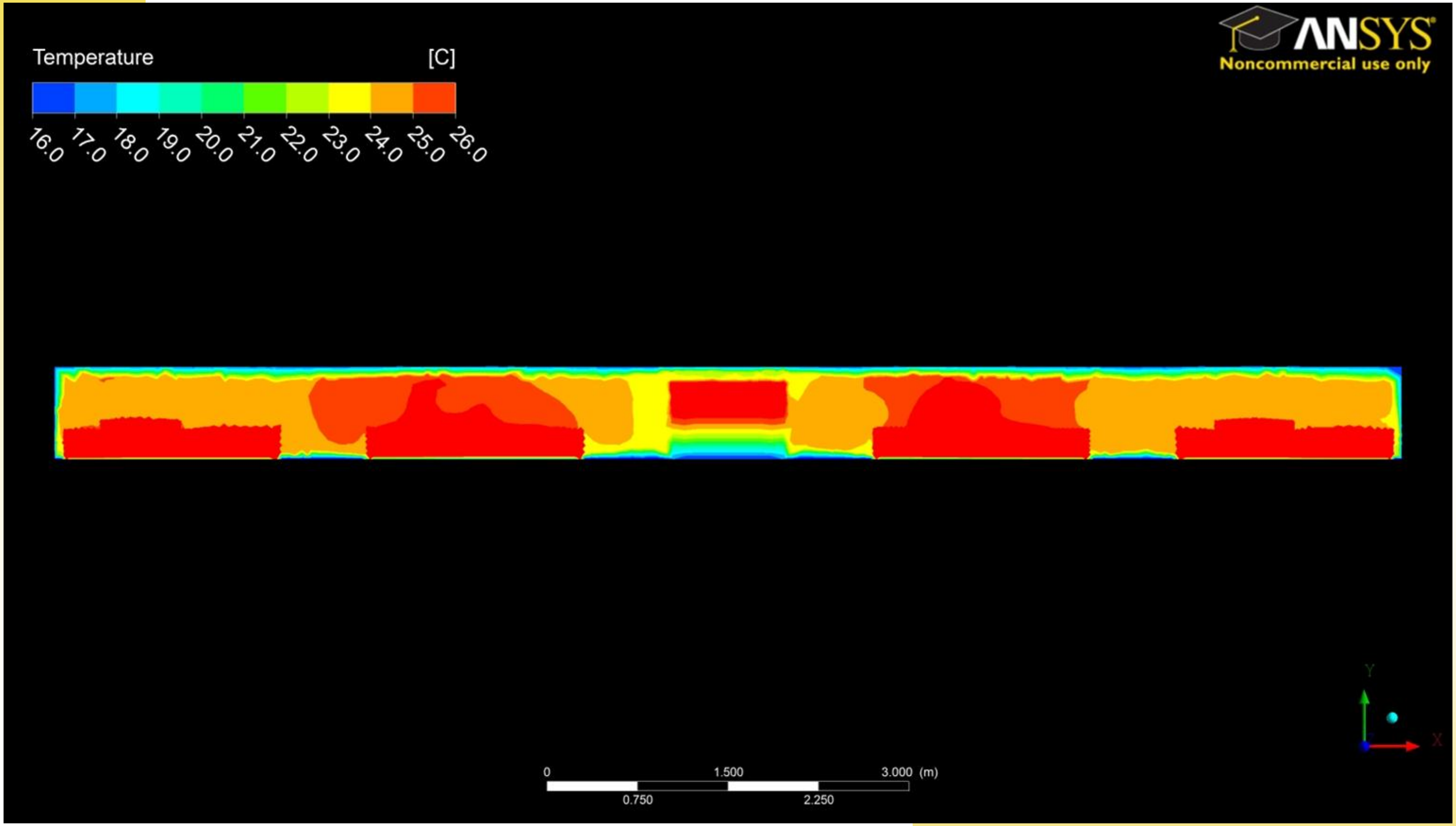
Velocity Vectors for the High Seam Refuge Chamber (External Temp. 16° C)

