ENCLOSURE A

AB79-COMM-10-1

BRUCE WATZMAN
Senior Vice President, Regulatory Affairs

EMERGENCY RULEMAKING PETITION

October 22, 2013

The Honorable Joseph Main
Assistant Secretary for Mine Safety & Health
U.S. Department of Labor
1100 Wilson Boulevard
Arlington, VA

Dear Mr. Secretary:

As you will see below, the National Mining Association (NMA) is filing with you this emergency rulemaking petition. It requires your immediate attention to ensure that the safety of the Nation's underground coal miners will not be compromised due to the newly recognized potential hazards associated with the currently required fleet of refuge chambers in underground coal mines.[1] We ask that you respond to this request by Nov. 5, 2013.

More specifically, pursuant to the authority of section 101 of the Federal Mine Safety and Health Act of 1977 and section 553(e) of the Administrative Procedure Act, NMA hereby petitions the Mine Safety and Health Administration to amend the mandatory safety standard for underground coal mines contained in the Secretary's regulation at 30 C.F.R. § 75.1506(a)(2) and (3) to provide that mine operators will have until Dec. 31, 2018 to continue to use their existing fleet of refuge chambers.[2]

We seek your adoption of this new deadline because resolution of the heat, humidity, and (especially) the purging hazards identified by the NIOSH research we discuss in more detail below are very likely to remain problems for many months (if not years). Whether retrofitting the existing fleet of currently deployed refuge alternatives will be

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[1] These hazards began to be known to MSHA as long ago as May 2010. However, MSHA apparently took no action. Infra at 7

[2] As you know, this Dec. 31, 2018 date is currently provided in 30 C.F.R. § 75.1506(a)(3) permitting all prefabricated refuge alternatives in service prior to March 2, 2009, and approved by states and accepted by MSHA in approved Emergency Response Plans, to remain in service until Dec. 31, 2018, or until replaced, whichever comes first.

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necessary, or whether a new generation of refuge alternatives will be required is simply unknown at this time. NMA believes, however, that the heat, humidity, and purging hazards discussed below will present enormously significant problems at least through the end of 2018. To be very clear, Mr. Secretary, NMA's concerns are not intended to disrupt efforts to provide miners with last resort life-saving technology. Rather, our concerns are driven by the aforementioned NIOSH research which we commit to immediately analyze, along with MSHA, NIOSH, refuge alternative manufacturers, representatives of miners, and all other stakeholders as soon as it is publicly available.

NMA's objective in this entire effort is (as is the stated objective of the current rules) to provide coal miners with "refuge alternatives that are practical and will increase the chance for survival for persons trapped in underground coal mines, when integrated into the mine's comprehensive escape and refuge plans."[3]

Of course, during this time, the fleet of refuge alternatives currently deployed and approved in the emergency response plan of every underground coal mine in the United States will remain available to miners. Should it be possible to solve the problems identified in the NIOSH research prior to Dec. 31, 2018, and correct them in the field, the NMA would support establishment of a reasonable deadline prior to Dec. 31, 2018.

The details of the basis for making this urgent emergency request follow.

First (and identical to the extension request we filed in response to the agency's Request for Information regarding refuge chambers), there is an urgent need for all stakeholders to have the opportunity to obtain and review new, but as yet unpublished, studies conducted by the National Institute for Occupational Safety and Health (NIOSH) regarding the ability of currently deployed and retrofitted prefabricated self-contained refuge chambers to: (1) purge potentially deadly levels of carbon monoxide (CO) that may enter the main chamber; and (2) maintain humidity and ambient temperatures at levels that will permit miners to survive, in place, for no less than 96 hours. NMA and other parties had anticipated NIOSH would have released peer-reviewed, pre-publication copies of these documents by now. In particular, it was our understanding that the pre-publication, but peer-reviewed purging study was to have been made available on or around Oct. 9. However, perhaps because of the just-ended government shutdown, we have not been able to obtain either of these studies as yet.

Furthermore, as noted above, while we have yet to receive the pre-publication versions of NIOSH's studies, a PowerPoint presentation we have seen summarizing the purging, heat, and humidity hazards identified in these studies (and we understand you have seen the same presentation) categorically calls into question the ability of both the

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[3] *See* Proposed Rules for Refuge Alternatives for Underground Coal Mines, 73 Fed. Reg. 34,140 (Mon., June 16, 2008) at 34,141. *See* also a similar statement in the final refuge alternative rules, published in the Federal Register for Dec. 31, 2008. 73 Fed. Reg. 80,656, at 80,657.

existing cadre of units, as well as those being retrofitted in accordance with § 75.1506, to provide life-saving capabilities in the event of an emergency.

You should know too that an NMA member company, using the Freedom of Information Act (FOIA), has since May 29, 2013, been attempting to seek information available from NIOSH about its ongoing research on refuge alternative hazards. Responses to these FOIA inquiries have been slow, sporadic, and incomplete, due to the fact that it is the FOIA Office of NIOSH's parent agency, the Centers for Disease Control (CDC), which controls responses to FOIA inquiries. Nevertheless, significant information about the heat and humidity hazards has been obtained. We discuss key portions of that information below. However, information about the purging hazard has not yet been produced by the CDC.

NMA hastens to add, Mr. Secretary, that these problems exist despite refuge alternative manufacturers working hard (in cooperation with your Approval and Certification Center (A&CC)) to comply with the requirements for Part 7 approval and mine operators having deployed units in accordance with § 75.1506.

Second, NMA remains very concerned that Part 7 approval by MSHA of refuge alternative breathable air, air monitoring, and harmful gas removal components of refuge alternatives will not be completed by the end of this year. This concern has been exacerbated by the inability of the A&CC to carry on its work during the government shut-down. In addition, if approvals are granted, mine operators (working with refuge alternative manufacturers) will not be able to retrofit their fleets of deployed refuge alternatives to Part 7 specifications by the end of the year. Indeed, in the case of some operators who have constructed units consisting of 15 psi stoppings in a secure space and in an isolated atmosphere, those operators are being required by MSHA to seek Part 7 approval (as applicants) of the breathable air, air monitoring, and harmful gas removal components of these refuge alternatives. We add that those 15 psi refuge alternatives are approved by MSHA in the emergency response plans of these mines.

On this important point, NMA must remind you that, in the preamble to the final rules for refuge alternatives, published on Dec. 31, 2008,[4] MSHA anticipated that Part 7 approvals would be completed by Dec. 31, 2009.[5] As it turns out, in reality, it has taken five years to approach the accomplishment of what MSHA predicted would take only one year. And, as we speak, a number of breathable air, air monitoring, and harmful gas removal components of refuge alternatives have yet to be approved under Part 7.

Even more importantly, it seems clear to us that the NIOSH research on heat, humidity, and (especially) purging at issue here, is validated properly, will necessitate significant (but as yet unknown) revisions to the current Part 7 requirements.

[4] 73 Fed. Reg. 80,656.
[5] *Id.* 80,682.

Specific Information in Support of NMA Emergency Petition

In support of this emergency petition we offer the following specific information.

On Dec. 19, 2007, Dr. Jeffrey L. Kohler, Ph.D., (Associate Director of NIOSH for Mining and Construction and head of NIOSH's Office of Mine Safety and Health) delivered to then Governor Joe Manchin of West Virginia and Ronald L. Wooten, Director of West Virginia's Office of Miners' Health and Safety a letter summarizing NIOSH's research and planned report to Congress.[6] In his letter (copy attached), Dr. Kohler outlined four areas of refuge alternatives that were of significant concern, based on NIOSH's work:

- Oxygen: Two of the four refuge alternatives had oxygen flow rates less than minimum value.
- Carbon dioxide: Three of four refuge alternatives were unable to provide adequate scrubbing of carbon dioxide.
- Apparent temperature: Two of the four refuge alternatives developed an apparent temperature greater than the specified maximum value.
- Purging: NIOSH stated that its work indicated that the "purging" capability of the refuge alternatives (i.e., the capability of the chamber to clear contaminated air from within the chamber each time the chamber door is opened to the outside) could be "problematic", and
- Operating instructions for refuge alternatives were difficult to understand and in one case erroneous.

Nevertheless, Dr. Kohler expressed confidence that many of the shortcomings observed by NIOSH could be addressed quickly. Manufacturers did address the vast majority of these and other concems, and today's refuge alternatives are greatly improved over the designs first approved in West Virginia.

In December 2009, NIOSH provided its only known public update to its January 2008 report to Congress. See, "Update on refuge alternatives: research, recommendations and underground deployment," ER Bauer and JL Kohler, *Mining Engineering*, Dec. 2009 (copy attached). In the update, NIOSH continued to express optimism about refuge

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[6] Section 13 of the Mine Improvement and New Emergency Response Act of 2006 (MINER ACT) (Pub. L. No. 109-236), enacted on June 15, 2006, required NIOSH to conduct research, including field tests, concerning the utility, practicality, survivability, and cost of various refuge alternatives in an underground coal mine environment. NIOSH was required to report on this research to the Congress and to the Secretary of Labor, no later than 18 months from the date of enactment. The NIOSH report was published in January 2008. That, in turn, triggered an obligation on the part of the Secretary of Labor to respond to the NIOSH Report in 180 days, including, if he chose to do so, proposing regulatory changes. The Secretary (through MSHA) proposed regulations for refuge alternatives in underground coal mines in the Federal Register for June 16, 2008 (73 Fed. Reg. 34,140). The preamble to the proposal stated that it included MSHA's response to the NIOSH report (*id.*), and that the agency had "determined that refuge alternatives are practical and will increase the chance for survival for persons trapped in underground coal mines, when integrated into the mine's comprehensive escape and rescue plans." *Id.* at 34,141. These regulations were finalized on Dec. 31, 2008 (73 Fed. Reg. 80,656).

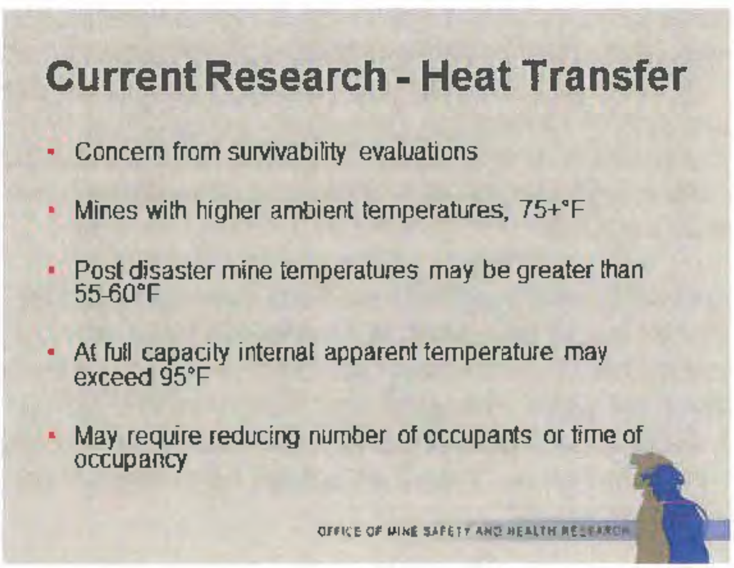
alternatives and declared, "Finally, all research has led to the conclusion that refuge alternatives have the potential for saving the lives of mine workers if they are part of a comprehensive escape and rescue plan and if appropriate training is provided. *Id.* at 57. This conclusion was consistent with that of MSHA in its proposal[7]; and in its final refuge alternative rules, the agency reiterated that it had "determined that refuge alternatives are practical and, when integrated into the mine's comprehensive escape and rescue plans, will increase the chance for survival for persons trapped in underground coal mines."[8]

Heat and Humidity Hazards

In the first hint that all was not as both agencies had earlier stated, NIOSH then warned, in the *Mining Engineering* update "Recently, a problem has surfaced concerning the apparent temperature in refuge chambers employed in mines where the ambient temperature is greater than 13-16°C (55-60°F). This could force a reduced occupancy requirement in some cases due to expected apparent temperatures above 35°C (95°F). *These might need further investigation*." *Id.* at 56, emphasis added.

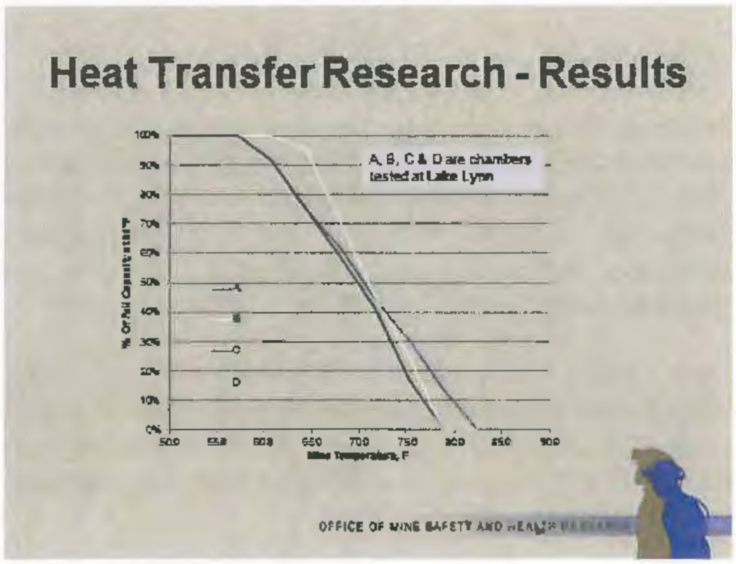
The investigation was carried out pursuant to NIOSH Contract No. 254-2010-M-34264 in 2010 by NIOSH contractor O'Donnell Consulting Engineers, Inc. (OCEI). While the OCEI work was being performed, Dr. Eric Bauer of NIOSH provided an update and overview of NIOSH refuge alternatives research at a town hall meeting sponsored by Pennsylvania State University on May 27, 2010.

Dr. Bauer provided the following summary of NIOSH's 2010 research:



7 73 Fed. Reg. 34,141.
8 73 Fed. Reg. 80,657.

Although the OCEI report would not be finalized until December 2010, NIOSH's concerns—first raised in the aforementioned Dec. 2009 *Mining Engineering* update—continued to be supported. In fact, it appears that based, at least in part, on the significance of these concerns that NIOSH updated its initial testing of refuge alternatives. Thus, during his May 27, 2010 presentation, Dr. Bauer provided attendees with a chart that showed the performance of four refuge alternatives that were tested by NIOSH at the Lake Lynn Experimental Mine.



This chart clearly showed that the four refuge alternatives tested by NIOSH were incapable of providing a safe environment for miners for the required 96-hour occupancy term when mine temperatures exceeded @ 62 degrees Fahrenheit. As you know, when the mine temperature increases, the capacity of refuge alternatives falls. This derating begins around 62 degrees Fahrenheit. In fact, three of the refuge alternatives tested were incapable of safely supporting miners at temperatures over 78 degrees and only one refuge alternative was capable of supporting miners at temperatures over 80 degrees.

Mr. Secretary, you should know that the Penn State event at which Dr. Bauer presented his work was supported in part by an MSHA Brookwood-Sago grant. Furthermore, prior to Dr. Bauer's presentation, Dr. Jeff Kravitz of MSHA provided a presentation on "Latest from MSHA on Mine Emergency Preparedness, Response and Refuge Alternatives." Later that day, Mr. Mike Getto, Team Leader for the Applied Engineering Division at MSHA provided a presentation on "Latest on Refuge Alternatives from the MSHA Certification and Approval Center."

It is clear to NMA, therefore, that the problems with refuge alternatives began to be known by MSHA as long ago as May of 2010, if not before. NMA is deeply disappointed that MSHA did not act proactively by investigating the potential ramifications of these early concerns and recognize the need for the Part 7 approval requirements to be modified based on the very serious problems reflected in Dr. Bauer's update.

OCEI issued its final report to NIOSH on Dec. 3, 2010 (copy attached). The report listed six different tasks that were performed under the NIOSH contract:

> **Task 1** - Provide a brief description of the thermodynamic heat transfer processes, i.e. radiation, convection and conduction, accompanying the occupation of a refuge chamber during a mine emergency;
>
> **Task 2** - Develop heat transfer equations and an appropriate heat transfer modeling program;
>
> **Task** 3 - Determine the baseline predicted maximum apparent temperature (heat + humidity) inside one rigid steel refuge chamber for an ambient mine temperature of 55°F and expected heat load and humidity at full occupancy
>
> **Task 4** - Provide the correlation between internal apparent temperature and a range of external mine temperatures (55 to 95°F, or until no heat transfer occurs) for one rigid steel refuge chamber at full occupancy;
>
> **Task 5** - Provide an estimate for occupancy de-rating based on the expected internal apparent temperature remaining at or below 95°F for various mine temperatures using the results of Task **4**, for one rigid steel refuge chamber; and
>
> **Task 6** - Provide an estimate of the maximum time of acceptable occupancy, at the manufacturer's recommended full capacity, and the estimated internal apparent temperature remaining at or below 95°F, resulting from a range of external ambient mine temperatures (55 to 95°F, or until no heat transfer occurs) for one rigid steel refuge chamber."

The results of these tasks contained in the OCEI report presented to NIOSH reinforced the information relayed by Dr. Bauer earlier in 2010. Among their more alarming conclusions, OCEI stated that (emphasis added):

- Task 6 requested a time of acceptable occupancy, at full capacity and internal apparent temperatures at or below 95°F, for various external mine temperatures. Figures 19 through 27 illustrate these relationships. Figure 19 illustrates that ***at full capacity, 60°F external mine temperature, and regardless of the RH [relative humidity], the apparent temperature***

reaches 95°F in approximately 9 hours, reaching a maximum of 102.5°F in approximately 40 hours after occupation. At higher external mine temperatures of 75°F and 90°F, as shown in Figures 20 and 21, time of acceptable occupancy is reduced dramatically. Similar results for 10 and 8 miners are presented in Figures 22 and 27.

- Under the conditions considered in this report (see Figure 2), ***it only takes a few hours for a single person to increase the level of humidity to full saturation***. Therefore, the humidity level must be kept under control for successful use of chambers.
- ***Presently refuge chambers are not designed to withstand the potential excessive heat created by a fire***. As discussed in this report, increases in the mine environment temperature could reduce or even reverse the heat flow from the chamber. This issue should be addressed on a priority basis in future work.

Based on Dr. Bauer's May 2010 presentation, NIOSH Contract No. 254-2010-M-34264, and the resulting OCEI report, it appears to NMA that there have been concerns about the performance of refuge alternatives under post-accident mine conditions for at least three years, and that these concerns have not been shared with stakeholders and appropriately addressed as part of the Part 7 approval process.

The current Part 7 approval application process requires manufacturers to specify in their application the maximum mine temperature for full occupancy at which the component may be used. Upon approval, the various components are required to "be conspicuously labeled to show your company's name, model number, the maximum mine temperature for full occupancy, and the assigned MSHA [component] Approval number."

In addition, mine operators are required to submit in their MSHA approved Emergency Response Plans the estimated maximum mine temperature at the locations where refuge alternatives are deployed. Together, the component temperature ratings and mine temperature information are intended to assure that miners are afforded safe conditions for 96 hours in a refuge alternative deployed as a last resort in an emergency situation.

After NIOSH received the OECI report in Dec. 2010, additional research was performed under contract for NIOSH in 2011 and 2012 that further demonstrated the significance of mine temperature. In the Executive Summary of "Underground Mine Shelter Thermal Analysis: Final Report," Klein, M. and Rynes, P., ThermoAnalytics Incorporated, Aug. 17, 2012, (the "Thermal Analysis Report", copy attached) the authors presented the following conclusions:

- The analysis indicates that certain thermal conditions, known to occur underground, could cause extreme physiological stress to miners over a four-day period within a refuge chamber.

- The mine ribs, roof, and floor in close proximity to the occupied shelter do not behave as an infinite heat sink. Consequently, the type of material found in the seam, and the seam size, affect the thermal environment that miners experience.
- Air flowing through the mine at the location of the occupied shelter can significantly affect its temperature, either positively or negatively, depending on the temperature of the air.
- Increasing the thermal mass of the rigid shelter tends to keep the interior temperatures lower by absorbing more heat generated within the shelter.

Id. at Page 3 of 39.

This work demonstrates that the interaction between refuge alternatives and the mine environment is more complex than has been previously understood and accounted for in the Part 7 approval process. NMA is not at all confident that refuge alternative components currently approved under Part 7 have demonstrated the required 96 hours of safety required for such approval. This is not because of a failure of the particular components, but because the performance of the approved products has not taken into consideration that the particular characteristics of the mine environment that can materially affect the maximum number of miners who can use the refuge alternative during the 96 hour period. Refuge alternative manufacturers have not had the benefit of this work during the Part 7 approval application process. The interaction of these factors needs to be addressed in the Part 7 approval process, to assure that both miners and operators can have confidence in their deployment in underground coal mines.

The importance of appropriately considering these factors can be seen in the Upper Big Branch (UBB) disaster. Because of changes in mine temperature after the explosion at UBB the refuge alternatives, had they been deployed at the mine, may not have provided a safe environment for miners. The refuge alternatives deployed at UBB appear to have been similar to the 26-miner unit evaluated in the Thermal Analysis Report ("Tent – 26 people.") UBB's maximum mine temperature was listed in its ERP as "60 to 75 degrees F." The examination records of UBB's refuge alternatives reflect that mine temperatures at the location of the refuge alternatives was between 60-65°F.

However, one spotter recovered from the longwall face area at UBB retained its data-logging ability after the explosion. The spotter's data reflected that the explosion heated the mine air to around 91°F and drifted down to 79°F approximately thirteen hours later. It is reasonable to believe that as the explosion travelled through UBB a similar increase in ambient mine temperature occurred. The unfortunate point that must be stated is that even if the UBB miners closest to the longwall face had managed to retreat to the closest refuge alternative the unit may not have provided the life-saving protections believed before rescue teams were able to reach them.

The State of West Virginia, along MSHA and NIOSH, worked with operators and manufacturers in an effort to provide miners such as those at UBB a safe refuge when escape was impossible because of a disaster. No one intended to provide any miner with a false or misplaced sense of security. Nor was it anyone's intent to suggest that compliance with the law carried anything less than the "chance for survival" intended by the combined efforts of all those involved in bringing refuge alternatives to market and deploying them in underground mines.[9]

In fact, NMA believes that the relationships that have developed between refuge alternative manufacturers, operators and MSHA—by working closely together during the Part 7 approval process—can serve to improve miner safety in addressing these issues. Many refuge alternative manufacturers have already developed performance based ratings based on ambient mine temperature. Operators and MSHA have used this information to establish maximum occupancy ratings for individual mines, and this information is routinely supplied (and subsequently approved) in Emergency Response Plans. Moreover, the Thermal Analysis Report does not appear to suggest that the current Part 7 approval process could lead to dangerous conclusions in mines where the ambient mine temperature is 70 degrees or less.

Experience, however, indicates that it is vital to have the performance information for refuge alternatives at temperatures above a mine's normal maximum temperature. The mine environment at UBB changed in the hours immediately following the explosion, to such an extent that the survivability of the deployed refuge alternatives may have been affected. It is imperative that miners be able to determine the safest length of time offered by a refuge alternative so that they do not choose to seek refuge under conditions that are dangerous. It is equally imperative that rescuers understand exactly how post-accident mine conditions affect the chances for mine rescue. Simply stated, when time is of the essence, it is most important to know how much time you have.

<u>Refuge Alternatives' Problems with Purging are Potentially of Even Greater Concern</u>

As stated earlier, NIOSH first raised concerns regarding the ability of refuge alternatives to purge carbon monoxide in Dr. Kohler's Dec. 2007 letter to Governor Manchin and Mr. Wooten:

> NIOSH did not develop and execute a quantitative evaluation of chamber purging or positive-pressurizing ability, but our work-to-date indicates that this could be problematic for all four chambers, and that an alternative may be required.

In fact, the extent of NIOSH's concerns was relegated to footnote 10 in its report, as follows:

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[9] *See* 73 Fed. Reg. 80,657: "MSHA reviewed NIOSH's report and determined that refuge alternatives are practical and, when integrated into the mine's comprehensive escape and rescue plan will increase the *chance for survival* for persons trapped in underground coal mines." (Emphasis added.)

> It is unclear whether all commercial chambers can purge contaminated air from the chamber; this will require further investigation.

Based on NIOSH's aforementioned briefings, it is clear that further investigation has only clarified the nature and gravity of the agency's early concerns.

On July 10, 2012, Dr. Eric Bauer emailed the authors of the Thermal Analysis Report and invited them to submit an abstract reflecting their progress to a session he was co-chairing at the February 2013 Society of Mining Engineers annual meeting in Denver, Colorado. It appears that Dr. Bauer may have sent a similar invitation to other researchers performing refuge alternative research under contract for NIOSH. One of the abstracts presented at the session co-chaired by Dr. Bauer covered three dimensional modeling of refuge alternative purging.

It appears that this and perhaps other research has demonstrated that the current guidelines for refuge alternatives fail to provide for sufficient purging capacity to prevent contaminated air from contaminating the chamber. It further appears that the ability of a refuge alternative to purge contaminated air may be a significant limiting factor in determining their capacity.

In the preamble to the Final Rule on Refuge Alternatives, MSHA stated:

> MSHA has performed limited carbon monoxide purge testing that indicates a 50 percent carbon monoxide concentration reduction with each purge. In PIB P07–03, under Safe Haven Assumptions providing breathable air, MSHA addressed carbon monoxide (CO) purging. Purging "efficiency" was estimated to require compressed air cylinders providing at least three times the amount of safe haven volume. Miners are to be inside the volume being purged wearing an SCSR until purging is accomplished. The Agency anticipated using compressed air cylinders as necessary to reduce Safe Haven concentration to less than 25 parts per million (ppm) for safe havens with a captive volume (not using positive pressure forced air from either a compressed air line or borehole from the surface).[10]

In addition, the preamble stated:

> MSHA reviewed data from previous accidents and found that a carbon monoxide concentration of 999 ppm may exist following an explosion or fire. It is necessary to evaluate the effects of

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[10] 73 Fed. Reg. 80,666.

the higher concentrations on the instruments because the higher limits may exist prior to purging the airlock.[11])

NIOSH's research indicates that MSHA's adoption of a 400 ppm carbon monoxide reference standard for determining the effectiveness of harmful gas removal components (*see*, 30 C.F.R. § 7.508 (c)(2)) may result in insufficient capacity to purge carbon monoxide concentrations of 999 ppm or more. In effect, while MSHA acknowledged that carbon monoxide concentrations of 999 ppm may exist following an explosion or fire, the existing regulations and Part 7 approval requirements provide miners no information regarding the level of CO at the refuge alternative and whether the purging capacity of the refuge alternative will allow them safe refuge, or whether they should head to the next SCSR cache.

NMA recognizes that there are going to be practical limits to the amount of carbon monoxide or other harmful gases that can be neutralized or eliminated by purging, while at the same time maintaining the portability of refuge alternatives. The problem is that the current Part 7 approval process fails to acknowledge that carbon monoxide concentrations in excess of 400 ppm may exist and that miners faced with such a situation are not currently informed of how such high concentrations affect the capacity of the refuge alternative—nor are they trained on what concentrations of carbon monoxide render the refuge alternative uninhabitable.

While the ability of current refuge alternatives to purge such high concentrations of carbon monoxide may be in NIOSH's unreleased reports, NMA does not believe that the question has been adequately addressed by MSHA during the Part 7 approval process. It is absolutely essential for miners to know the purging limits of refuge alternatives, and they must be trained on how to determine if the mine environment is safe for the deployment of a refuge alternative. Without such knowledge and training, miners may perish rather than make further efforts to escape or reach SCSR caches.

NMA regrets that it was unable to receive a copy of NIOSH's data on this matter. NMA believes that the purging issue is of potentially greater concern than the heat and humidity problems discussed at length, earlier. The purging issue could affect every refuge alternative, and every miner. Even if MSHA disagrees about the gravity of the heat and humidity issues raised by NIOSH research, NMA believes that the purging issue alone is of sufficient importance to justify providing the additional time we are requesting.

<u>Miners Need Appropriate Training on Refuge Alternatives</u>.

Mr. Secretary as you are know very well, mine emergencies present miners with life-or-death decisions. NMA is concerned that, cumulatively, the problems raised by

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[11] *Id.* 80,674.

NIOSH's research, may leave miners with an false sense of security. Contrary to the view held by some, based on our understanding of NIOSH's research, we cannot simply teach and train the nation's miners on how to deploy and operate a refuge alternative, and tell them that they will be able to survive for four days.

Should you reject our emergency rulemaking petition and leave your current rule intact, MSHA's message to the nations miners will be that refuge alternatives and components that have been approved under Part 7 will provide a safe haven if they are operated according to manufacturer specifications. In our view, NIOSH's work calls this message into question. While the underlying reasons for granting our petition are based in the performance of refuge alternatives, it is even more important that we provide miners with an honest appraisal of their safety so that they can make educated decisions if they are forced to choose between seeking refuge in a refuge alternative, or making another attempt at escape.

Mr. Secretary, for all the reasons stated above, we believe it is in the interest of all stakeholders for MSHA, on an urgent, emergency basis, to extend the deadline so as to permit the consideration and analysis of this crucially important NIOSH information in advance of operators having to remove from service the current cadre of prefabricated units, as well as to achieve an orderly transition to Part 7 compliance.

NMA is prepared to work immediately with you and your colleagues, as well as with NIOSH and all other stakeholders to:

- analyze the new NIOSH research and validate it; and

- work cooperatively with all parties to develop any necessary revisions to 30 C.F.R. Parts 7 and 75.

We look forward to your rapid and favorable consideration of this urgent request. In light of its emergency nature (and as noted at the outset of this letter), please let us have your answer to this petition no later than Nov. 5.

Sincerely,

Bruce Watzman
Attachments

DEPARTMENT OF HEALTH & HUMAN SERVICES

Public Health Service

Centers for Disease Control
and Prevention (CDC)
National Institute for Occupational
Safety and Health (NIOSH)
Office of Mine Safety & Health
P.O. Box 18070
Pittsburgh, PA 15236-0070

December 19, 2007

Mr. Ronald Wooten
Director, Office of Miners' Health, Safety & Training
West Virginia Department of Commerce
1615 Washington Street East
Charleston, West Virginia 25311-2126

Dear Mr. Wooten:

Thank you for meeting with me on December 19, 2007 to discuss information that the National Institute for Occupational Safety and Health (NIOSH) in the Centers for Disease Control and Prevention of the United States Department of Health and Human Services has recently generated that may have an immediate impact on the health and safety of mine workers within the State of West Virginia.

NIOSH conducts a program of mining safety and health research as a part of its portfolio of 32 occupational safety and health programs. Section 13(a) of the Mine Improvement and New Emergency Response Act of 2006 ("MINER Act") requires that NIOSH "provide for the conduct of research, including field tests, concerning the utility, practicality, survivability and cost of various refuge alternatives in an underground coal mine environment, including commercially-available portable refuge chambers."

Section 13(b) mandates that "[N]ot later than 18 months after the date of enactment of this Act (June 15, 2006), the National Institute for Occupational Safety and Health shall prepare and submit to the Secretary of Labor, the Secretary of Health and Human Services, the Committee on Health, Education, Labor and Pensions of the Senate, and the Committee on Education and the Workforce of the House of Representatives a report concerning the results of the research conducted under subsection (a) including any field tests."

Shortly after passage of the MINER Act, NIOSH began to discuss the elements of an appropriate refuge chamber testing protocol with many different stakeholders including representatives from the State of West Virginia. As a result of those discussions, NIOSH agreed to include in the peer-reviewed testing protocol certain parameters designed to assess the ability of refuge chambers to meet certain key regulatory provisions recently promulgated by the State of West Virginia.

NIOSH understood before commencing testing at its Lake Lynn Experimental Mine that the State of West Virginia refuge chamber approvals were based on data and calculations provided by the manufacturers, as certified by a registered professional engineer. Furthermore, NIOSH

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understood from a preliminary review of refuge chamber capabilities, and from a meeting between NIOSH scientists and members of the State of West Virginia Task Force, that several areas of chamber performance were of significant concern. These areas were: (1) level of oxygen when miners occupied the chamber; (2) level of carbon dioxide inside the chamber when miners occupied the chamber; (3) apparent temperature inside the chamber when miners occupied the chamber; (4) the "purging" capability of the chamber, i.e., capability of the chamber to clear contaminated air from within the chamber each time the chamber door is opened to the outside; and (5) other specific areas such as set-up time and operating instructions.

NIOSH is now preparing a report entitled "*Report of Research on Refuge Alternatives*" to meet the requirements of Section 13(a) and (b) of the MINER Act. The NIOSH Report will be assembled in December of 2007, submitted to the parties named in Section 13(b) of the MINER Act, and will be disseminated in early January.

However, NIOSH believes that findings in the four areas of chamber performance that are of significant concern to the State of West Virginia and need to be communicated to the State prior to the formal completion of the Report. NIOSH understands refuge chambers mandated by West Virginia Regulation Code, Title 56, Series 4, Section 8 will shortly be moved underground for operational use by miners in the case of an emergency. Since findings from our field testing raise issues about the performance of such refuge chambers, NIOSH believes it is imperative to inform you of our findings as soon as possible before deployment of refuge chambers.

What follows is a brief summary of our findings to date.

NIOSH conducted refuge chamber testing by NIOSH scientists at its Lake Lynn Laboratory. Various phases of the testing of each chamber were observed by representatives from the West Virginia Task Force and the Mine Safety and Health Administration's Approval and Certification Center. Results of testing four refuge chambers from different manufacturers were as follows:

(1) Oxygen (O_2)

Two of the four chambers had an O_2 flow rate less than the specified minimum value.

(2) Carbon dioxide (CO_2)

Three of the four chambers had a CO_2 level in excess of the specified maximum value; and practical difficulties with the process of scrubbing were observed, to a greater or lesser extent, in all four chambers.

(3) Apparent Temperature

Two of the four chambers developed an apparent temperature greater than the specified maximum value.

(4) Purging

NIOSH did not develop and execute a quantitative evaluation of chamber purging or positive-pressurizing ability, but our work-to-date indicates that this could be problematic for all four chambers, and that an alternative may be required.

(5) Operating Instructions

Instructions provided with the chambers were sometimes difficult to understand, and in one case, the instructions for CO_2 scrubbing were erroneous. None of the chambers contained "quick start" instructions and most lacked comprehensive instructions to deal with malfunctions or problems in critical systems.

NIOSH believes that many of the experimentally observed shortcomings can be addressed quickly through improved engineering design, minor technical modifications, and/or the use of improved instructional materials. Indeed, based on our preliminary feedback to the manufacturers, changes may have already been implemented, but we do not have first-hand knowledge of these changes. However, NIOSH would be pleased to evaluate the efficacy of any changes made to improve chamber performance.

As you are already aware, NIOSH is not an approval and certification agency. Findings from NIOSH's refuge chamber testing should be correlated with other sources of data on refuge chamber performance and with the experience of users. NIOSH does believe that laboratory testing of refuge chamber performance may be a valuable adjunct to any governmental refuge chamber approval and certification process.

Thank you for meeting with me on December 19, 2007 to discuss these important findings.

Sincerely,

Jeffery L. Kohler, Ph.D.
Director, Office of Mine Safety and Health

JLK/mc

cc: The Honorable Edward M. Kennedy
Chair, Committee on Health, Education, Labor, and Pensions
U.S. Senate

The Honorable George Miller
Chair, Committee on Education and Labor
U.S. House of Representatives

The Honorable Richard Stickler
Assistant Secretary for Mine Safety and Health
U.S. Department of Labor

John Howard, M.D.
Director, National Institute for Occupational Safety and Health

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TECHNICAL PAPERS

Update on refuge alternatives: research, recommendations and underground deployment

E.R. BAUER AND J.L. KOHLER

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Introduction

The U.S. coal mining industry experienced an increase in fatalities during 2006 when 37 miners perished in the nation's underground coal mines. Nineteen miners perished in three disasters: 12 miners perished in a methane explosion at the International Coal Group, Sago Mine, two more miners died in a fire at the Aracoma Coal Co., Alma No. 1 Mine, while another methane explosion resulted in the loss of five more miners at the Kentucky Darby, LLC, Darby No. 1 Mine. This reversed the downward trend of fatalities that had taken place during the previous 21 years (Fig. 1). The causes of all the underground coal mine fatalities in 2005, 2006 and 2007 are listed in Table 1. Table 1 illustrates that fewer fatalities occurred in 2005 and 2007 than 2006 with the goal of zero fatalities as desirable.

The Mine Improvement and New Emergency Response Act of 2006 (MINER Act), PL 109-236, was passed in response to this increase in fatalities resulting from the three mine disasters that occurred in 2006 (United States, 2006). Section 13 of the Act – Research Concerning Refuge Alternatives, specifies NIOSH's responsibilities with respect to refuge alternatives. Section 13, subsection (a) of the Act states that "The National Institute for Occupational Safety and Health (NIOSH) shall provide for the conduct of research, including field tests, concerning the utility, practicality, survivability and cost of various refuge alternatives in an underground coal mine environment, including commercially available portable refuge chambers." Subsection (b)(1) then states that "Not later than 18 months after the date of enactment of this Act, the National Institute for Occupational Safety and Health shall prepare and submit to the Secretary of Labor, the Secretary of Health and Human Services, the Committee on Health, Education, Labor, and Pensions of the Senate, and the Committee on Education and the Workforce of the House of Representatives a report concerning the results of the research conducted under subsection (a), including any field tests." This document summarizes NIOSH's refuge alternatives research that was included in the report to the U.S. Congress.

Abstract

In response to the mandates in the MINER Act of 2006, the National Institute for Occupational Safety and Health (NIOSH) conducted refuge alternatives research that included characterizing the utility, practicality and survivability of refuge chambers and outby safe havens. NIOSH also prepared and delivered a report to Congress in late December 2007 that summarized the findings of the research, included recommendations concerning the design and performance specifications for refuge alternatives, and focused on specific information that could inform the regulatory process on refuge alternatives. This paper highlights NIOSH's research and recommendations concerning refuge alternatives, survivability evaluations of refuge chambers and presents a brief review of the current deployment of refuge chambers in underground coal mines in the U.S. The research has lead to the conclusion that refuge alternatives have the potential for saving the lives of mine workers if they are part of a comprehensive escape and rescue plan and if appropriate training is provided.

The concept of utilizing refuge chambers dates back as far as 1912 when the U.S. Bureau of Mines advocated the building of refuge chambers to fight mine fires (Rice, 1912) in the main sections of mines (Paul et al., 1923). In the late 1930s and early 1940s, some small refuge chambers had been established in some coal mines in the central states and these chambers saved lives (Harrington and Fene, 1941). In addition, the Harwick Coal and Coke Co. built a number of large refuge chambers in the Harwick Mine. These chambers were 23-m- (75-ft-) long, 2.4-m- (8-ft-) high and 3.3-m- (11-ft-) wide, cut out of the coal and connected to the surface by two boreholes to provide air, communications, food and water (Harrington and Fene, 1941).

More recent research efforts were completed under contract for the U.S. Bureau of Mines starting around 1970 and extending into the mid-1980s. Five major contract efforts were completed between 1970 and 1983 that addressed mine rescue and survival, the design of explosion-proof bulkheads, post survival and rescue research needs, and guidelines for rescue chambers. As a result, one refuge chamber was constructed and is still located in NIOSH's Bruceton Safety Research Coal Mine (Fig. 2). In general, these contract efforts did not point to any one specific component that would ensure survival during a mine disaster but stressed that survival is a collaboration of subsystems. The subsystems that make up the overall survival strategy include escape, rescue, communications, breathable air and barricading (refuge).

NIOSH's recent research on refuge alternatives was limited to underground coal mine applications. Historically, the use of refuge alternatives has been more prevalent in underground metal/nonmetal mines. The underlying

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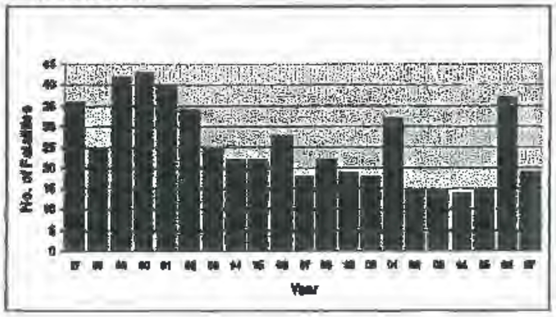
FIGURE 1

Underground coal mine fatalities 1987-2007 (Bauer Kohler, 2009.



differences between mining sectors are significant and practices in one sector cannot be generalized to the other. Even so, the findings from this research may be useful for metal/nonmetal application.

The research efforts summarized in this document involved a number of activities. First, a literature search was performed to identify the findings from any past research on refuge alternatives and topics related to mine refuge and mine disasters, escape and mine rescue. Visits were made to mines, nationally and internationally, and meetings were held with mining experts from labor, industry and government in the U.S., Australia and South Africa to collect information on refuge alternatives, specific refuge regulations and to discuss contemporary issues associated with refuge alternatives. Several contract efforts were completed that examined existing U.S. and international practices, regulations and refuge products. However, these efforts revealed very little information related to coal mining refuge applications, while identifying several knowledge and technology gap areas. In response, a major research contract was awarded to address the gap areas, including guidance for locating and positioning refuge alternatives and establishing specifications for chambers and in-place shelters[1].

Concurrently, NIOSH researchers examined nonmining applications where survival in confined spaces is critical – notably civil defense shelters, submarines and space capsules – in search of guidance for application to coal mining. Overall, NIOSH researchers studied a range of practical issues associated with refuge such as movement of chambers from place to place, collected cost data and performed cost analyses of refuge alternatives. NIOSH researchers also conducted survivability evaluations of refuge chamber performance at the Lake Lynn Experimental Mine.

Finally, separate research projects were initiated as gap areas were uncovered and several research efforts remain ongoing. These research areas include the development of communications technology specifically for use in refuge alternatives and the development of training modules for using refuge alternatives during escape and rescue. These projects are expected to continue through 2009 and will be reported on in future publications.

Table 1

Underground coal mine fatalities for 2005-2007 (MSHA 2008).

Cause of fatality	2005	2006	2007
Electrical	0	0	0
Exploding vessels under pressure	0	0	0
Explosives and breaking agents	0	0	0
Falling, rolling, sliding rock/material	0	0	1
Fall of face, rib, pillar or highwall	0	3	9
Fall of roof or back	9	7	3
Fire	0	2	0
Handling material	0	0	1
Powered haulage	5	6	2
Ignition/explosion of gas/dust	0	18	0
Machinery	0	1	2
Slip or fall of person	1	0	0
Stepping or kneeling on object	0	0	1
Mine Type Total	**15**	**37**	**19**

NIOSH refuge alternatives research

Utility. The utility, or usefulness, of refuge chambers has been debated in the U.S. at least since the passage of the Coal Mine Health and Safety Act of 1969, P.L. 91-173, which authorized the Secretary of Labor to prescribe in any coal mine that rescue chambers, properly sealed and ventilated, be erected at suitable locations in the mine to which persons may go in case of an emergency for protection from hazards. Despite this and the significant research conducted by the U.S. Bureau of Mines nearly 30 years ago, refuge chambers have not been embraced by industry, labor or government. The focus, understandably, has been on escape rather than refuge.

NIOSH investigated the utility of refuge alternatives to aid in the survival of miners following a mine disaster. Past mine disasters were reviewed to determine if the presence of refuge alternatives might have altered the outcome of these disasters. The results are mixed given the small number of disasters and the mine-specific circumstances under which they occurred. Thus, it is difficult to make a strong case for or against a specific refuge alternative, or even for or against the efficacy of coal miners taking refuge. Nevertheless, the recent mine disasters have refocused attention on the utility of refuge alternatives. And it has been argued that the availability of refuge alternatives may have been useful in these disasters.

An extensive study of the mining disasters in underground coal mines in the U.S. from 1970-2006 involving fires, explosions and inundations in which fatalities occurred revealed the potential affect of refuge alternatives on both survivors and fatalities (Ounanian, 2007a, 2007b). This included 17 major disasters in which five or more miners perished; 20 disasters in which one to four miners were killed; one disaster in which no miners were killed, the July 2002 inundation at Black Wolf Coal Co.'s Quecreek No. 1 Mine in which all nine miners trapped in a flooded mine were rescued as well as four other disas-

[1]The gap areas were identified at the end of the international survey effort, which was performed during July through October 2006. The technical part of the contract to address these areas was completed at the end of October. The actual contract award, conducted in compliance with the Federal Acquisition Rules, was made in March 2007. Work on this contract will continue through 2009. The contractor was able to provide key inputs for the preparation of the report to Congress.

ters involving fatalities that were not deemed applicable. In all, 38 disasters were investigated for inclusion in the analysis.

From the disaster analysis, a number of positive impacts were identified. The term "positive impact" described when the presence of a refuge alternative might have changed the final outcome of a disaster in a positive manner such as miners surviving instead of perishing. First, it was estimated that the presence of a refuge alternative (chamber or safe haven) might have positively impacted the outcomes in 12 of the 38 disasters studied. Second, of the 429 miners who were underground and impacted (forced to escape, injured, barricaded or perished) by the 38 disasters, 83 might have been positively impacted by the presence of a refuge alternative. Finally, if a refuge alternative had been present, 74 of the 252 fatalities might have been positively impacted, resulting in the potential survival of the miners.

The group of miners that might have been most impacted were those who perished during their escape attempts. The analysis indicated that 57 of the 67 miners who expired while escaping might have been positively impacted if an outby refuge station had been present, the escaping miners found it and they successfully activated the breathable air systems. A second group most likely to benefit were the miners who barricaded. While barricades were used in only two relevant incidents, these

FIGURE 2

Refuge chamber located in Bruceton Safety Research Mine.