Results—Impact due to Chamber Size

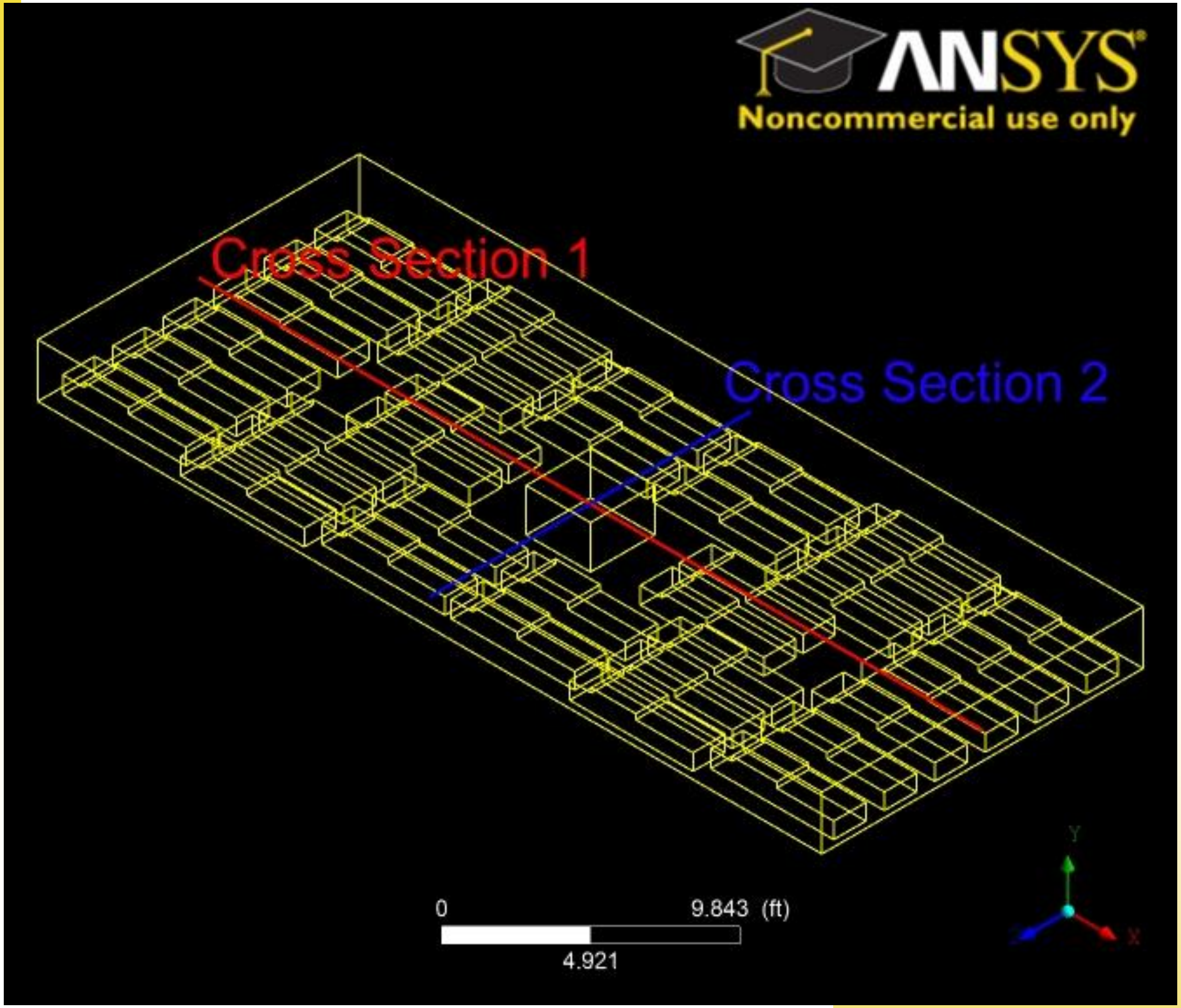
- Chamber size does influence internal temperature
- At an external temperature of 16° C (60° F), the high seam steel chamber had an average internal temperature of 23.6° C (74.5° F)
- The low seam steel chamber had an average internal temperature of 24.5° C (76.0° F)