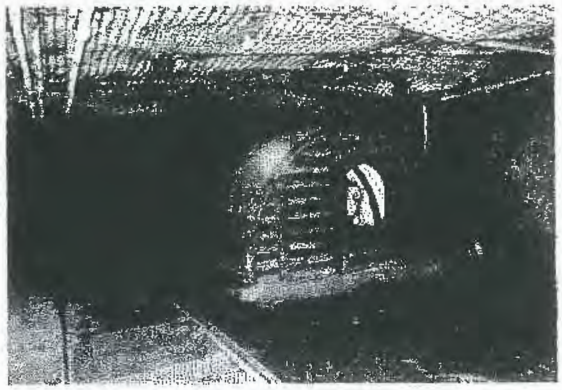


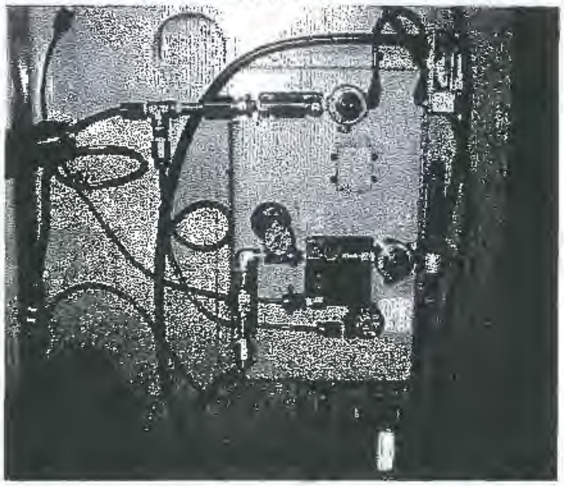
Table 2

Design and performance specifications for refuge alternatives (NIOSH 2007).

Parameter	Recommended value or practice
Minimum rated duration	48 hours.
Strength	15 psi overpressure for 0.2 seconds.
Anchor system	Not recommended at this time.
Fire resistance	148° C (300° F) for 3 seconds.
Deployment time	Minimize this time when establishing the location of the refuge alternative and consider as part of the travel time.
Min. concentration O_2	18.5%.
Max. concentration O_2	23%.
Max. concentration CO	25 ppm.
Gases to be monitored inside chamber	O_2, CO, CO_2
External gases to be monitored	O_2, CO.
Max. concentration CO_2	1.0%, not to exceed 2.5% for any 24-hour period.
Apparent temperature	35° C (95° F).
Entry and Exit	Provide a means of egress without contaminating the internal environment and/or a means to maintain a safe environment during and after ingress/egress.
Potable water per person	2 to 2.25 qt per 24 hour.
Durability	Structurally reinforced and of sufficient physical integrity to withstand routine handling.
Purge air volume	No specific recommendation (see entry and exit parameter).
Food, per person	2000 cal per 24 hour.
Human waste disposal system	Required.
First aid kit	Required.
Occupant-activated annunciation	Battery-powered strobe light or radio homing signal.
Communication with surface	Survivable post-disaster system.
Minimum distance to working face	305 m (1,000 ft).
Maximum distance from working face	Distance that a miner could reasonably travel in 30–60 minutes, under the expected travel conditions.
Security	Visual indication that a refuge alternative has been entered; inspection and maintenance actions required subsequent to discovery.
Repair materials	Materials and instructions supplied by manufacturer.
Testing and approval	Required.
Unrestricted floor space	> 1.4 m² (15 sq ft) per person.
Unrestricted volume	> 2.4 m³ (85 cu ft) per person.
Capacity	Sufficient to accommodate the maximum number of miners in the area to be served by the refuge alternative.

FIGURE 3

Example of oxygen supply system in a refuge chamber.



incidents resulted in at least 17 and possibly 19 fatalities. All of these miners might have been positively impacted (survived) by the presence of a refuge chamber on the working section.

Based on the disaster analysis and numerous other NIOSH research efforts associated with the utility of refuge alternatives, the significant opportunity today is to recognize that refuge alternatives can be useful to facilitate escape from the mine as well as to serve as a safe haven of last resort. The potential of refuge alternatives to save lives will only be realized if mine operators develop comprehensive escape and rescue plans that incorporate refuge alternatives. Such an approach would be far superior to one in which refuge chambers are simply placed into the mine to comply with a regulation. Thus, it does make sense to use refuge alternatives because it is likely that miners' lives could be saved.

Practicality. The practicality of refuge alternatives encompasses whether or not they can be implemented, moved and maintained in underground coal mines. Refuge chambers are commercially available and have been successfully installed in underground coal mines abroad and, to a limited extent, in the U.S. Although there are no documented cases of successful use of a refuge chamber in an underground coal mine in an emergency, there is no evidence to suggest that refuge chambers or alternatives are impractical, but their use will be challenging. The installation of refuge alternatives and the moving and maintenance of such chambers will require an ongoing effort on the part of mine operators. There was a concern that the moving of refuge alternatives to advance or retreat with mining could be difficult and possibly impractical. After a thorough investigation of this issue including numerous site visits, it was found that the moving of refuge alternatives can be done safely and feasibly (NIOSH, 2006a). Also, it is thought that it may be impractical to implement viable refuge alternatives in the few mines that operate in very low coal, e.g. less than 914 mm (36 in.). The finding of the NIOSH research is that refuge alternatives, to facilitate escape and to serve as a refuge of last resort, are practical for use in most underground coal mines.

Survivability. Survivability focuses on the ability of refuge alternatives to ensure that the workers who use the alternatives will survive for a specific duration. The most crucial specifications for the survivability of miners who seek refuge in a chamber or safe haven are: maintaining the structural integrity of the unit through an initial explosion; initiating and maintaining an atmosphere that will support life; and providing for basic human needs. These parameters need only address the support of life for a limited time under emergency conditions since refuge alternatives are not intended to serve as routine workplaces. Ultimately, the desired result is a survivable event and not necessarily the most comfortable experience.

The likelihood of a refuge alternative to survive an explosion is enhanced by the integrity of structural design, the positioning of the alternative out of the expected direct explosion force path, by minimizing the probability of being struck by flying debris, and by not locating the alternative near likely explosion/fire sources such as seals, belt drives, etc.

Providing and maintaining a survivable atmosphere has generally been solved by chamber manufacturers. Oxygen is supplied from breathable grade (99% pure with no harmful contaminants) oxygen bottles, flowing through manifolds and ball float meters (Fig. 3). Carbon dioxide scrubbing has been accomplished in a number of ways including passive lithium or soda lime curtains (Fig. 4), and air, or battery-powered fans pulling contaminated air through soda lime cartridges (Fig. 5). The control of heat and humidity was not an issue for the inflatable chambers since there is considerably more surface area for the heat to dissipate. Initially, this was a problem in the rigid steel chambers, but recent simulation testing and short duration human occupancy testing has indicated that the steel chambers can also be operated at apparent temperatures below 35° C (95° F), the WV standard for the combination of heat and humidity.

Basic human needs such as water, food and toilet facilities can and have been successfully addressed by all chamber manufacturers. All in all, there is no reason to believe that miners using a refuge alternative can not survive for the NIOSH recommended minimum duration of 48 hours.

Simulation testing

NIOSH, as part of its research and as required in the MINER Act, evaluated the performance of the West Virginia approved refuge chambers. NIOSH developed a protocol to simulate human occupancy based on a specific set of performance standards. The protocol was subsequently peer-reviewed and implemented.

The goals of the evaluations were limited to investigating the CO_2 scrubbing, oxygen flow rates and the heat index (i.e., apparent temperature during chamber operation). In addition, the overall deployment and operation of the chambers were observed and evaluated. Of critical importance was a chamber's ability to maintain a breathable atmosphere. This included maintaining O_2 above 19.5%, CO_2 below 0.5%, and a maximum 'apparent-temperature' of 35° C (95° F). The protocol defined the means of simulating human occupancy to facilitate the evaluation of the chambers as follows: the oxygen flow rate was measured and removed from the chamber

Table 3

Number of operating underground coal mines.

State	No. of Operating underground coal mines	Year	Source
Alabama	8	2007	http://dir.alabama.gov/mr/2007_ANNUAL.pdf
Arkansas	1	2006	http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html
Colorado	11	2007	http://mining.state.co.us/Reports/12-07CoalSummary.pdf
Illinois	15	2006	http://dnr.state.il.us/mines/public/asr2006.pdf
Indiana	8	2006	http://www.in.gov/dol/files/CoalMineStatistics91307.pdf
Kentucky	302	2006	http://www.omsl.ky.gov/NR/rdonlyres/6BAD4B78-7779-4BEE-873F-0960535D2685/0/2006ARbook.pdf
Maryland	3	2006	http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html
Montana	1	2006	http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html
New Mexico	1	2006	http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html
Ohio	11	2006	http://www.dnr.state.oh.us/Portals/10/pdf/min_ind_report/06minind.pdf
Oklahoma	1	2005	http://www.mines.state.ok.us/id20.htm
Pennsylvania	38	2006	http://www.dep.state.pa.us/dep/deputate/minres/bmr/annualreport/2006/table09_bituminous_operators_and_sites_summary.htm
Tennessee	10	2006	http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html
Utah	11	2006	http://168.179.220.114/idev/coalmines/coalsiteinfo.php
Virginia	76	2006	http://www.energy.vt.edu/vept/coal/coal_prod_eia.asp
West Virginia	330	2007	http://www.wvcoal.com/index.php?option=com_content&task=view&id=34&Itemid=41
Wyoming	1	2006	http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html
Total	828		

(a rate of 0.62 L/min (0.022 cuft/m) per occupant was desired); CO_2 was injected into the chamber based on the respiratory quotient of 0.8 or 0.51 L/min (0.018 cuft/m) per occupant; the heat from light bulbs was used to mimic the metabolic heat load of 117.24 W/hour (400 Btu/hr) per occupant; and humidified air was injected into the chamber at a rate of 1.5 L/day (0.4 gpd) per man to simulate moisture from human respiration and perspiration. The evaluations were conducted continuously over a 96-hour period unless developing problems necessitated shortening the evaluations. Four manufacturers provided chambers for testing, two inflatable and two rigid steel.

The testing revealed unanticipated shortcomings in some of the chambers. For instance, heat dissipation was more of a problem in the rigid steel than the inflatable chambers, and the heat stress index[2] in both steel chambers exceeded the levels established as acceptable by the state of West Virginia. It should be noted that the ambient mine air temperature for the tests was in the range of 13-16° C (55-60° F) with little if any airflow over the chambers. If the steel chambers were used in mines with ambient temperatures closer to 21° C (70° F), as is found in some deep mines, the problem would be exacerbated. Three of the four chambers were unable to maintain CO_2 concentrations below the level specified by West Virginia OMHST, while two of the four chambers were unable to deliver oxygen for the duration of the test. Finally, the time to activate[3] each chamber varied from a few minutes to more than 30 minutes in two cases. There is no consensus on what constitutes a reasonable activation time, but the time to activate a specific chamber should be considered when establishing the maximum distance that a chamber can be located from the face. These shortcomings are sufficiently serious in three of the chambers to require correction before deployment. In most cases, but not all, these shortcomings should be correctable, or have already been corrected, with minor technical changes, the addition of clear instructions, and/or improved design/engineering.

Testing also revealed deficiencies with the documentation provided for each chamber, and this information has been discussed with the manufacturers. As a result, NIOSH initiated research to define and develop improved documentation. Additional opportunities for improving the usability and performance of chambers were noted. Finally, the results of the simulated evaluations indicate the need for independent evaluations and testing beyond the chamber manufacturers. Computational modeling and other engineering and mathematical analyses proved to be inadequate.

Re-evaluations

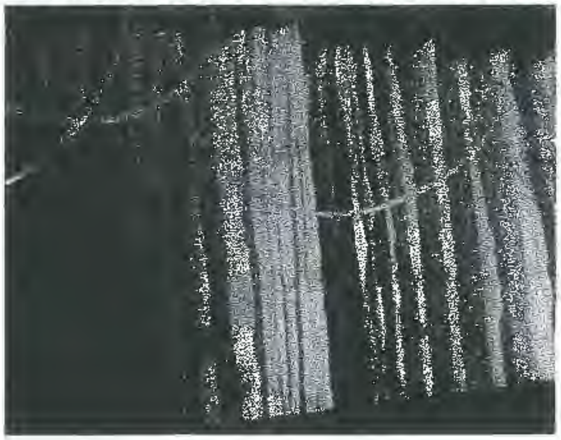
To address some of the deficiences found during the simulated occupancy evaluations, some additonal evaluations were conducted, modifications observed and chamber manufacturer test results analyzed. One manufacturer's redesigned curtain stands were viewed and found to be sufficiently strong to prevent tipping. Their oxygen flow meter problems were also addressed and a 96-hour test was observed that indicated the fluctuating flow was corrected. Another manufacturer's all-steel chamber was subjected to a repeat evaluation at Lake Lynn. This evaluation lasted 14 hours until a steady state condition was reached and demonstrated the chamber's ability to remain below 35° C (95° F) apparent tempera-

[2] West Virginia specified "apparent temperature" as a measure of heatstress and established an upper limit of 35° C (95° F), which is reasonable and is conservative.

[3] This is the elapsed time from arriving at the chamber until the environmental systems inside the chamber have begun to function. This time would include the setup and inflation time for an inflatable chamber in addition to the time required to start the oxygen flow and CO_2 scrubbing inside of the chamber.

FIGURE 4

Passive lithium curtains for scrubbing carbon dioxide.



ture. Finally, one manufacturer, without NIOSH participation, completed a short-term human subject evaluation. The results of the human occupation test were sent to and reviewed by NIOSH for verification that the scrubber containers were redesigned to prevent spillage and that the apparent temperature met the West Virginia standard.

Recommendations

NIOSH's Report to Congress on refuge alternatives contained many recommendations concerning the characteristics of refuge alternatives for use in underground coal mines (Table 2) (NIOSH 2007). A more complete explanation of the recommendations can be found in the original report at: http://www.cdc.gov/niosh/mining/mineract/pdfs/Report_on_Refuge_Alternatives_Research_12-07.pdf.

Chamber deployment in U.S. underground coal mines

Deployment possibilities. The number of underground coal mines in the U.S. in 2005 and 2006 was estimated to be between 600 and 670 (EIA 2006 and NIOSH 2006b).

FIGURE 5

Air powered soda lime carbon dioxide scrubber system.

MSHA data from August 2007 on mechanized mining units (MMU's) places the number of MMU's at 873 and the total underground mines at approximately 464. According to the individual states, the number of operating underground coal mines exceeds 800 as seen in Table 3. Despite this variation, if all underground coal mines in the U.S. were required to have a refuge chamber on each working face, it is estimated that from 450 to more than 1,000 chambers might be required.

Number and type of chambers ordered. Although the exact numbers and types of chambers ordered, sold and delivered is not readily identifiable because information from all chamber manufacturers was not obtained, some preliminary numbers are available.

First, according to Bruce Watzman, vice president for Safety and Health with the National Mining Association, in testimony before the Senate Subcommittee on Employment and Workplace Safety, the underground coal mining industry has spent $53 million for 752 total facilities to maintain trapped miners (Watzman, 2008). Also, from information provided by chamber manufacturers, as of August 2008, approximately 980 orders have been placed for rigid and inflatable refuge chambers, or bulkhead type systems. More than 90% of the chambers ordered were soft-side deployable (inflatable). It was also reported that more than 540 units have been delivered to underground coal mines in Alabama, Colorado, Illinois, Indiana, Kentucky, New Mexico, Ohio, Oklahoma, Pennsylvania, Utah, Virginia and West Virginia. The greatest number of units were delivered to West Virginia (approximately 36%).

Secondly, the capacity has been selected to cover the maximum number of expected users, based on between-shift and hot-seat change outs of personnel. The result is inflatable chambers of up to 36 person capacity being ordered. Finally, orders by the larger coal companies have been placed on a company-wide basis, resulting in chambers being placed not only in West Virginia mines but also in the company owned mines in other states as well.

Problems and concerns with underground deployment. NIOSH has heard minimal negative feedback about the deployment of the chambers, which is interpreted as little if any problems have been encountered. Issues have been mentioned concerning training, ie, availability of training models, in-mine or outside training, etc. In addition, at least two mines found that the rubber door seals had deteriorated after the chambers sat outside for the winter. These were replaced prior to deploying the chambers underground. It does raise questions as to the environmetal conditions that could lead to sealing problems. Recently, a problem has surfaced concerning the apparent temperature in refuge chambers employed in mines where the ambient temperature is greater than 13-16° C (55-60° F). This could force a reduced occupancy requirement in somes cases due to expected apparent temperatures above 35° C (95° F). These might need further investigation.

MSHA proposed refuse alternatives rules

The MINER Act required the Secretary of Labor to report on proposed regulatory changes within 180 days of receipt of NIOSH's refuge alternatives report. In response, MSHA published a Notice of Proposed Rule Making on Refuge Alternatives for Underground Coal Mines on June 16, 2008 (MSHA, 2008). At the time of the preparation of this manuscript, the comment period was closed, public hearings completed and MSHA was in the process of developing the final rule. The proposed rule contains many of NIOSH's recommendations found in the report to Congress, as well as solutions to other critical issues, a result of ongoing communications as part of the MSHA/NIOSH Refuge Alternatives Working Group and MSHA's diligent investigative efforts since passage of the MINER Act.

Summary and conclusions

The 2006 mine disasters and subsequent passage of the MINER Act has led to the development, testing and deployment of refuge alternatives in underground coal mines in the U.S. Specifically, a number of manufacturers have researched, developed, built and supplied refuge chambers to the coal industry.

The state of West Virginia has passed legislation requiring the use of refuge chambers in all the underground mines of that state and has approved a number of refuge chambers. MSHA has proposed rules for the use of refuge alternatives in all U.S. underground coal mines. NIOSH has conducted numerous research efforts to investigate the utility, practicality and survivability of refuge alternatives in underground coal mines, performed survivability analyses of a number of chambers and provided recommendations for use in the rule making process. Finally, all research has led to the conclusion that refuge alternatives have the potential for saving the lives of mine workers if they are part of a comprehensive escape and rescue plan and if appropriate training is provided. ■

Disclaimer

The findings and conclusions in this report have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

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FINITE ELEMENT SIMULATION OF MINE REFUCE CHAMBERS

Final Report
Contract No. 254-2010-M-34264

December 3, 2010

For

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Office of Mine Safety and Health Research

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FINITE ELEMENT SIMULATION OF MINE REFUGE CHAMBERS

December 3, 2010

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1. INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) has contracted O'Donnell Consulting Engineers, Inc. (OCEI) to provide an understanding of the heat transfer mechanisms associated with mine refuge chamber occupancy and the correlation between variables involved in the performance of refuge chambers.

The purpose of this research task is to address the heat and occupancy issues associated with the use of refuge chambers in underground mining operations. In particular, there is an interest in addressing the relationship between the chamber internal apparent temperature and external ambient mine temperature. It is also desirable to understand the de-rating capacity of refuge chambers based on the expected internal apparent temperature as the external mine temperatures increase. Finally, knowledge of the time it will take for a chamber to reach 95°F apparent temperature at full occupancy given varying external mine temperatures is desired. This research considers the specific heat load and humidity generated by occupants, carbon dioxide scrubbing system, and other known heat and humidity sources, as well as chamber specific information.
The following tasks, listed in the Statement of Work (SOW), are addressed in this Report:

Task 1. - Provide a brief description of the thermodynamic heat transfer processes, i.e. radiation, convection and conduction, accompanying the occupation of a refuge chamber during a mine emergency;

Task 2. - Develop heat transfer equations and an appropriate heat transfer modeling program;

Task 3. - Determine the baseline predicted maximum apparent temperature (heat + humidity) inside one rigid steel refuge chamber for an ambient mine temperature of 55°F and expected heat load and humidity at full occupancy;

Task 4. - Provide the correlation between internal apparent temperature and a range of external mine temperatures (55 to 95°F, or until no heat transfer occurs) for one rigid steel refuge chamber at full occupancy;

Task 5. - Provide an estimate for occupancy de-rating based on the expected internal apparent temperature remaining at or below 95°F for various mine temperatures using the results of Task 4, for one rigid steel refuge chamber; and

Task 6. - Provide an estimate of the maximum time of acceptable occupancy, at the manufacturer's recommended full capacity, and the estimated internal apparent temperature remaining at or below 95°F, resulting from a range of external ambient mine temperatures (55 to 95°F, or until no heat transfer occurs) for one rigid steel refuge chamber.

2. OVERVIEW OF REFUGE CHAMBER FUNCTIONAL REQUIREMENTS

Following several coal mine accidents, safety legislation was approved in 2006 to provide refuge chambers miners could access while waiting to be rescued. These refuge chambers are to provide the miners with necessary oxygen, food, water, livable temperature, and a way of eliminating harmful gases such as carbon dioxide and carbon monoxide for up to 96 hours. Due to the possibility of power loss in the mine as a result of an accident, all necessary life support systems must be designed to function independently of the mine's normal electric power system. Maintaining an acceptable combination of temperature and humidity, which defines the apparent temperature inside the chamber, is of major concern. Other important issues are the methods of providing oxygen, eliminating carbon gases from the air inside the chamber, and reducing the humidity in order to sustain miners' lives.

There are two types of temporary refuge chamber designs presently available, hard-shell (metal) and inflatable soft-shell (vinyl or rubber) units. The condition inside a hard-shell chamber at the time of the accident or inside a soft-shell chamber right after it is inflated is referred to herein as the chamber Initial Condition. If the hard-shell chamber has been sealed prior to entering the mine, the temperature, humidity, oxygen level, and carbon dioxide level are the same as when the unit was sealed. If the chamber has been accessed while in the mine, the Initial Condition would be similar to that of the mine interior environment. As miners enter the chamber, the temperature, humidity, and carbon gas levels begin to rise, and the oxygen level begins to decrease. The chamber temperature can be maintained at a safe level as long as the heat generated inside the chamber gets transferred to outside the chamber. The chamber air temperature and humidity rise as the mine environment temperature outside the chamber rises.

The best scenario for the chamber interior temperature is to reach an acceptable steady state condition following the initial rise in the chamber's interior temperature. However, the ability to achieve this acceptable steady state condition depends on the mine's environment temperature. If the mine environment temperature is high, the steady state apparent temperature may not be acceptable to support the miners. An increase in the internal chamber temperature due to the heat generation from the miners' bodies and the scrubbers reduces the heat transfer from the chamber to the surroundings, further increasing the chamber temperature. In addition, providing sufficient oxygen, eliminating carbon dioxide from the air inside the chamber, and keeping the humidity under control are necessary for sustaining miners' lives. The apparent temperature, which is a measure of an acceptable temperature, is based on the combination of heat and humidity. MSHA has limited the apparent temperature to 95°F for refuge chambers. The apparent temperature as a function of relative humidity and dry bulb temperature is presented in Table 1 and as a graph in Figure 1. The oxygen and carbon dioxide can be calculated based on the number of miners and their occupancy time period independent of the unit interior temperature.

Theoretically, if the oxygen supply is unlimited, the carbon gases are removed using scrubbers, and humidity is kept under control using desiccants many miners can survive much longer than the required 96 hours. The exception is if there is excessive heat generated in the mine in the close vicinity of the chamber.

3. CONTROL OF TRANSIENT REFUGE CHAMBER CONDITIONS

In addition to providing the necessary food, water, and sanitary facilities that are outside the scope of this study, maintaining proper levels of oxygen, carbon gases, temperature, and humidity are essential to support the miners in a refuge chamber. Human breathing consumes oxygen and expels carbon dioxide and water vapor. Therefore, in a closed system like a refuge chamber, the consumed oxygen needs to be replaced and carbon dioxide needs to be removed. The ratio of carbon dioxide produced to oxygen consumed is defined as the "Respiratory Quotient". The Respiratory Quotient varies from 0.8 to 1.0 depending on the person's activity level. Based on the MSHA regulations, breathing supplies should be designed to provide 1.32 CFH of oxygen and remove 1.08 CFH of carbon dioxide per miner.

The concentration of oxygen in the earth's atmosphere is approximately 20.8%. Air is considered oxygen deficient when oxygen concentration falls below 19.5%. The effects of various oxygen concentration levels are tabulated in Table 2. According to 30CFR Part 7.508 the recommended level of carbon dioxide in the chamber should not exceed 1.0%. The effects of various carbon dioxide concentration levels and the exposure times on humans are shown in Table 3. The physiological tolerance time for various carbon dioxide concentration levels is tabulated in Table 4.

There is always the possibility of high concentration of carbon monoxide in the chamber due to nearby fire and explosions in the mine. According to MSHA (30CFR Part 7.508) the recommended level of carbon monoxide in a refuge chamber is 25 ppm. An increase in the concentration from 200 to 800 ppm could result in headaches to convulsion in 45 minutes and insensibility in about 2 hours.

Oxygen may be provided in the chamber by different methods such as bottles of compressed medical grade oxygen stored in the chamber. Carbon dioxide may be removed using chemicals such as lithium hydroxide or soda lime. The use of these chemicals results in generating or removing heat from the chamber that should be taken into account in the heat transfer and analyses. Detailed analyses and efficiency of various methods of replacing the consumed oxygen and removing the carbon gases are feasible but are not in the scope of this study. Such analyses should be included for accurate modeling and simulation of refuge chambers.

According to 30CFR Part 7.505, refuge chambers should withstand 15 psi overpressurization for 2 seconds and 300 °F flash fire. Design modifications could be made to the chambers to make them more robust against potential external loads resulting from fire and explosions. These loads could be in the form of overpressurization, pressure spikes during short time periods, dynamic blasts, and impacts from projectiles such as cribs and roof fall materials. Design improvement and modifications could be accomplished using reliable finite element modeling and simulations. Such analyses could be used to quantify the improvements that could be achieved by various design changes.

An important factor in maintaining a livable environment in a refuge chamber is the air relative humidity. The relative humidity "Φ" of an air-water mixture is defined as the ratio of the partial pressure of water vapor "p_f" in the mixture to the saturated vapor pressure of water "P_{ws}" at the same temperature. Relative humidity is normally expressed as a percentage by the following equation:

$$\Phi = (p_f / P_{ws}) \times 100\%$$

Graphs in Figure 2 show that it takes less than 18 hours for a single miner to fully saturate the air at 90°F temperature with zero humidity in a 464-cubic feet chamber. Time to 100% saturation decreases linearly with increase in percentage of initial saturation. For instance, for the initial chamber at 90°F temperature and 75% humidity ratio, the time to 100% saturation would be less than 4.5 hours. For the same chamber at

60°F, the time to saturation with 0% and 75% relative humidity would be less than 7 hours and 2 hours, respectively. The calculation detail is presented in Appendix A. Graphs in Figure 2 also indicates that the change in temperature has a small effect on the partial water vapor pressure, however, it has a large effect on the saturated water vapor pressure, as shown in Figure 3.

Table 1. Apparent Temperature Chart

Relative	**TEMPERATURE (°F)**													
Humidity (%)	**70**	**75**	**80**	**85**	**90**	**95**	**100**	**105**	**110**	**115**	**120**	**125**	**130**	**135**
0	64	69	73	78	83	87	91	95	99	103	107	111	117	120
5	64	69	74	79	84	88	93	97	102	107	111	116	122	126
10	65	70	75	80	85	90	95	100	105	111	116	123	131	
15	65	71	76	81	86	91	97	102	108	115	123	131		
20	66	72	77	82	87	93	99	105	112	120	130	141		
25	66	72	77	83	88	94	101	109	117	127	139			
30	67	73	78	84	90	96	104	113	123	135	148			
35	67	73	79	85	91	98	107	118	130	143				
40	68	74	79	86	93	101	110	123	137	151				
45	68	74	80	87	95	104	115	129	143					
50	69	75	81	88	96	107	120	135	150					
55	69	75	81	89	98	110	126	142						
60	70	76	82	90	100	114	132	149						
65	70	76	83	91	102	119	138							
70	70	77	84	93	106	124	144							
75	70	77	85	95	109	130	150							
80	71	78	86	97	113	136								
85	71	78	87	99	117	140								
90	71	79	88	102	122	150								
95	71	79	89	105	126									
100	72	80	90	108	131									

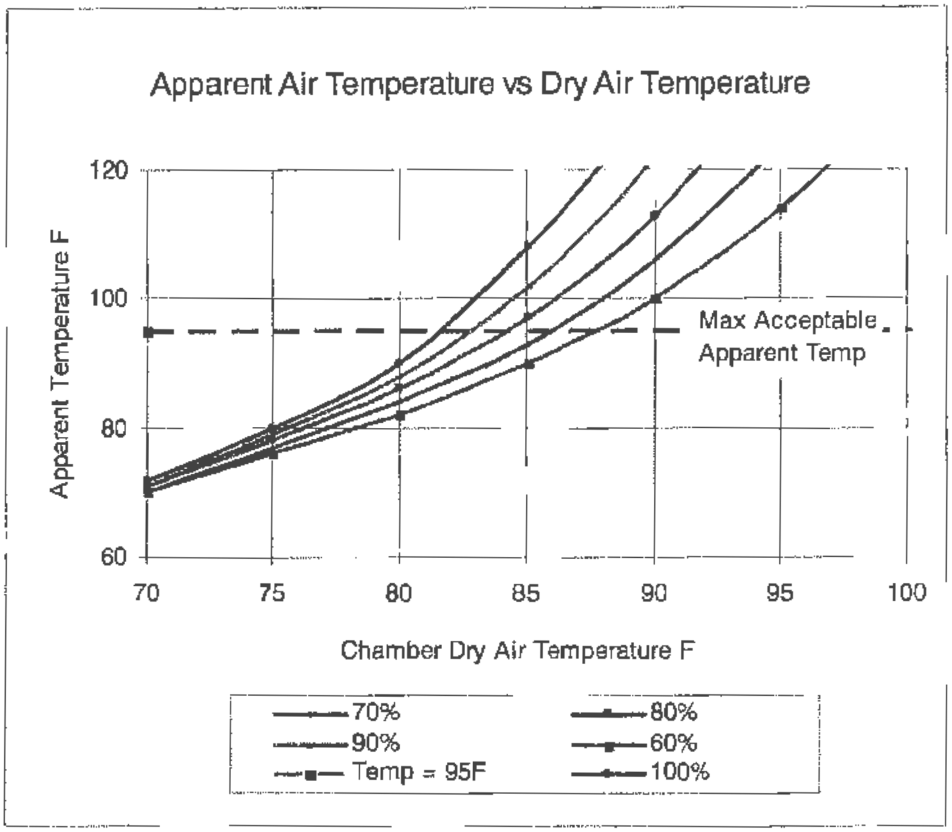


Figure 1. Apparent Temperature v. Dry Bulb Temperature and Relative Humidity

Table 2. Effects of Oxygen Concentration Levels

Concentration of Oxygen in Air (percent by Volume)	Effect on the Human Body
Over 24	Increase risk of fire
18	Slight increase in breathing rate
17	Faster, deep breathing, possible impaired judgment
15	Dizziness, buzzing in ears, rapid heartbeat
13	May lose consciousness with prolonged exposure
9	Fainting, unconsciousness
7	Life endangered
6	Convulsive movements, death

Table 3. Effects of Carbon Dioxide Concentration Levels

Carbon Dioxide Concentration %	Exposure Time	Effects
17 - 30	Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsion, coma, and death
Less than 10 - 15	1 to several minutes	Dizziness, drowsiness, severe muscle twitching, and unconsciousness
7 - 10	Few minutes	Unconsciousness or near unconsciousness
7 - 10	1.5 minutes to 1 hour	Headache, increased heart rate, shortness of breath, dizziness, sweating, and rapid breathing
6	1 - 2 minutes	Hearing and visual disturbances
6	Less then 16 minutes	Headache and dyspnea
6	Several hours	Tremors
4 - 5	Within a few minutes	Headache, dizziness, increased blood pressure, indomitable dyspnea
3	1 hour	Mild headache, sweating, and dyspnea at rest
2	Several hour	Headache, dyspnea with mild activity
1	Long time	No effect

Table 4. Physiological Tolerance Time for Various Carbon Dioxide Concentrations

Concentration of Carbon Dioxide in Air (percent by Volume)	Maximum Exposure Limit (Minutes)
0.5	indefinite
1.0	indefinite
1.5	480
2.0	60
3.0	20
4.0	10
5.0	7
6.0	5
7.0	Less than 3

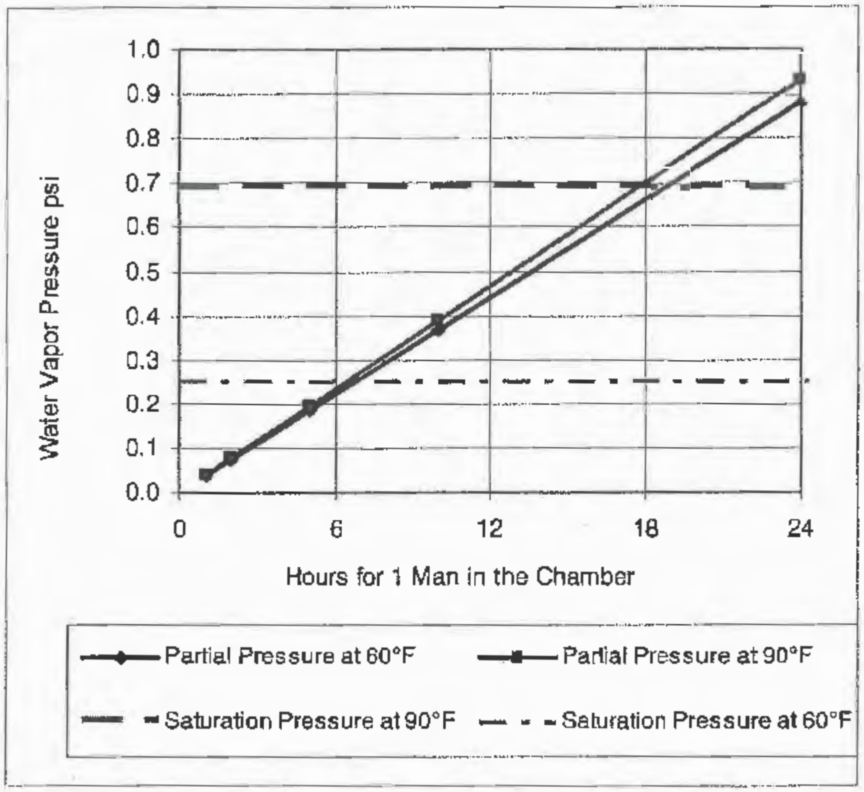


Figure 2. Partial Water Vapor and Saturation Pressures vs. the Time for One Miner Occupying the Chamber

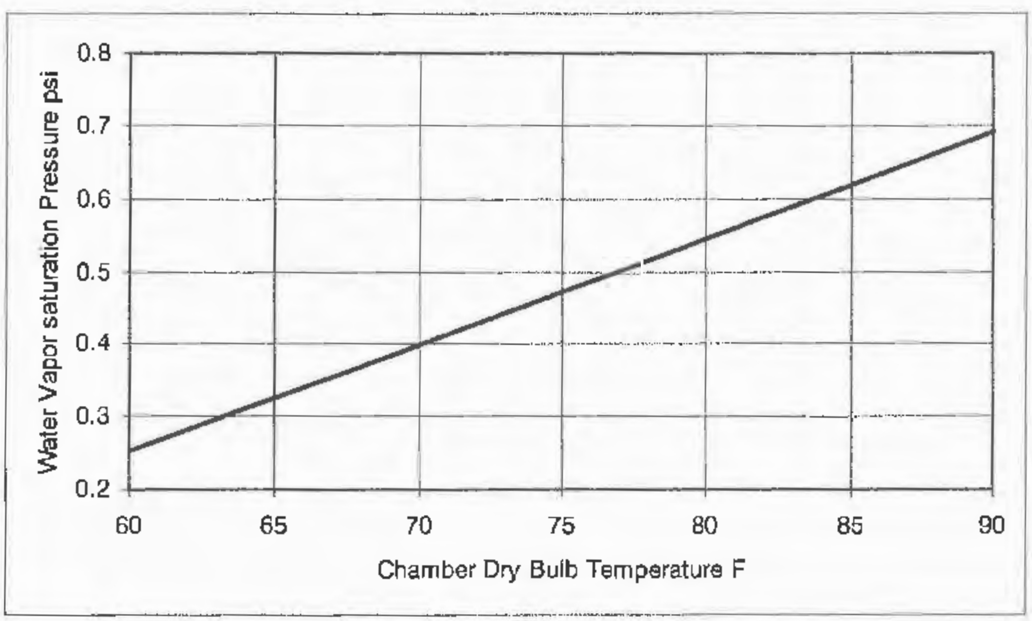


Figure 3. Water Vapor Saturation Pressures vs. Temperature

4. HEAT TRANSFER MECHANISM IN REFUGE CHAMBERS (SOW Task 1)

Heat generated in the chamber gets transferred to the chamber's interior walls, through the walls, and then to the mine environment. Heat is transferred by conduction, convection, and radiation from heat sources inside the chamber, namely from miners' bodies and scrubbers, to the chambers interior wall through the air. Due to low air conductivity, the amount of heat transferred by conduction is small. Since there is air movement inside the chamber, most of heat is transferred by convection. There is also some radiation heat transfer within the chamber. Heat is transferred though the chamber wall thickness by conduction only. Due to the chamber's thin wall thickness and its material conductivity, there is a minimal heat flow resistance and a small temperature drop across the chamber's walls. Adding insulation to the walls protects the chamber from external heat due to fire and explosions, however, it also reduces the chamber's beneficial heat flow to the outside when chamber's inside temperature is higher than the outside. The benefits of increasing the wall's external heat transfer surfaces, such as installing fins, can be quantified using finite element modeling. Fins should be protected from getting damaged during hauling and placement of the chamber inside the mine.

From the chamber outside wall surfaces heat is transferred by convection and radiation to the mine's interior surfaces. The amount of heat transferred by conduction in the air is small. Since the air flow outside the chamber is stagnated, the heat transfer coefficient between the chamber exterior surfaces and the air is relatively small, resulting in a low convection heat transfer. Due to low heat transfer by conduction and convection, radiation heat transfer is the prominent heat transfer mode. Radiation is affected by the level of humidity in the air surrounding the chamber.

Appropriate heat transfer models were developed to simulate the heat flow between the chamber internals and the mine environment. Finite element technology was employed to construct and perform the analyses.

5. FINITE ELEMENT ANALYSES (SOW Task 2)

5.1 Geometry

A three-dimensional model of a typical mine refuge chamber was constructed to quantify the heat flow between a refuge chamber and its surroundings. This model consisted of more than 37,000 three-dimensional solid elements. The finite element model included the chamber, men, carbon dioxide scrubber, and the mine environment. Model dimensions were based on one of the Strata's hard-shell refuge chambers that was made available for evaluation. This chamber was designed to hold up to 20 miners. The overall dimensions of the model were 96" wide 72" tall and 115" long with 0.25" thick walls, resulting in approximately 464 ft^3 of internal volume.

A cross-section of the chamber showing two miners sitting across from each other, a box in front of them representing a dioxide carbon scrubber, and the mine walls is presented in Figure 4. Figure 5 shows the 3-dimensional view of the chamber, cut and expanded at the middle. The finite element mesh density of the chamber model is reproduced in Figure 6. This model was built to simulate the chamber performance for up to 20 miners.

5.2 Steady State Analyses

A number of three dimensional finite element steady state thermal analyses were performed on the above-described model simulating various conditions. These conditions were based on varying the number of miners in the chamber, the temperature of the mine walls, and the air temperature outside the chamber. The heat flow from each person was set at 400 BTU/hr and their skin temperature was set at 93°F. The heat flow generated by the carbon gas scrubbers was set at 87 BTU/(hr-person).

Figures 7 through 11 show dry bulb temperature distributions in the chamber for the case of 20 miners with the mine wall and air temperature at 60°F. Figure 7 shows 3-D view of the air temperature distribution on a vertical plane across the center of the chamber. Figure 8 shows 3-D view of the air temperature distribution on a vertical plane at the center of the chamber. These graphs show the increase in the air temperature near the carbon dioxide scrubber. The air temperature distribution on the plane across the body of a miner sitting in the middle of the chamber is reproduced in Figure 9. Figures 10 and 11 show the air temperature distribution on two horizontal planes at the miners' head and feet levels, respectively.

The temperature values throughout the chamber are averaged to represent the average dry bulb temperature in the chamber. Generally the mine's air and wall temperatures are approximately the same and in equilibrium unless an explosion or fire occurs. The effect of the change in the mine's air and wall temperatures and also the number of miners on the average dry bulb temperature in the chamber are presented in Figures 12 and 13. Figure 12 shows the average dry bulb temperature in the chamber for 10, 14, 16, and 20 miners when the mine's air and wall temperature were equal. Figure 13 shows the change in the average dry bulb temperature in the chamber for 20 miners vs. mine wall temperatures of 55 to 95°F for mine air temperatures of 55, 65, 75, 85, and 95°F.

All above temperature plots are for the chamber dry bulb without accounting for humidity in the air. The combination of the air temperature and humidity defines the apparent air temperature (see Figure 1 and Table 1) which is the measure of "feels like" comfort for the human body. Figures 14, 15, and 16 show the change in the apparent temperature of the chamber at various levels of relative humidity for 20, 10, and 8 miners vs. the change in the mine's equal air and wall temperatures, respectively.

5.3 Transient Analyses

Transient thermal analyses were performed to determine the time that it takes from when the miners enter the chamber until the thermal condition inside the chamber reaches equilibrium. All temperatures were set to 60°F at time equal to zero. The change in the chamber average dry bulb temperature for 8, 10, 14, 16, and 20 miners when the mine's air and wall temperature were equal to 60°F is plotted in Figure 17. This plot indicates that the temperature in the chamber reaches the steady state condition in about 36 hours. This data is plotted on a semi-log scale in Figure 18. The change in the chamber apparent air temperature for 20 miners when the mine's air and wall temperature were equal to 60°F, 75°F, and 90°F are plotted in Figures 19, 20, and 21, respectively. Similar plots for 10 and 8 miners in the chamber are plotted in Figures 22 through 27.

5.4 Analyses Results

Finite element heat transfer analyses results show that for the refuge chamber considered herein, the heat flow from the chamber to its environment is more sensitive to the mine interior wall temperature than the air temperature surrounding the chamber.

Analyses results show that the chamber air gets oversaturated in a relatively short time. It takes less than 1.8 hours for 10 miners to fully saturate the air at 90°F temperature with zero humidity in a 464-cubic feet chamber. This shows the importance of humidity level in extending the capacity and occupation times of mine refuge chambers.

5.4.1 SOW Task 3

Task 3 in the Statement of Work (SOW) involved determining the baseline predicted maximum apparent temperature with an ambient mine temperature of 55°F and full occupancy. Figure 14 illustrates this relationship for ambient mine temperatures of 55°F to 95°F. The apparent temperature for various relative humidity at an ambient mine temperature of 55°F varies from approximately 82 to 97°F. For instance, at dry conditions, the predicted maximum apparent temperature is approximately 82°F while at 100% RH, the maximum predicted apparent temperature is 97°F. Similar results for 10 and 8 miners are presented in Figures 15 and 16, respectively.

5.4.2 SOW Task 4

Task 4 involved providing the correlation between internal apparent temperature and a range of external mine temperatures, again at full occupancy. Figure 14 also illustrates this relationship. The internal apparent temperature reaches 95°F at various external temperatures and internal RHs. For instance, the apparent temperature reaches 95°F at 80°F mine temperature and 50% RH. At 100% RH, the chamber is estimated to be above

95°F apparent temperature at 55°F mine temperature. Similar results for 10 and 8 miners are presented in Figures 15 and 16, respectively.

5.4.3 SOW Task 5

Task 5 requested an estimate of occupancy de-rating for various external mine temperatures with the chamber remaining at or below 95°F apparent temperature. Figures 14 through 16 provide an estimate of the occupancy de-rating needed as the external mine temperatures increase. Where each of the RH lines cross the 95°F apparent temperature line indicates the external temperature at which occupancy de-rating must occur. For instance, if occupancy is halved to 10 miners as shown in Figure 15, the exterior mine air/wall temperature can be only 62°F at 100% RH and as high as 95°F at dry interior conditions for the chamber's apparent temperature to remain at or below 95°F.

5.4.4 SOW Task 6

Finally, Task 6 requested a time of acceptable occupancy, at full capacity and internal apparent temperatures at or below 95°F, for various external mine temperatures. Figures 19 through 27 illustrate these relationships. Figure 19 illustrates that at full capacity, 60°F external mine temperature, and regardless of the RH, the apparent temperature reaches 95°F in approximately 9 hours, reaching a maximum of 102.5°F in approximately 40 hours after occupation. At higher external mine temperatures of 75°F and 90°F, as shown in Figures 20 and 21, time of acceptable occupancy is reduced dramatically. Similar results for 10 and 8 miners are presented in Figures 22 and 27.

6. DISCUSSION AND RECOMMENDATIONS

The work performed herein was concentrated on the basic heat transfer mechanisms governing the heat flow and heat balance between a typical refuge chamber and its surrounding environment in the mine using finite element analyses. There are many variables involved in designing and evaluating the capacity of a reliable refuge chamber to support miners for a desired time period. These variables include temperature, humidity, oxygen, carbon dioxide, carbon monoxide, chamber's dimensions, chamber's material of construction, chamber's fire resistancy, chamber's structural integrity when subjected to external pressure, and the chamber's placement in the mine for optimum heat flow. Under the conditions considered in this Report (see Figure 2), it only takes a few hours for a single person to increase the level of humidity to full saturation. Therefore, the humidity level must be kept under control for successful use of chambers.

At the present time, in order to design or evaluate the performance of a refuge chamber, a comprehensive heat transfer, thermodynamics, and structural analyses must be performed. These analyses involve computational fluid dynamics (CFD), finite element (FEA) analysis, and engineering calculations. OCEI recommends performing an extensive parametric evaluation of the effects of all the variables involved in the design of a reliable refuge chamber. In these transient evaluations, the chamber dry bulb temperature and relative humidity as a function of time will be monitored and quantified. A detailed evaluation of all heat sources (the sensible and latent heat loads) in the chamber including humans, chemical reactions, scrubbers, and other equipment will be included. The exact concentration of gases present in the chamber will be considered to make sure the system is functioning as required for maintaining livable conditions for miners. Factors affecting the flow of heat between the chamber and the mine include mine air transient temperature due to potential fire or explosions, mine wall temperature gradient, air flow and movement around the chamber (if any), level of humidity and gases in the mine air affecting the radiation from the chamber to the mine walls, conductivity of the mine wall materials, and distances between the chamber outer surfaces and the mine walls.