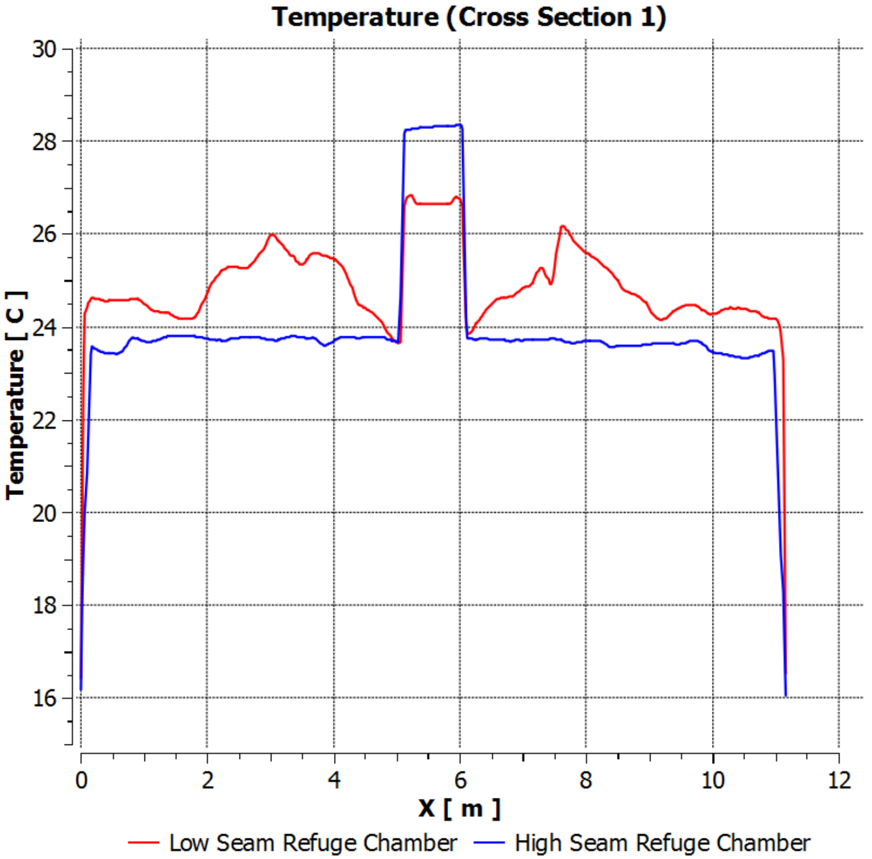
Temperature Contours for the High Seam Chamber (External Temp. 16° C)



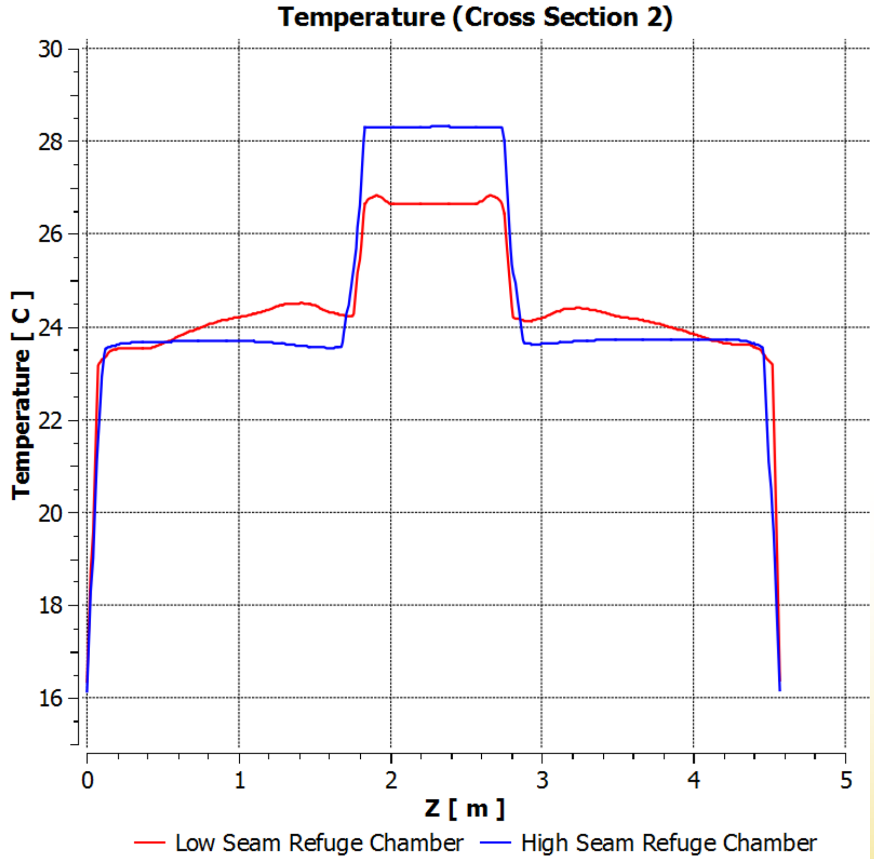
Temperature Contours for the Low Seam Chamber (External Temp. 16° C)