Based on the results of such a study, an interactive stand-alone software program can be developed for design and verification purposes covering various designs of refuge chambers, without having to perform time consuming CFD and/or FEA analyses and simulations on each individual unit.

Certain input values and assumptions for the above-mentioned work may need to be verified by testing, experimentation, or physical modeling. To reduce the cost and increase the efficiency of these verification tests, CFD and FEA modeling can be employed to define the test procedures and parameters.

Presently refuge chambers are not designed to withstand the potential excessive heat created by a fire. As discussed in this Report, increases in the mine environment temperature could reduce or even reverse the heat flow from the chamber. This issue should be addressed on a priority basis in future work.

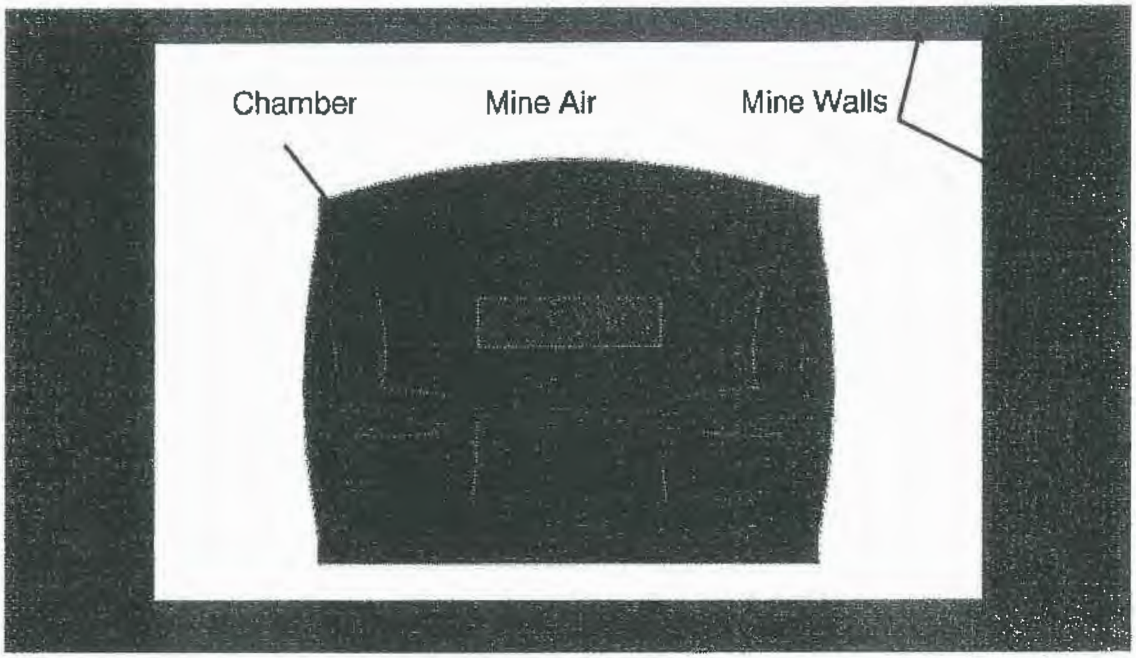


Figure 4. Cross-Section of the Chamber Showing Two Miners across from Each Other

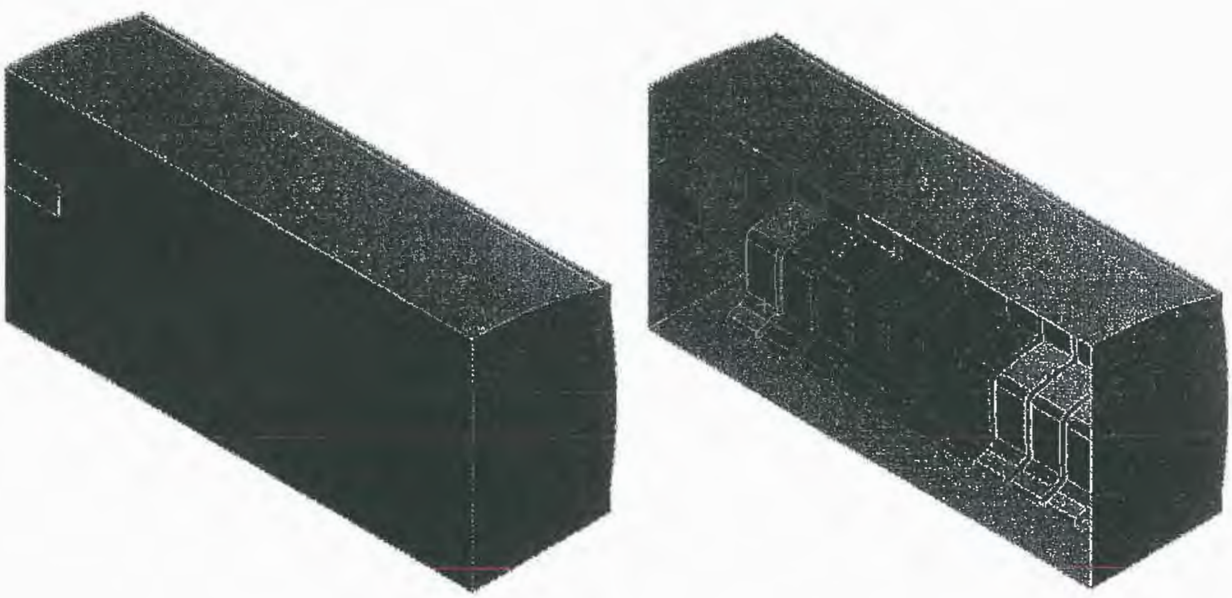


Figure 5. 3-Dimensional View of the Chamber Cut in the Middle

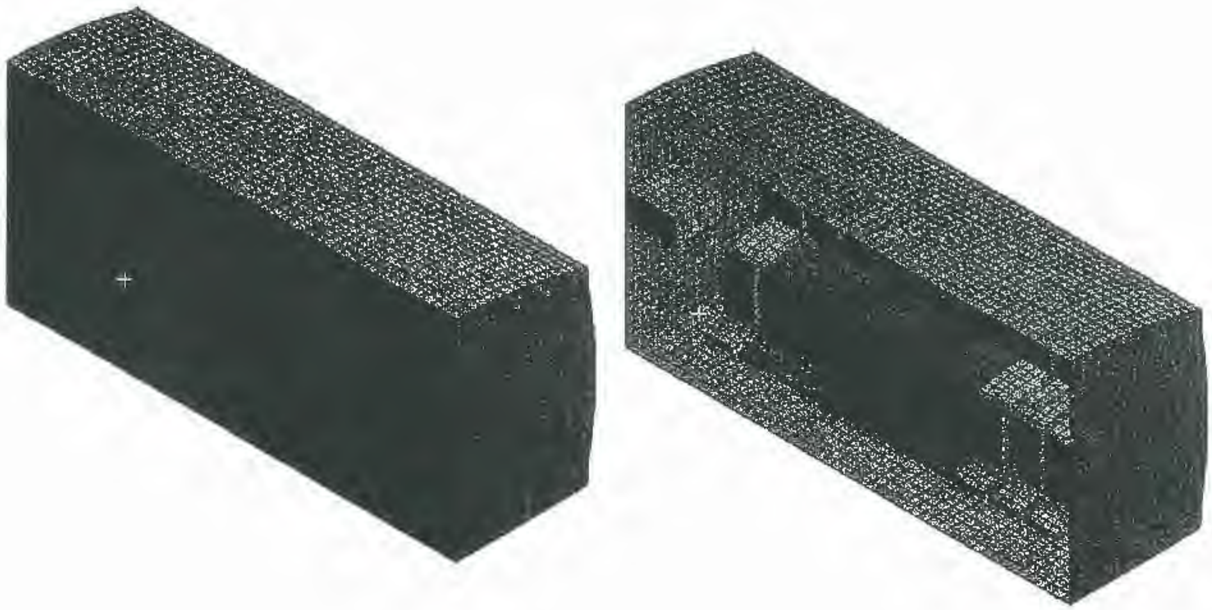


Figure 6. Chamber Finite Element Mesh Density

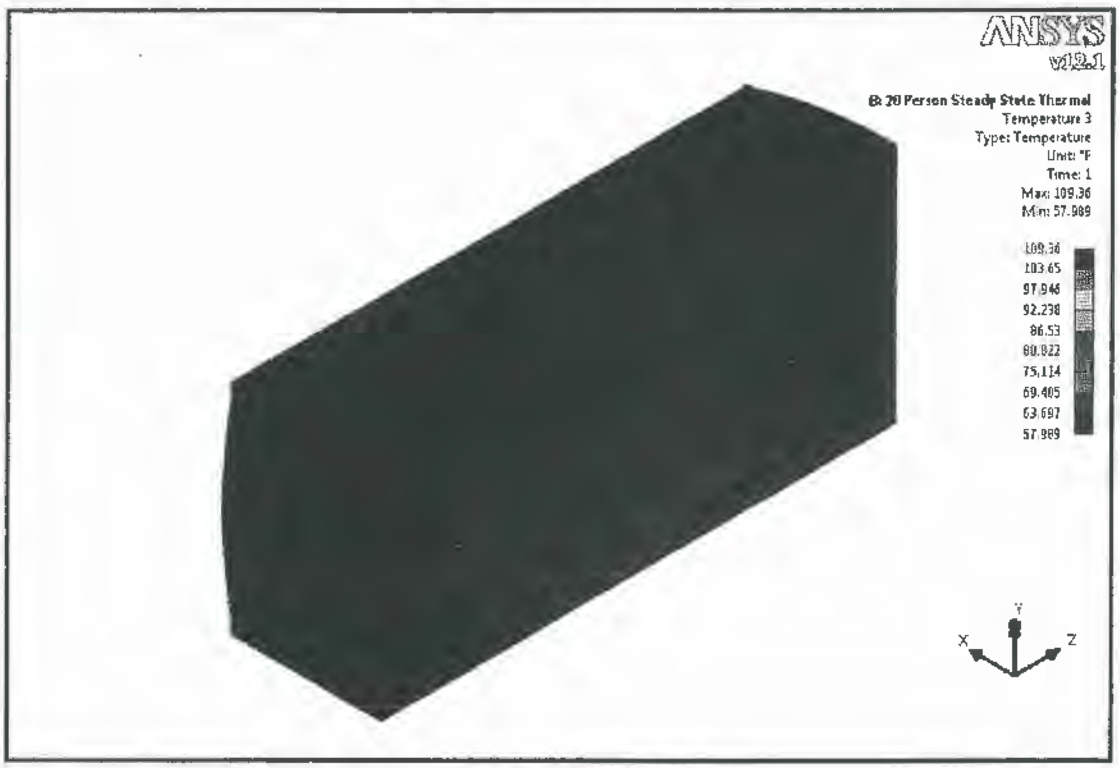


Figure 7. 3-D View of the Chamber Temperature Distribution

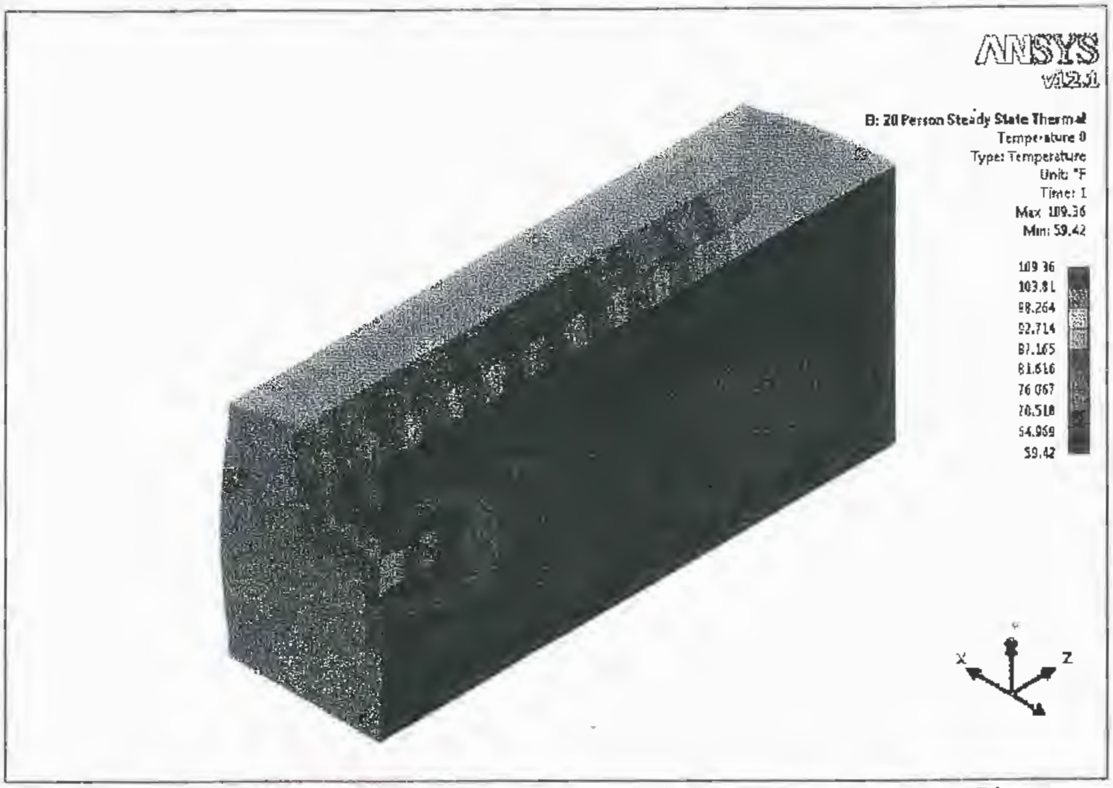


Figure 8. Air Temperature Distribution on the Chamber's Vertical Center Plane

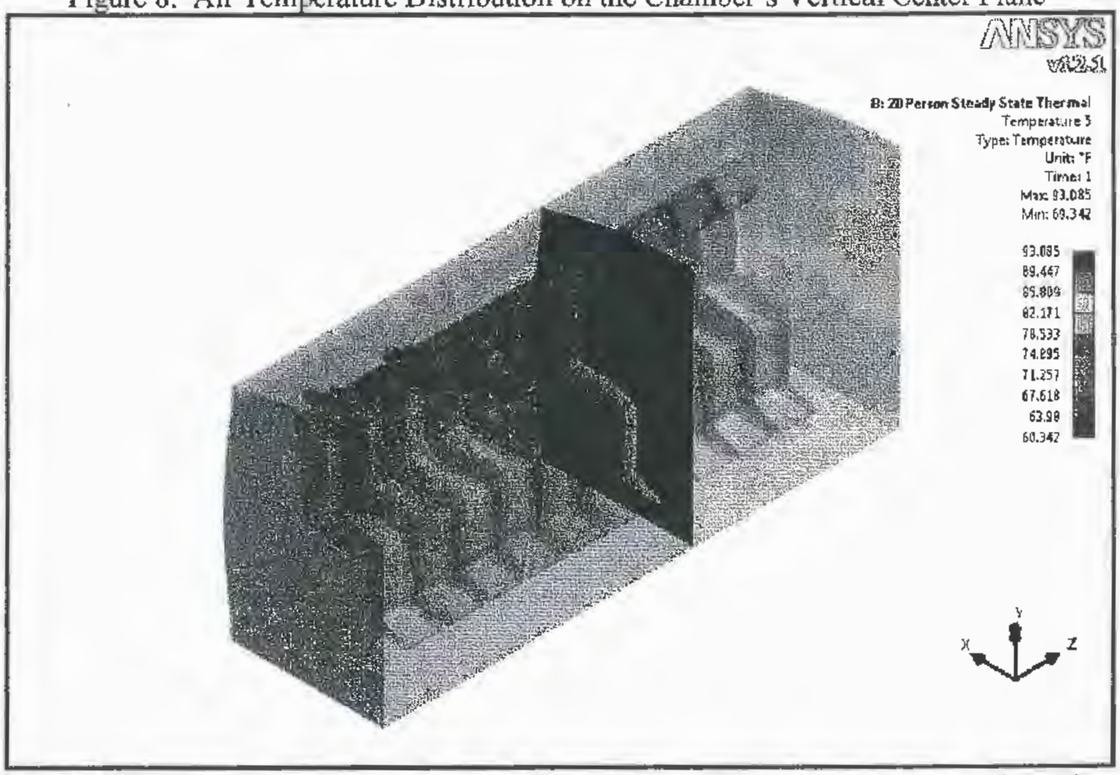


Figure 9. Air Temperature Distribution on a Plane across the Body of a Miner Sitting in the Middle of the Chamber

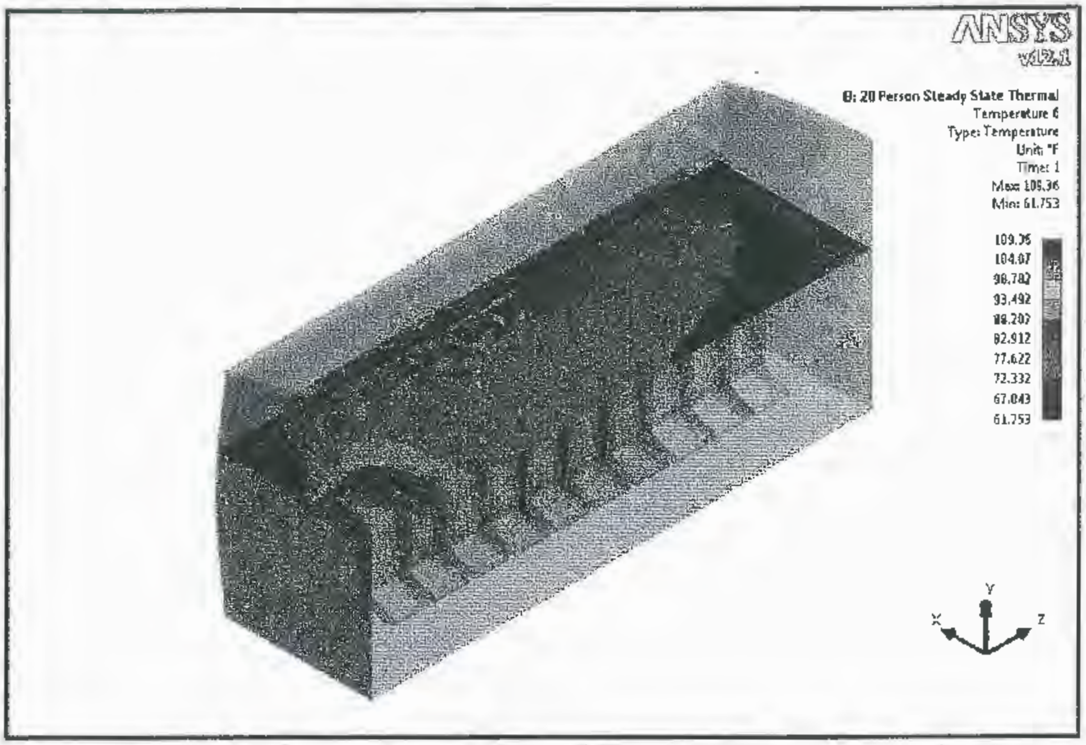


Figure 10. Air Temperature Distribution on a Horizontal Plane at the Miners' Head Level

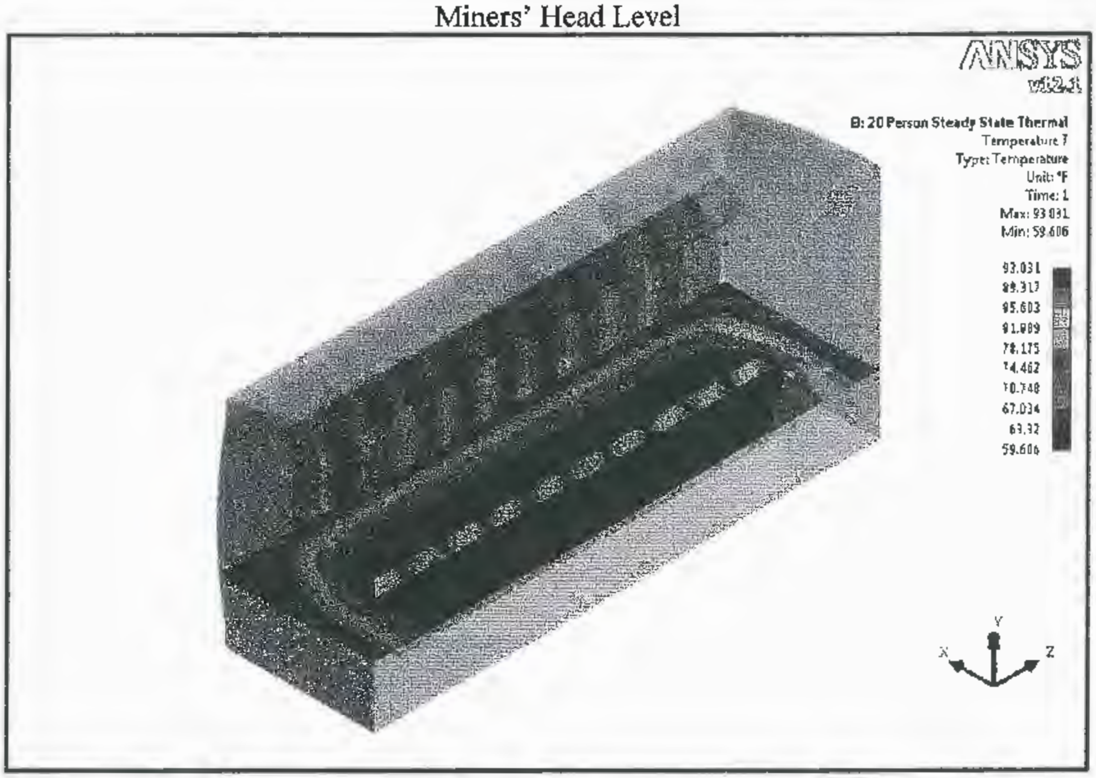


Figure 11. Air Temperature Distribution on a Horizontal Plane at the Miners' Foot Level

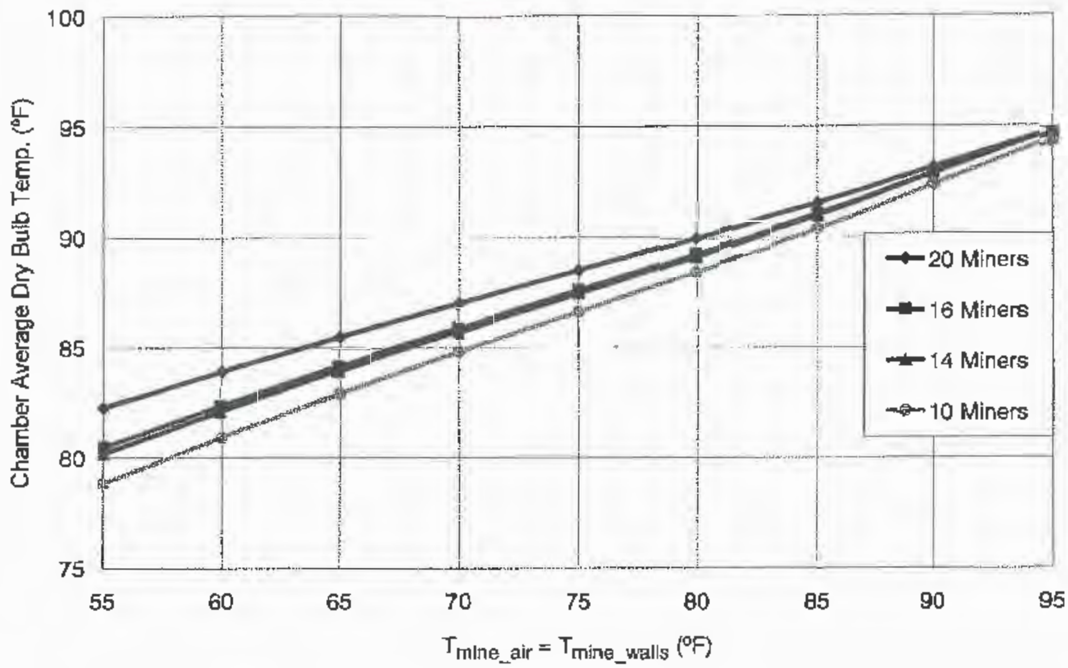


Figure 12. Average Dry Bulb Temperature in the Chamber for 10, 14, 16, and 20 Miners vs. Mine Air and Wall Temperatures

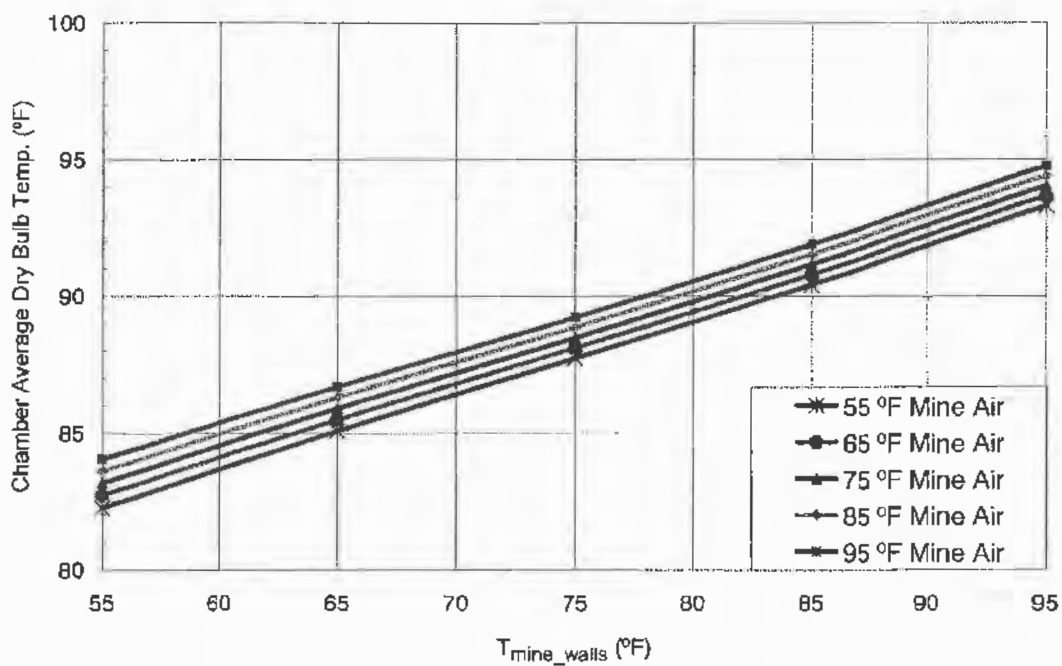


Figure 13. Average Dry Bulb Temperature in the Chamber for 20 Miners vs. Mine Wall Temperatures of 55 to 95°F

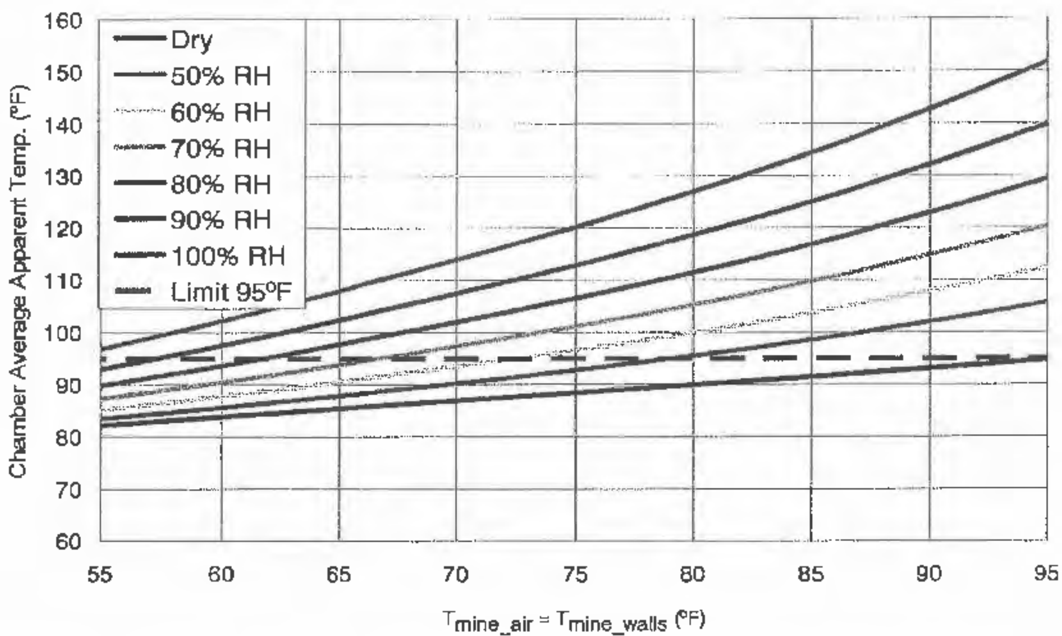


Figure 14. Average Apparent Chamber Temperature at Various Relative Humidity Levels for 20 Miners (Full Occupancy) vs. Mine's Equal Air and Wall Temperatures

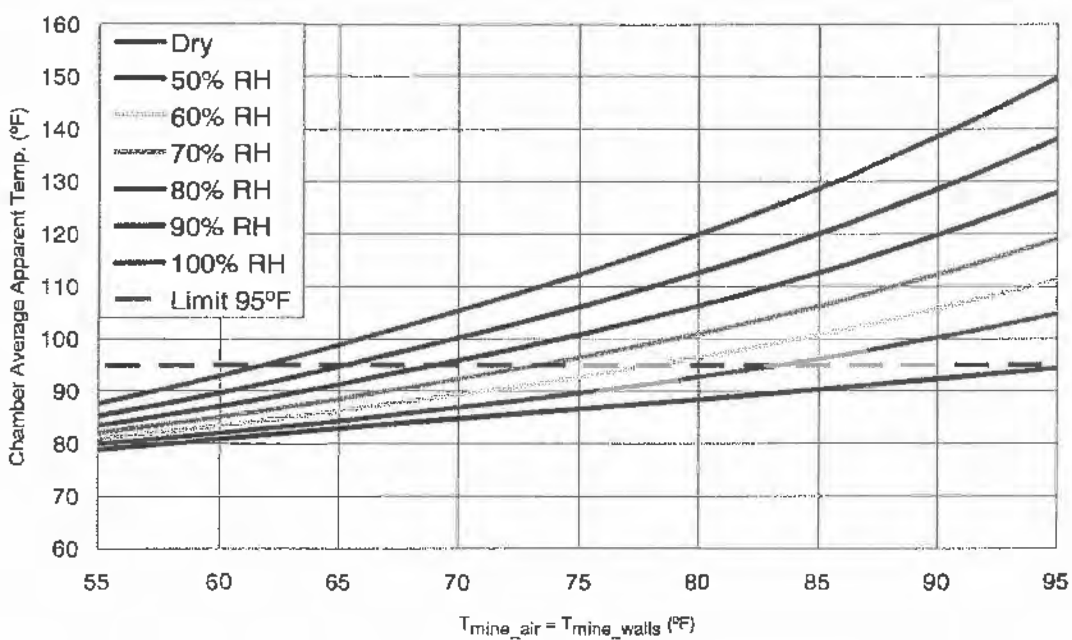
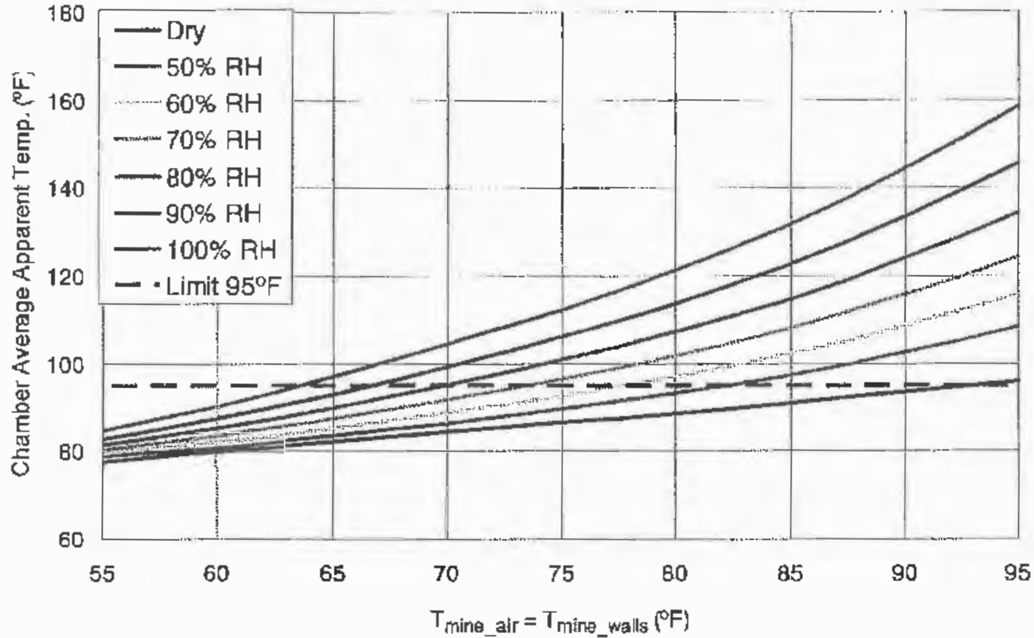


Figure 15. Average Apparent Chamber Air Temperature at Various Relative Humidity Levels for 10 Miners vs. Mine's Equal Air and Wall Temperatures



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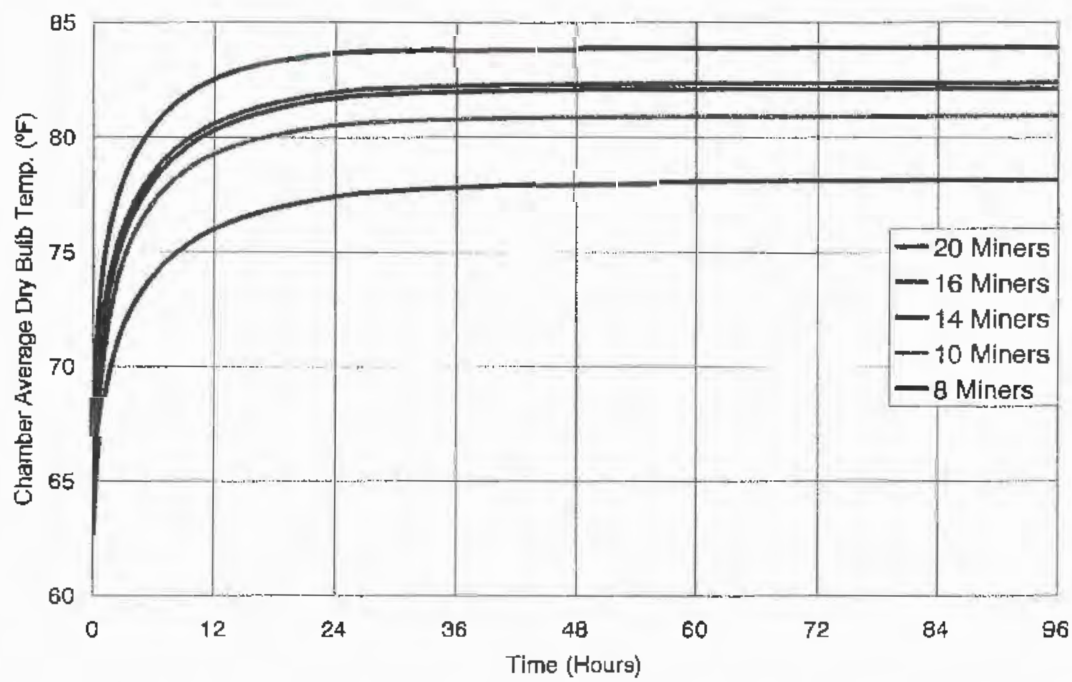

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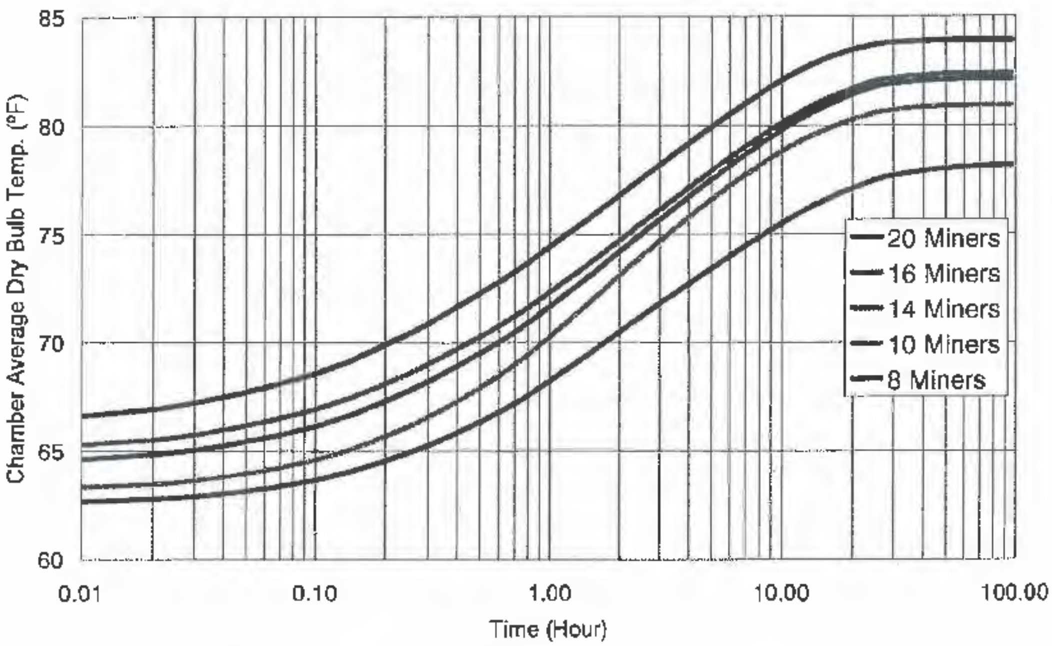

Figure 18. Average Dry Bulb Chamber Air Temperature for 8, 10, 14, 16, and 20 Miners vs. Occupancy Time for Mine's Air and Wall Temperatures of 60°F

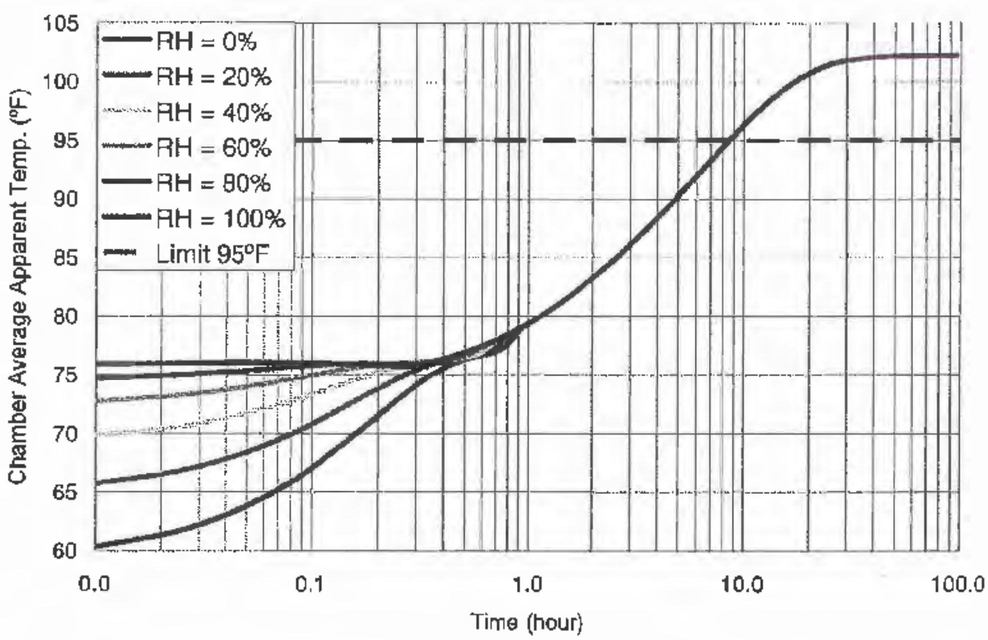

Figure 19. Average Apparent Chamber Air Temperature vs. Occupancy Time of 20 Miners for Mine's Air and Wall Temperatures Equal to 60°F

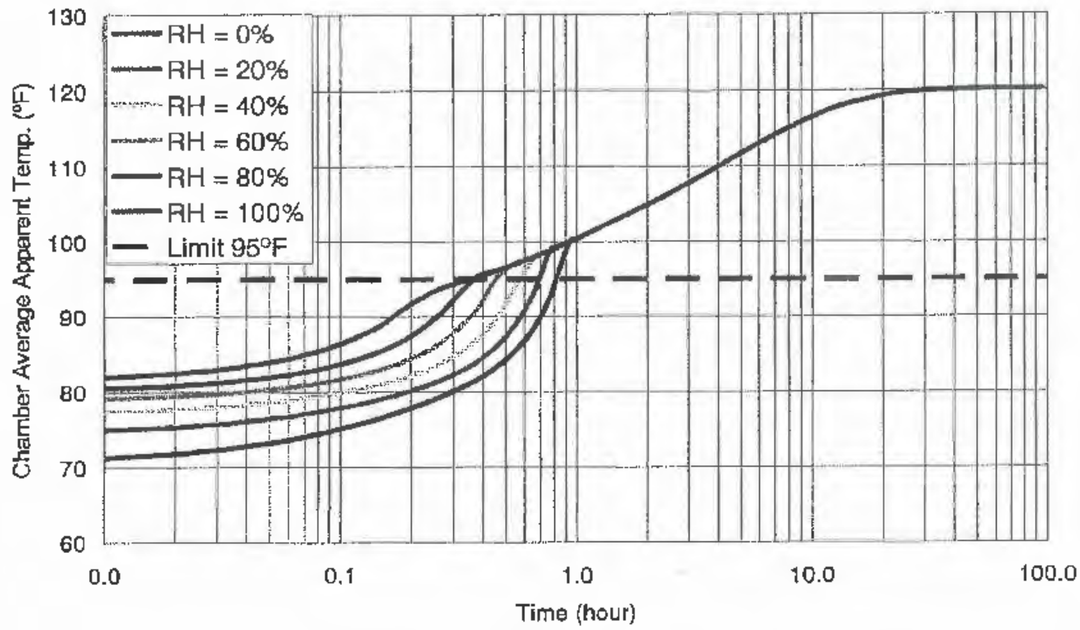

Figure 20. Average Apparent Chamber Air Temperature vs. Occupancy Time of 20 Miners for Mine's Air and Wall Temperatures Equal to 75°F

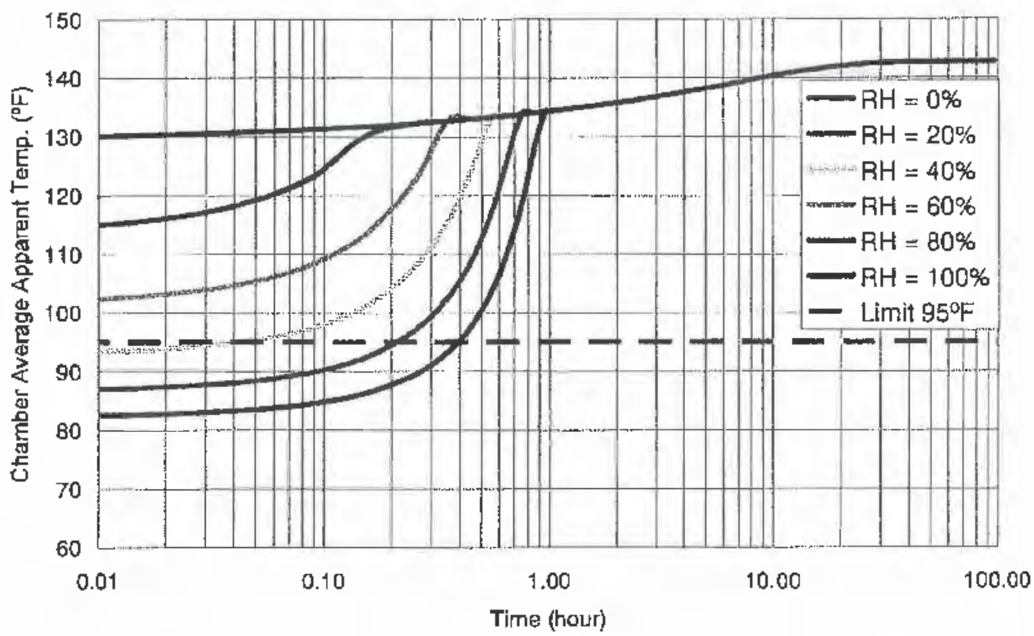

Figure 21. Average Apparent Chamber Air Temperature vs. Occupancy Time of 20 Miners for Mine's Air and Wall Temperatures Equal to 90°F