Cross Sections for Temperature Plots



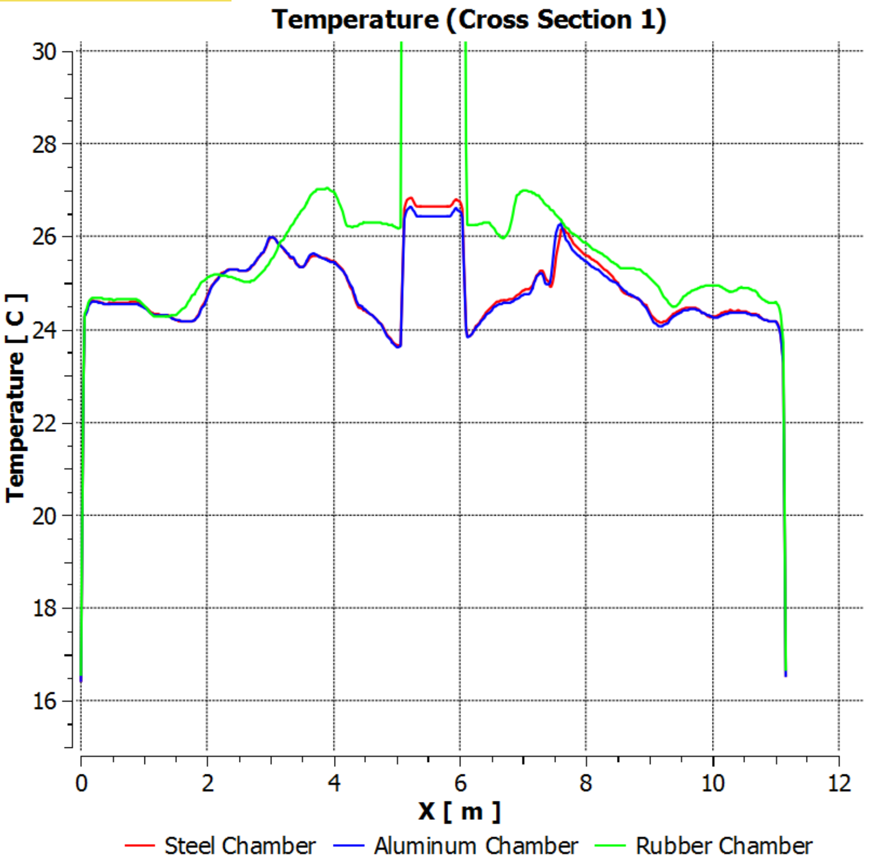
Internal Temperature Along Cross Section 1



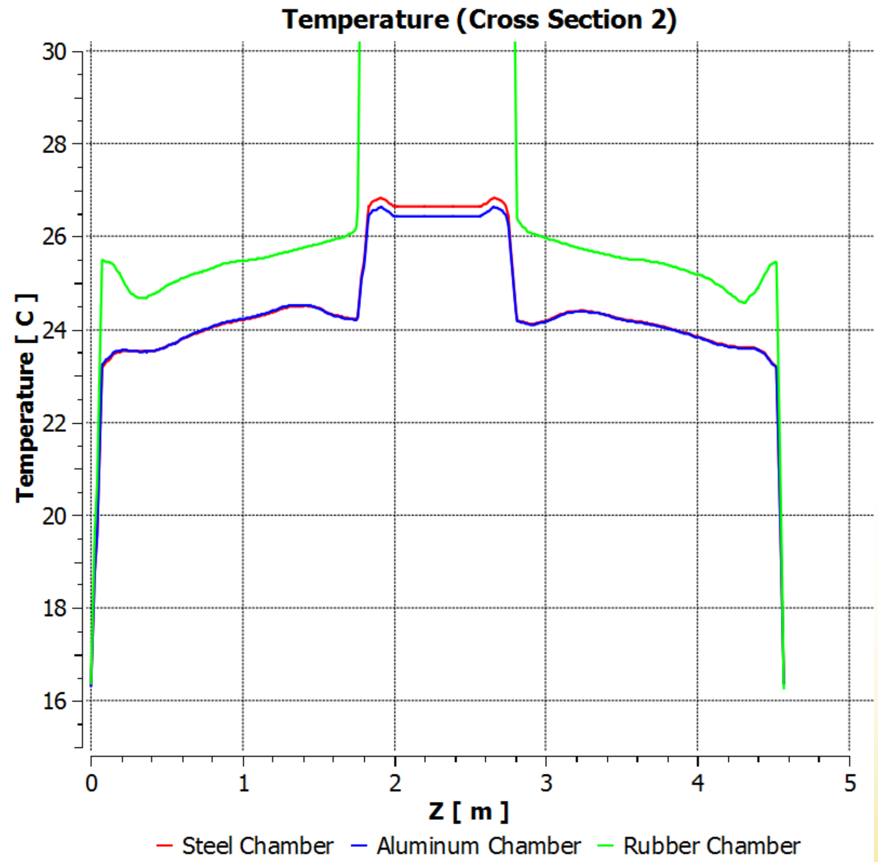
Internal Temperature Along Cross Section 2

Results—Impact due to Chamber Structure

- The structural material of the chamber does impact the internal temperature
- Conduction resistance is insignificant
- Radiation resistance is important
- Temperature inside steel and aluminum chamber is virtually identical
- Rubber chamber is approximately 0.5°C (1°F) hotter on average



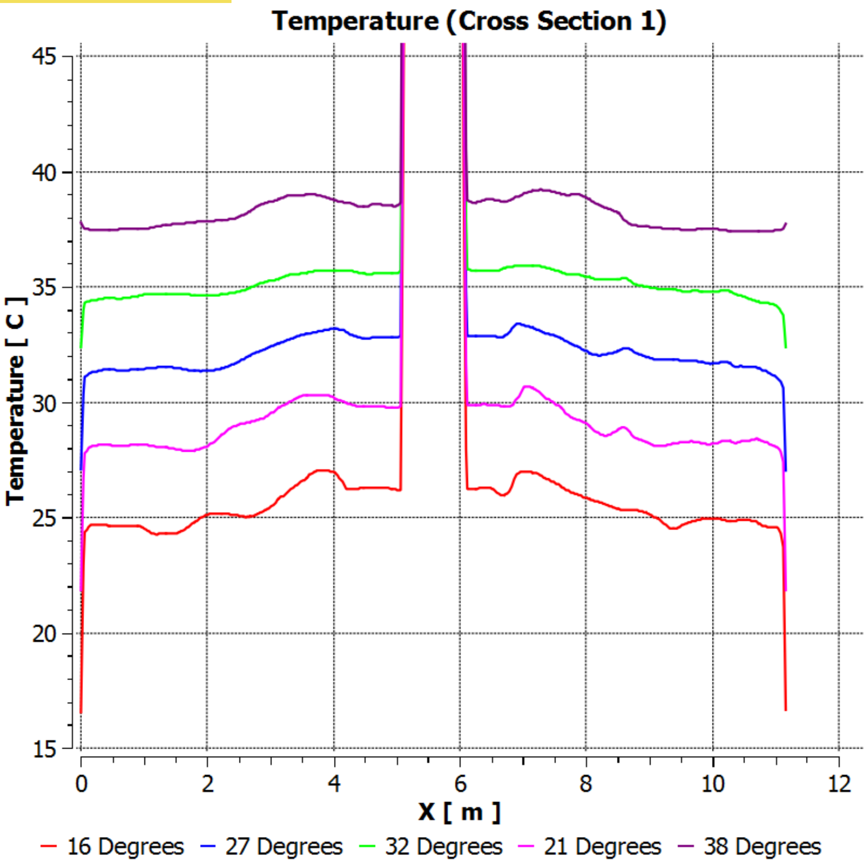
Internal Temperature Along Cross Section 1