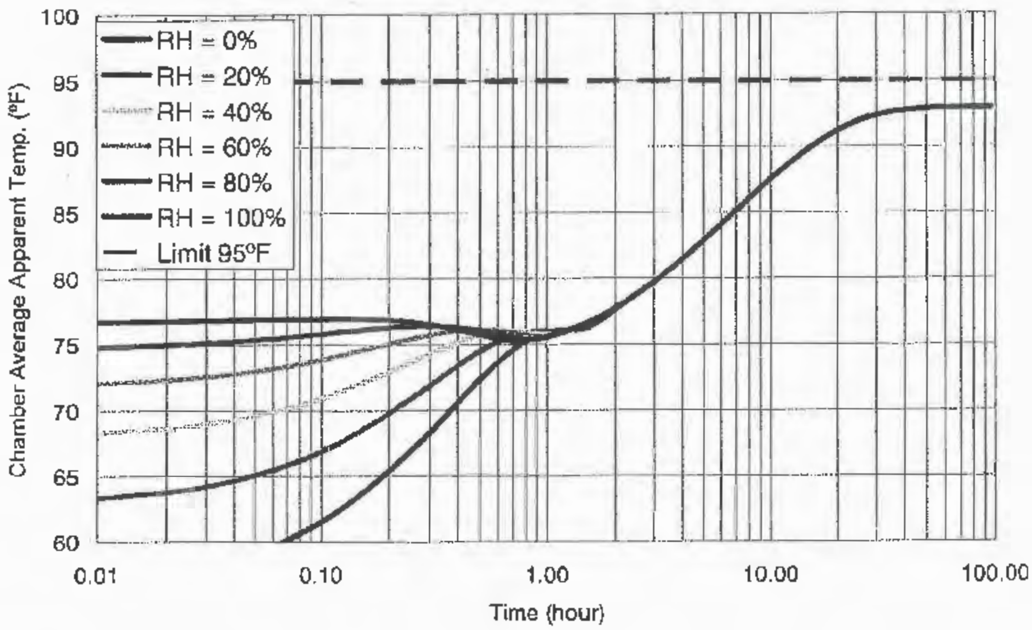

Figure 22. Average Apparent Chamber Air Temperature vs. Occupancy Time of 10 Miners for Mine's Air and Wall Temperatures Equal to 60°F

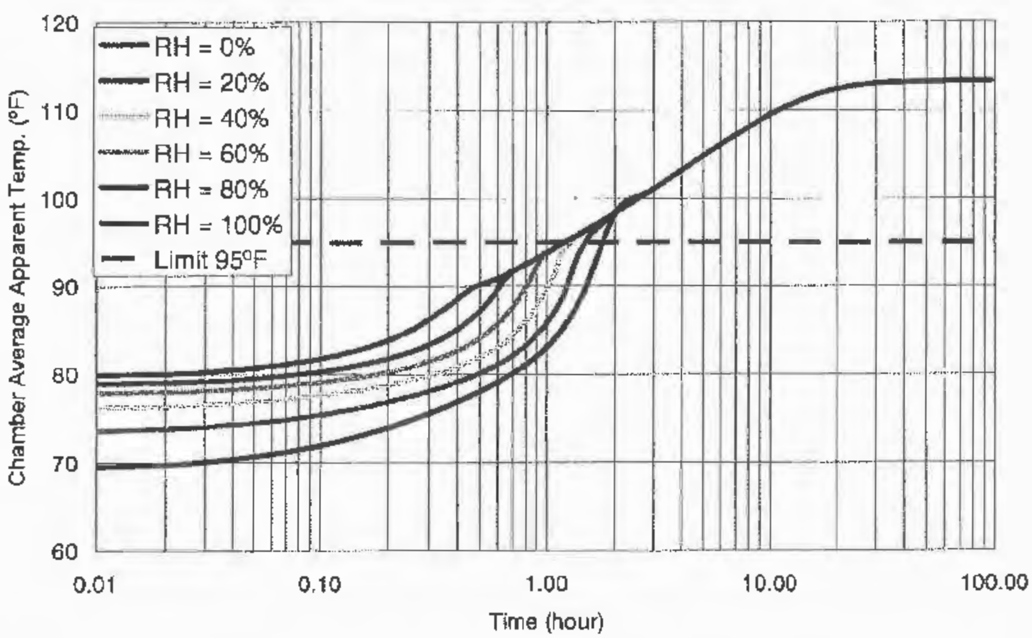

Figure 23. Average Apparent Chamber Air Temperature vs. Occupancy Time of 10 Miners for Mine's Air and Wall Temperatures Equal to 75°F

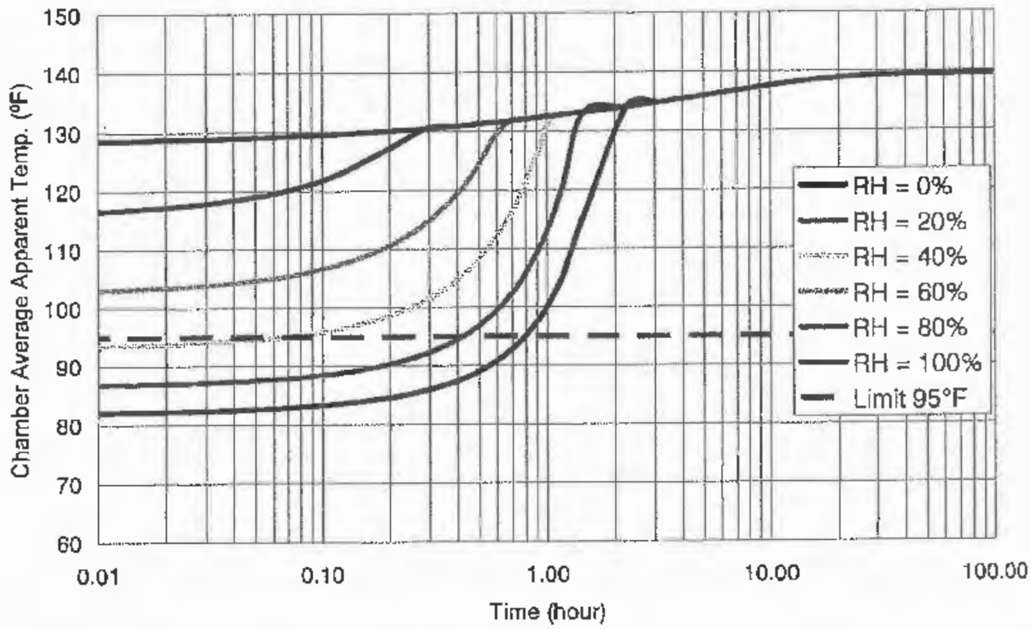

Figure 24. Average Apparent Chamber Air Temperature vs. Occupancy Time of 10 Miners for Mine's Air and Wall Temperatures Equal to 90°F

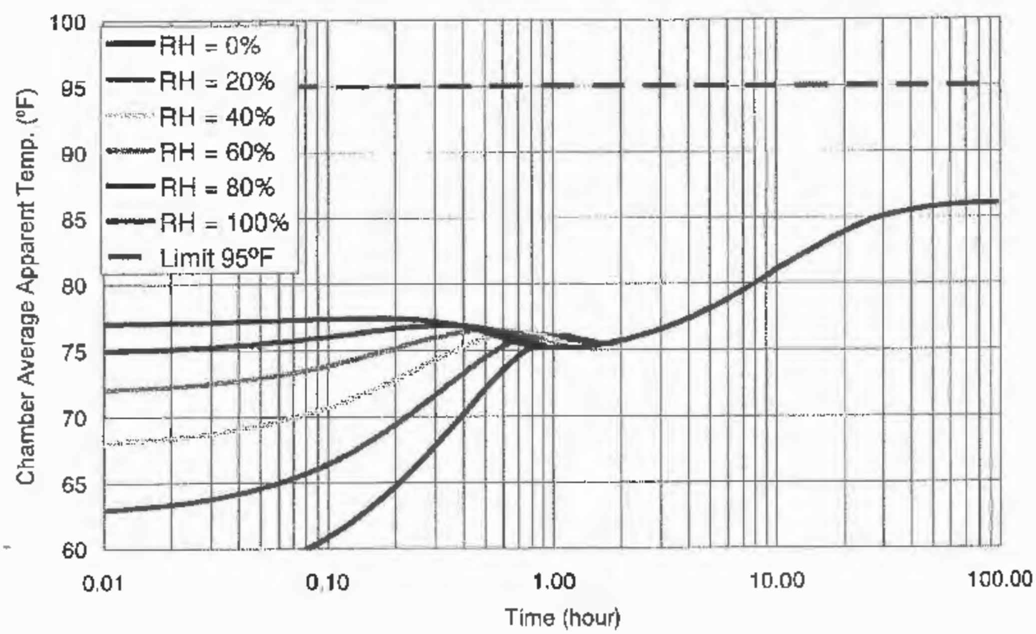

Figure 25. Average Apparent Chamber Air Temperature vs. Occupancy Time of 8 Miners for Mine's Air and Wall Temperatures Equal to 60°F

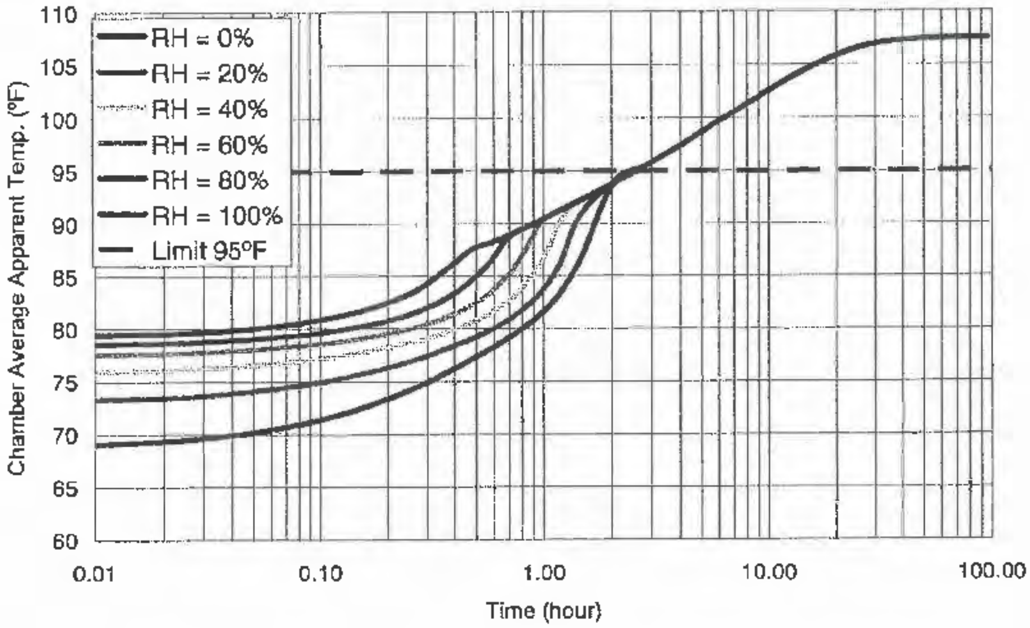

Figure 26. Average Apparent Chamber Air Temperature vs. Occupancy Time of 8 Miners for Mine's Air and Wall Temperatures Equal to 75°F

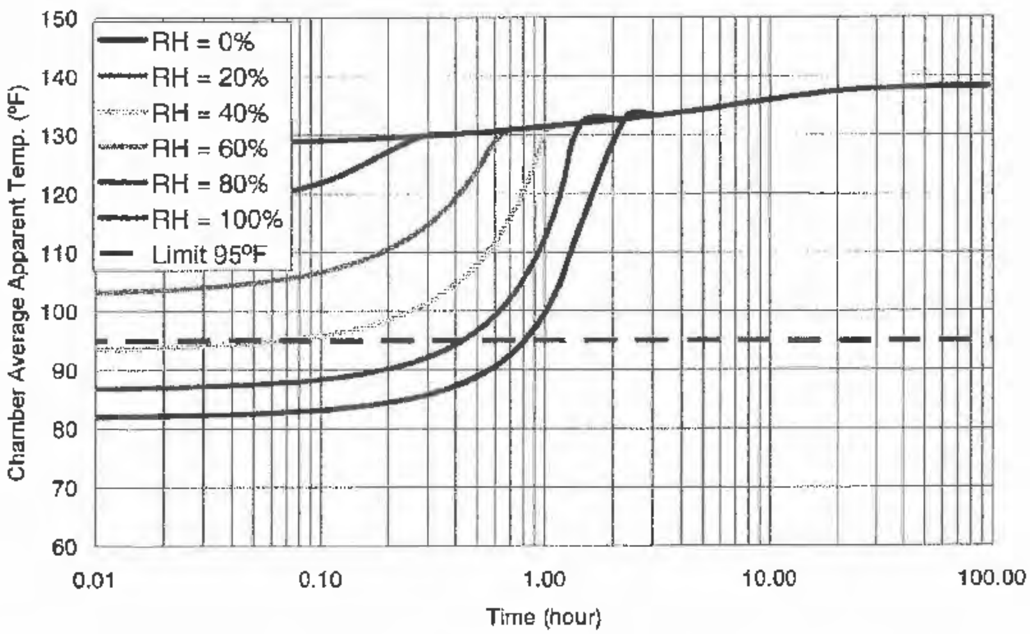

Figure 27. Average Apparent Chamber Air Temperature vs. Occupancy Time of 8 Miners for Mine's Air and Wall Temperatures Equal to 90°F

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APPENDIX A

Water Vapor Partial and Saturation Pressure Calculations

$Vol := 463.7 ft^3$ — Chamber Volume

$m_{1man} := 1.32 \cdot \frac{lb}{24 \cdot hr}$ — Water from 1 man per 24 hours

$R_{gas} := 1545.4 \frac{ft \cdot lbf}{lb \cdot R \cdot mol}$ — Ideal Gas Constant

$Hrs := \begin{pmatrix} 1 \\ 6 \\ 12 \\ 24 \\ 36 \end{pmatrix} \cdot hr$ — Hours in the chamber

$m_1 := m_{1man} \cdot Hrs$ $\quad m_1 = \begin{pmatrix} 0.055 \\ 0.33 \\ 0.66 \\ 1.32 \\ 1.98 \end{pmatrix} \cdot lb$ — Water from 1 man in 1,6, 12, 24, and 36 hours

$M_1 := 18 \cdot \frac{lb}{lb \cdot mol}$ — Water Molecular weight

$N_1 := \frac{m_1}{M_1}$ $\quad N_1 = \begin{pmatrix} 3.056 \times 10^{-3} \\ 0.018 \\ 0.037 \\ 0.073 \\ 0.11 \end{pmatrix} \cdot mol \cdot lb$ — Water Molar mass

$R_1 := \frac{R_{gas}}{M_1}$ $\quad R_1 = 85.856 \frac{ft \cdot lbf}{lb \cdot R}$ — Specific gas constant for water vapor

$t_{60} := 60$ $\quad T_{60} := (t_{60} + 460) \cdot R$ $\quad T_{60} = 520 R$ — Chamber air Temperature

$p_{60} := \frac{m_1 \cdot R_1 \cdot T_{60}}{Vol}$ $\quad p_{60} = \begin{pmatrix} 0.037 \\ 0.221 \\ 0.441 \\ 0.883 \\ 1.324 \end{pmatrix} \cdot psi$ — Water vapor partial pressure in 1 to 36 hours at 60°F

$t_{90} := 90$ $\quad T_{90} := (t_{90} + 460) \cdot R$ $\quad T_{90} = 550 R$ — Chamber air Temperature

$$p_{90} := \frac{m_l \cdot R_l \cdot T_{90}}{Vol} \qquad p_{90} = \begin{pmatrix} 0.039 \\ 0.233 \\ 0.467 \\ 0.933 \\ 1.4 \end{pmatrix} \cdot psi$$

Water vapor partial pressure in 1 to 36 hours at 90°F

$$t := \begin{pmatrix} 90 \\ 60 \end{pmatrix}$$

Temperature for saturation pressure calculation in °F

$$T_k := (t - 32) \cdot \frac{5}{9} + 273 \qquad T_k = \begin{pmatrix} 305.222 \\ 288.556 \end{pmatrix}$$

Temperature for saturation pressure calculation K

$$P_{ws} := \frac{e^{77.345 + 0.0057 T_k - \frac{7235}{T_k}}}{{T_k}^{8.2}} \cdot Pa$$

Saturation pressure for water vapor

$$P_{ws} = \begin{pmatrix} 0.691 \\ 0.253 \end{pmatrix} \cdot psi$$

Saturation pressure for water vapor at 60°F and 90°F

$$m_{sat} := \frac{Vol}{R_l} \cdot \overrightarrow{\left(\frac{P_{ws}}{T_k \cdot K} \right)} \qquad m_{sat} = \begin{pmatrix} 0.977 \\ 0.379 \end{pmatrix} \cdot lb$$

Water weight in full saturation at temperature of 60F and 90°F

$$Time_{to\_sat} := \frac{m_{sat}}{m_{l\,man}} \qquad Time_{to\_sat} = \begin{pmatrix} 17.773 \\ 6.89 \end{pmatrix} \cdot hr$$

Time to saturation from initial 0% to 100% at 90°F and 60°F

This indicates that for the assumed chamber volume of 464 cubic feet it takes less than 18 hours for a single miner to fully saturate the chamber air that had zero humidity at 90°F. The time to 100% saturation decreases linearly with increase in percentage of initial saturation. If the initial chamber humidity ratio was at 75% at 90°F, the time to reach 100% saturation would be less than 4.5 hours.

Underground Mine Shelter Thermal Analysis

Final Report

Submitted To:
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Office of Mine Safety and Health Research

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Table of Contents

1.0 Introduction

The following report summarizes a Thermal Analysis of Underground Coal Mine Refuge Chambers, Contract No 200-2011-41690, awarded by the Centers for Disease Control and Prevention to ThermoAnalytics, Inc., dated September 15, 2011.

1.1 Executive Summary

This report describes a thermal analysis of occupied refuge shelters and the surrounding mine following a traumatic event which compels miners to take shelter over a four-day duration. The objective of this work is to furnish NIOSH/OMSHR with engineering expertise, providing mine workers with the most thermally survivable refuge chambers possible. This objective was addressed by simulating thermally stressing conditions which could not be safely tested with real human subjects. Factors such as mine initial temperature, shelter type, and the number of occupants were varied in this work. The outcome of these studies is a series of predictions of the thermal environment within the refuge, and the associated human core temperature response to those conditions (core temperature can be considered an important survivability indicator in heat stress situations).

The models described in this document were developed using ThermoAnalytics' validated commercial heat transfer prediction code, RadTherm v10.3. Three different mine refuge shelters were modeled:

1. Rigid steel shelter with 14 people
2. 3.5' tall inflatable tent with 26 people
3. 5.5' tall inflatable tent with 36 people

The work was organized into six unique simulation studies, which are described in the next sections. Certain high-level observations can be drawn based on the overall outcome of this now-completed work. These observations are described in detail within the body of this report, and are summarized here:

- The analysis indicates that certain thermal conditions, known to occur underground, could cause extreme physiological stress to miners over a four-day period within a refuge chamber.
- The mine ribs, roof, and floor in close proximity to the occupied shelter do not behave as an infinite heat sink. Consequently, the type of material found in the seam, and the seam size, affect the thermal environment that miners experience.
- Air flowing through the mine at the location of the occupied shelter can significantly affect its temperature, either positively or negatively, depending on the temperature of the air.
- Increasing the thermal mass of the rigid shelter tends to keep the interior temperatures lower by absorbing more heat generated within the shelter.

Note: Significant conclusions are called out in bold text at the end of each section of this report.

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1.2 Task Description

Table 1 shows the six tasks defined for the project. While each task was relevant to the overall goals of the project, the tasks were not worked in numerical order. Tasks 1, 5, and 6 were completed first because they included creation of the baseline models, and answered questions about how to best model the interaction between the shelter and mine seam. The remaining tasks (2, 3, 4) involved modifying the baseline models and iterating to better understand how shelter material properties, mine environment, and air flow affected the shelter environment.

Section 2 of this report describes the work and assumptions that went into creating the baseline shelter models (Tasks 1, 5, 6). Section 3 describes the parametric studies that were done to expand the knowledge gleaned from the baseline models (Tasks 2, 3, 4)

Table 1 - Task descriptions

Detailed Requirements, by Task (from SOW)
Task 1: Examination of the heat transfer mechanisms associated with the occupation of mine refuge chambers including the heat generated by the occupants. Please note that the manpower estimate to meet this objective includes construction of two refuge models, development of the mine model itself and development of human occupant models.
Task 2: Sensitivity study of how material properties of refuge chamber constructions affect heat transfer, and trial optimizations of material properties
Task 3: Determination of how the mine environment, i.e. temperatures of the mine air and mine structure surfaces, impacts the thermal environment inside refuge chambers
Task 4: Analysis of how the ambient mine air affects the heat transfer from the chamber into the mine, including investigating how air flow and possible stratification (i.e. cold near floor and warm near roof) of the mine air affects the thermal environment inside refuge chambers
Task 5: Examination of the heat conduction path between the chamber and mine floor, including determination of the contact resistance between chamber/skid and ground, and subsequent effect on heat transfer from the structure into the mine floor
Task 6: Determination of whether the mine structure and/or mine air acts as an infinite heat sink, i.e. does thermal interaction with the chamber cause a significant rise in the temperature of mine structure and/or mine air

1.3 Heat Transfer Overview

There are three primary modes of heat transfer - conduction, convection, and radiation. Conduction is heat transfer within a solid object. Convection is heat transfer between a solid surface and an adjacent fluid (e.g. air). Thermal radiation is heat transfer between two solid objects by electromagnetic waves, mostly in the infrared wavelengths. All three heat transfer modes must be modeled along with the thermal interaction of the human occupants in order to accurately characterize the thermal behavior of a mine refuge chamber. Figure 1 shows a schematic detailing the heat transfer mechanisms associated with a mine refuge chamber. Heat is transferred within the shelter by conduction, convection, and radiation*. It is then transferred through the walls by conduction, and finally to the mine structure by conduction, convection, and radiation. This report will provide detailed descriptions of how these heat transfer mechanisms were modeled in order to characterize the thermal environment within mine refuge chambers and the effects on occupants.

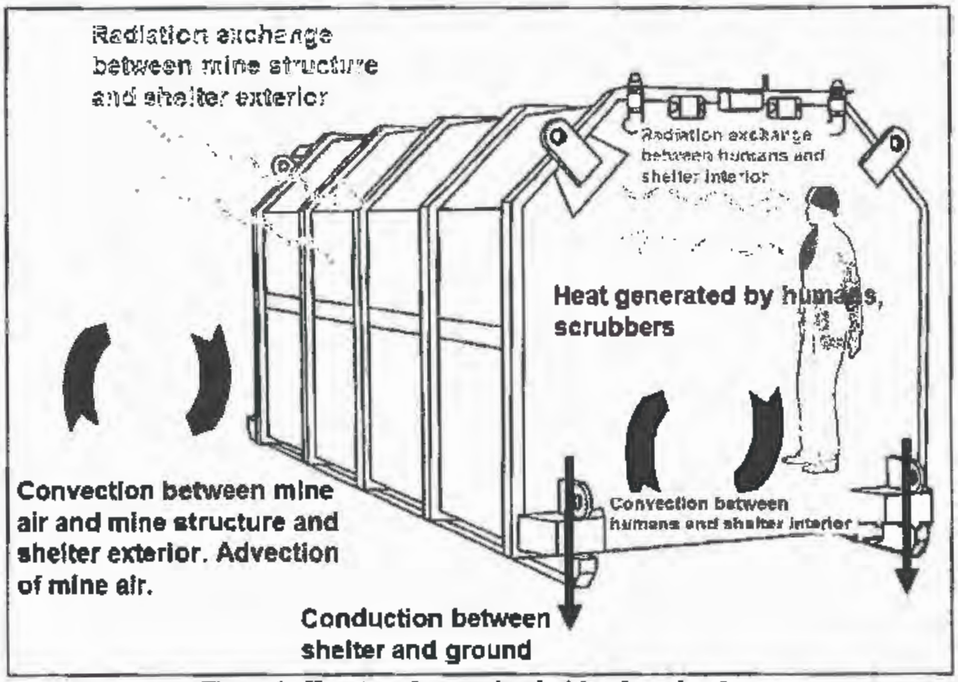

Figure 1 - Heat transfer associated with refuge chambers

Note: The heat loss from the human occupants was modeled to also account for the cooling effect of evaporation from sweat and respiration; however, the subsequent warming of the mine shelter walls due to condensation of that moisture was not considered in the current effort. Preliminary studies indicate that the inner surface temperatures of the shelter would be affected by this latent heat transfer. It is recommended that future studies be performed to quantify the resulting increase in temperature of the walls following their dewpoint being reached in order to assess the additional contribution to the sensible thermal load on the occupants.