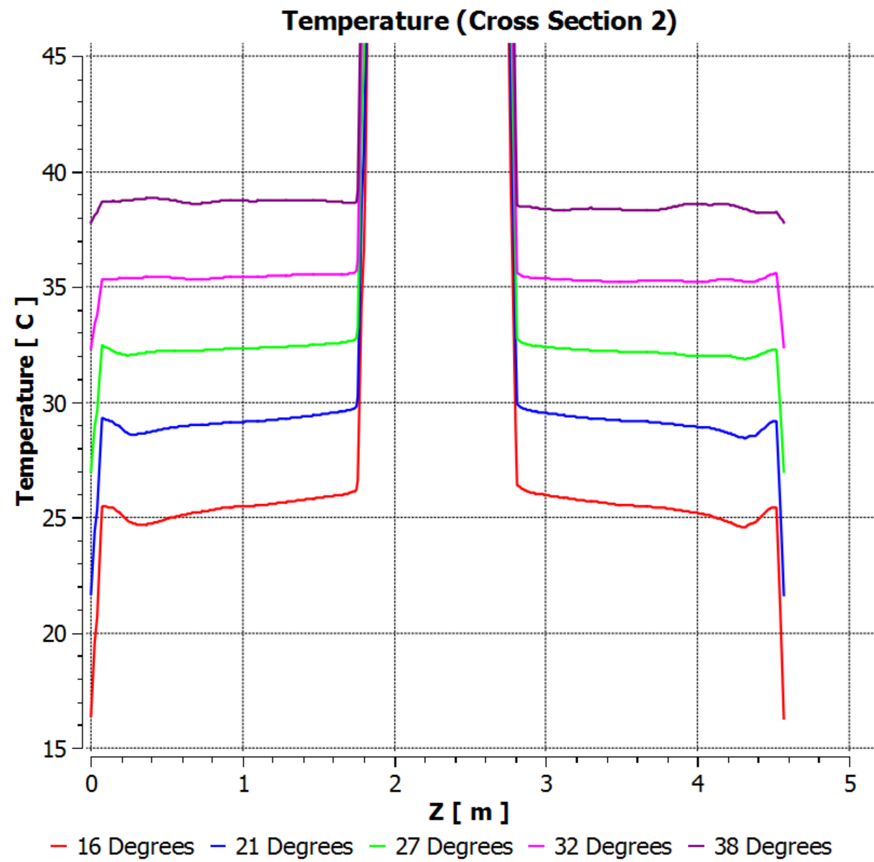
Internal Temperature Along Cross Section 2

Results—Effect of External Temperature

- The rubber, low seam chamber was used
- For saturated air, a temperature of 28° C (82° F) exceeds the Steadman Heat Index criteria
- An average internal temperature of 38.3° C (101.0° F) was observed for an external temperature of 38° C (100° F)
- Heat stress a major concern



Internal Temperature Along Cross Section 1



Internal Temperature Along Cross Section 2

Conclusions

- Simulation is a valuable tool for modeling refuge alternatives
- Size has some impact on the internal temperature of the chamber
- Structural materials plays a small role in determining the internal temperature of the chamber
- Heat stress would become a serious concern as external temperatures increase

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