2.0 Baseline Model Description

Three different mine refuge chambers were modeled for this project:

- Rigid steel shelter with 14 people
- 3.5' tall inflatable tent with 26 people
- 5.5' tall inflatable tent with 36 people

3D CAD geometry of the rigid steel refuge chamber and a 3.5' tall inflatable tent was received from Strata Products. TAI modified the geometry so that a finite element shell mesh could be applied. Also, the 26 person tent geometry was modified to create a 5.5' tall 36 person tent. The following sections describe the individual shelter thermal models, and the engineering assumptions that went into the baseline models.

2.1 Rigid Steel Shelter

Figure 2 shows the Strata Products steel refuge chamber. Figure 3 shows a wireframe view of the mesh representation of the steel refuge chamber. The mine seam geometry is represented with a shell element mesh. Thickness was modeled virtually with RadTherm "multi-layer" parts. The roof, ribs and floor were modeled as bituminous coal with a total thickness of 6', and discretized with 24 layers (each layer 3" thick). All models in Sections 2.1 through 2.6 used this mine configuration.

Figure 2 - Strata Products steel refuge chamber

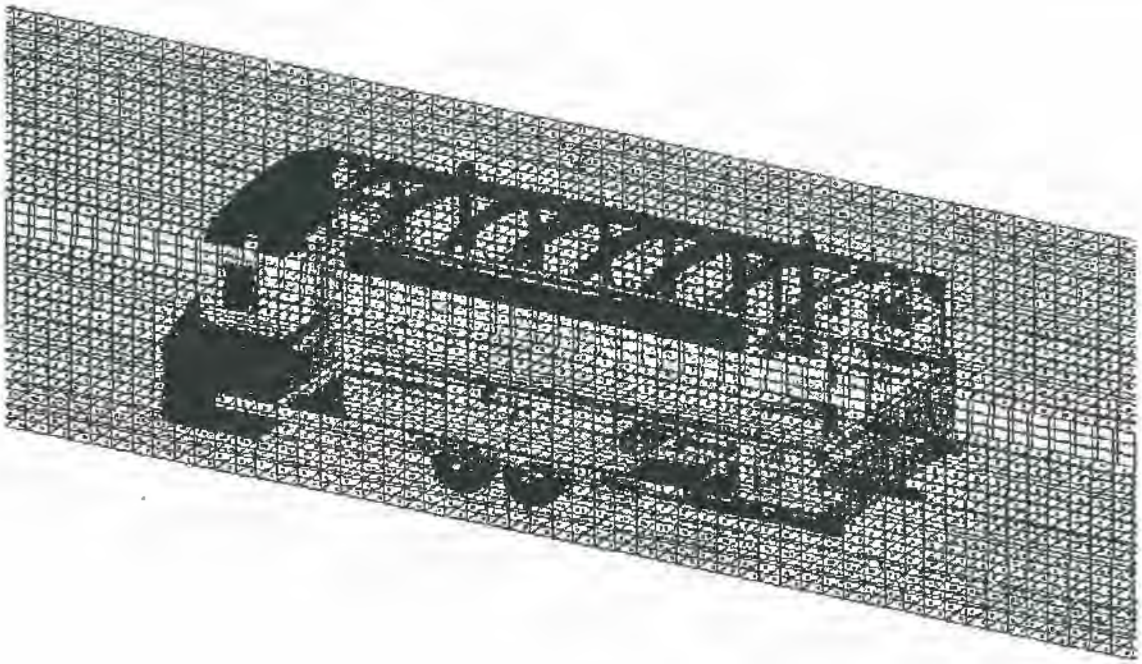

Figure 3 - Wireframe mesh view of the rigid shelter (green box represents coal seam)

Figure 4 shows a cut away view looking down on the rigid shelter. Fourteen humans were modeled (highlighted geometry). Figure 5 shows temperature results at the end of a 96 hour simulation where the initial mine ambient temperature was 75°F. The only heat sources are the humans and CO_2 scrubber.

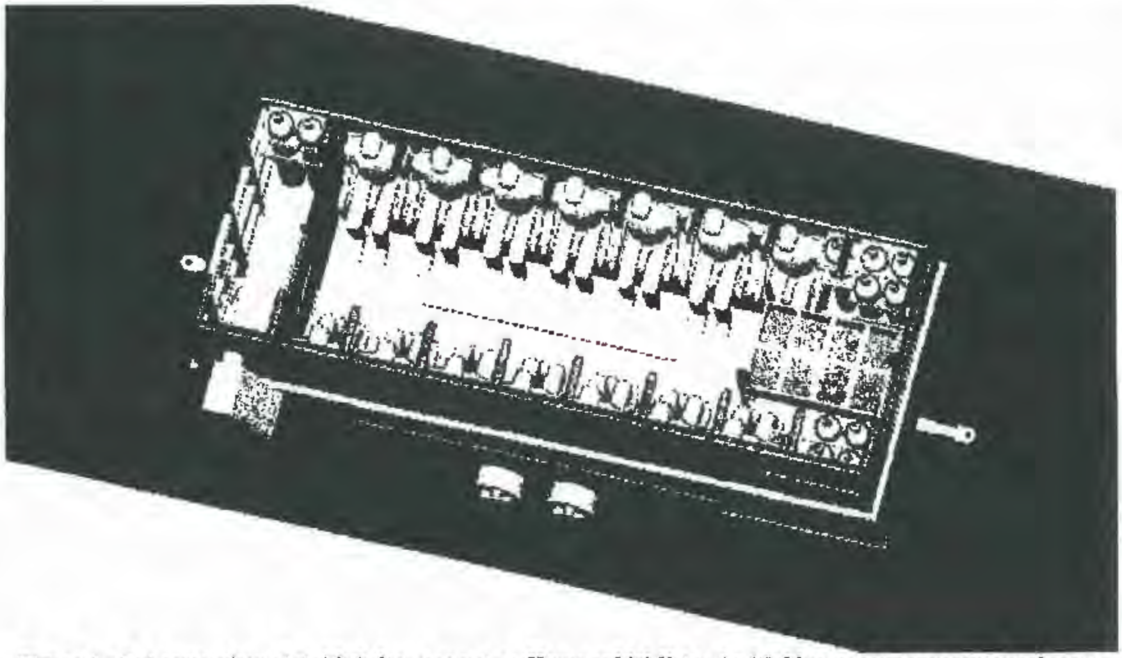

Figure 4 - Cut away view of rigid shelter geometry. Humans highlighted with blue, green represents coal seam.

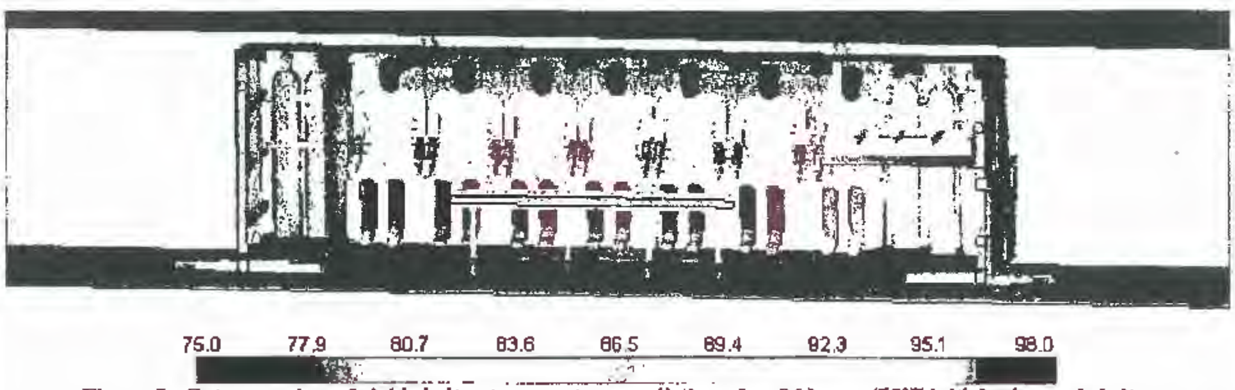

Figure 5 - Cut away view of rigid shelter temperature prediction after 96 hours (75°F initial mine and shelter temperature)

Table 2 summarizes the boundary conditions in the baseline rigid chamber model.

Table 2 - Rigid shelter boundary conditions

Shelter	Rigid Steel
Material:	A36 Steel
Shelter dimensions (LxWxH):	20.5' x 8.3' x 5.8'
Shelter weight (modeled):	~21000lbs
Thermal Emmisivity:	0.9
Conduction to mine:	None for wheeled shelter
Convection:	3 W/m²-K (Stagnant air - natural convection)
CO_2 Scrubber:	16.2 W per person applied to air in shelter
Mine Strata (roof, ribs, floor)	
Material:	Bituminous coal
Thickness:	6 ft (24 layers)
Surface Area:	2329 ft^2
Thermal Emissivity:	0.95
Humans	
Number of People:	14 (sitting on benches)
Average activity level (MET):	1.1
Clothing:	t-shirt and boxer shorts
Contact Resistance:	0.01 m^2-K/W (legs to bench)

2.2 26 and 36 Person Inflatable Tent

The 26 and 36 person inflatable tents were modeled in the same manner as the rigid steel chamber. Table 3 summarizes the boundary conditions for the baseline tent models. Figure 6 shows a wireframe view of the 26 person tent. The 26 person tent model consists of 44,164 shell elements, while the 36 person tent model has 51,997 shell elements. Figure 7 shows a cut away view of the 26 person tent, and Figure 8 shows a similar view of the 36 person tent. The occupants were positioned lying on the floor in the 26 person tent due to the limited height. A mix of sitting and lying occupants were modeled in the 36 person tent.

Table 3 - Inflatable tent boundary conditions

Shelter	26 man inflatable tent	36 man inflatable tent
Material:	Tent: Polyurethane Case: A36 Steel	Tent: Polyurethane Case: A36 Steel
Shelter dimensions (LxWxH):	29' x 12.4' x 3.5'	32.3' x 12.4' x 5.5'
Shelter weight (modeled):	~170lbs (tent only)	~210lbs (tent only)
Thermal Emissivity:	0.9	0.9
Conduction to mine:	0.01 m^2-K/W contact resistance (tent to mine floor)	0.01 m^2-K/W contact resistance (tent to mine floor)
Convection:	3 W/m^2-K (Stagnant air - natural convection)	3 W/m^2-K (Stagnant air - natural convection)
CO_2 Scrubber:	16.2 W per person applied to air in shelter	16.2 W per person applied to air in shelter
Mine Strata (roof, ribs, floor)		
Material:	Bituminous coal	Bituminous coal
Thickness:	6 ft (24 layers)	6 ft (24 layers)
Surface Area:	4323 ft^2	5986 ft^2
Thermal Emissivity:	0.95	0.95
Humans		
Number of People:	26 (laying on floor)	36 (7 laying on floor, 29 sitting on floor)
Average activity level (MET):	1.1	1.1
Clothing:	t-shirt and boxer shorts	t-shirt and boxer shorts
Contact Resistance:	0.01 m^2-K/W (legs, torso, arms, and head to floor)	0.01 m^2-K/W (legs, torso, arms, and head to floor)

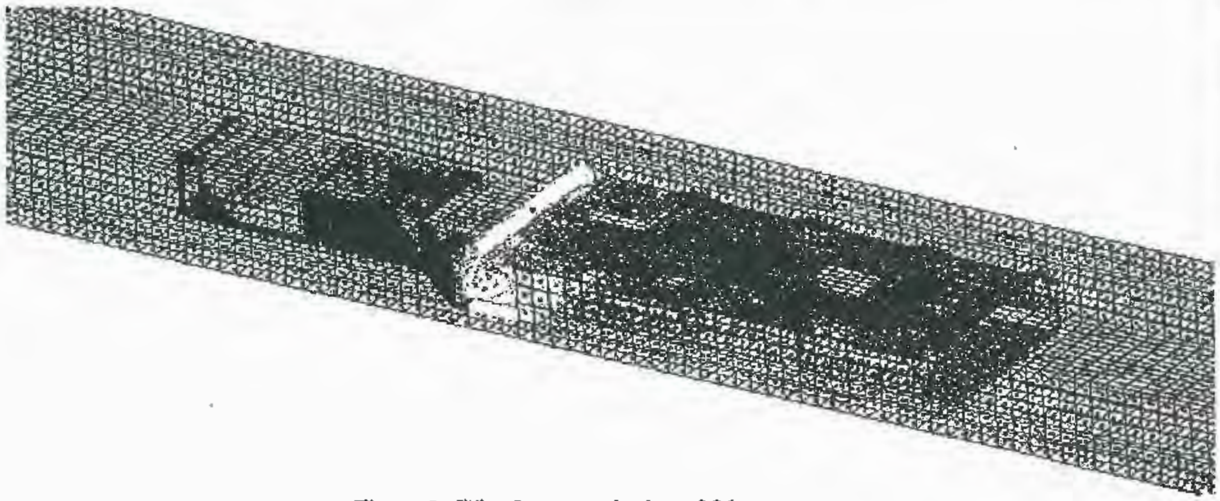

Figure 6 - Wire frame mesh view of 26 person tent

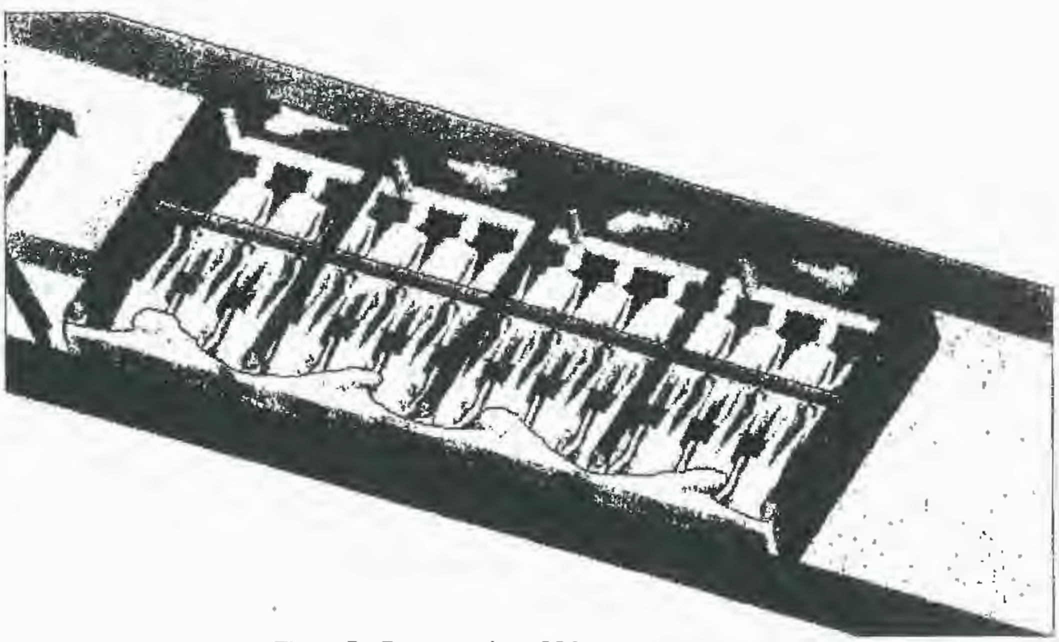

Figure 7 - Cut away view of 26 person tent geometry

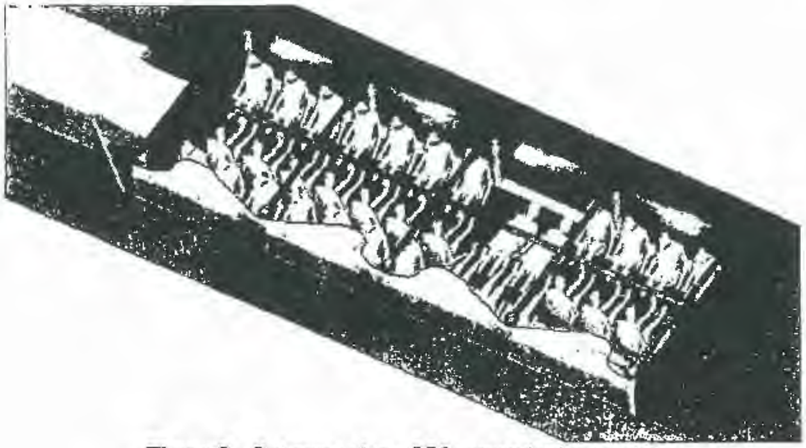

Figure 8 - Cut away view of 36 person tent geometry

Figure 9 shows a cut away view of the 36 person inflatable tent with surface temperatures after 56 simulated hours. 56 hours is when the average occupant core (rectal) temperature reached 101.3°F, which is the compensated heat stress limit. The initial mine temperature was 75°F.

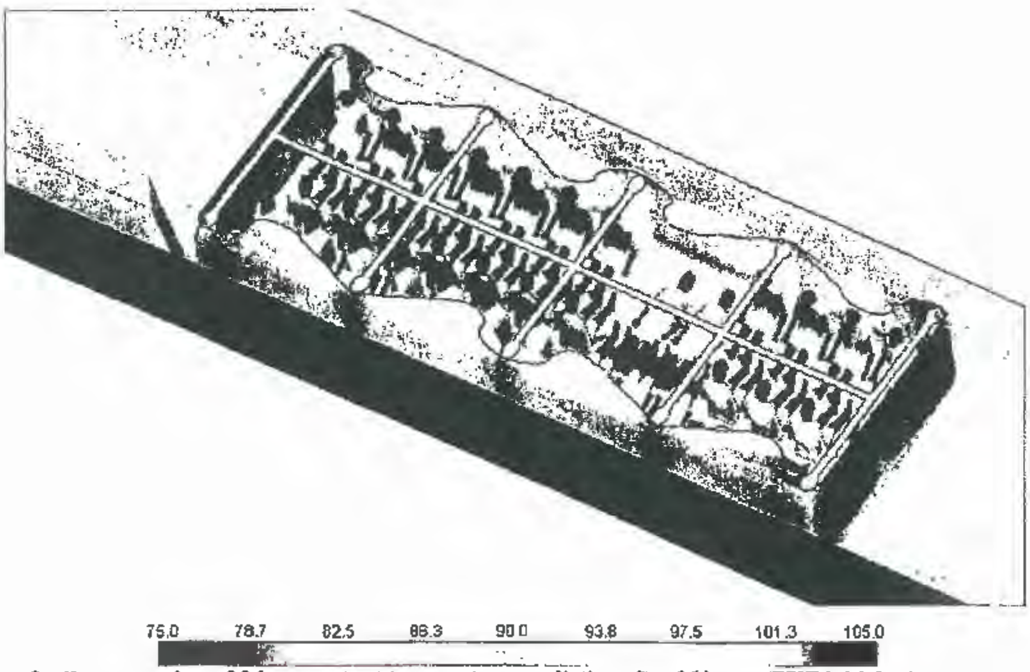

Figure 9 - Cut away view of 36 person tent temperature prediction after 96 hours (75°F initial mine temperature)

2.3 Human Thermal Modeling

RadTherm's human thermoregulation model was used to simulate the heat generated by the shelter occupants, and to determine the miner's skin and core temperatures. Thermoregulation is the process by which the body attempts to maintain a constant core temperature, and includes shivering, sweating and changes in skin blood flow. Segmented thermoregulation models are the most accurate way to predict the body's core temperature when subjected to transient, asymmetric environments. The thermoregulation model calculates tissue temperatures for a human body as described by a surface mesh. A surface mesh is essential to the accurate calculation and application of non-uniform boundary conditions (radiation, conduction and convection) present in a mine refuge shelter.

The human thermal module in RadTherm is based on a complex physiological model in which the body is divided into 20 segments (face, head, neck, chest, right and left shoulders, etc) [3,4,5]. As Figure 10 shows, the model accounts for metabolic heating, shivering, sweating, respiration, and vasomotion. The model uses multilayer parts to characterize the transport of heat and moisture through tissue and clothing layers. Clothing is defined by its thermal resistance, evaporative resistance, and local clothing area factor. By solving the bio-heat transfer equation, the model predicts skin, tissue, blood, and body core temperatures based on environmental conditions, clothing, and activity level.

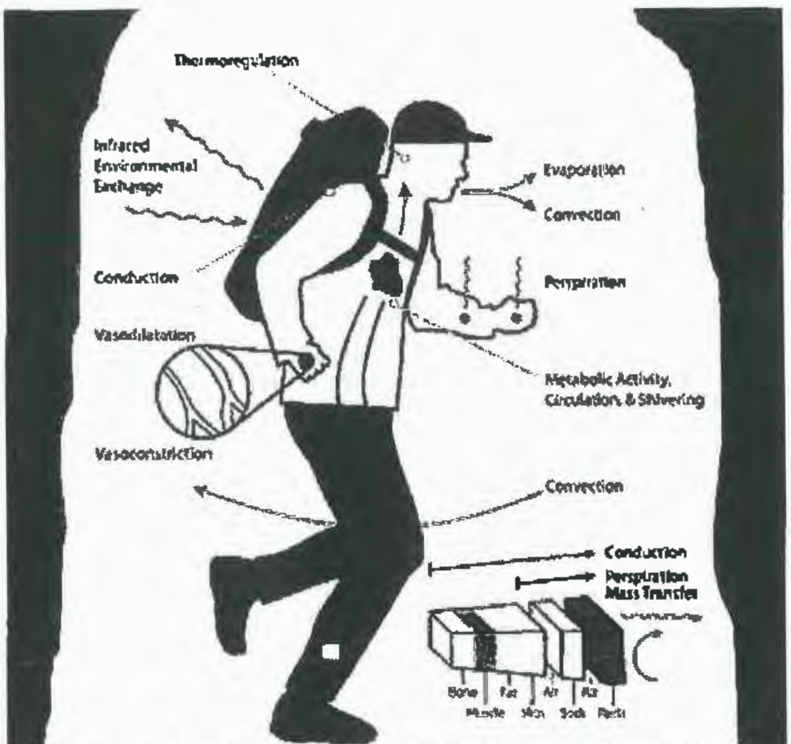

Figure 10 - Human Thermoregulation Modeling in RadTherm

An important determinant in the amount of heat generated by humans is their activity level. In a refuge chamber, the occupants will spend most of their time inactive but there will be periods of activity such as maintaining the CO_2 scrubbers, eating, etc. Activity level is commonly specified in metabolic units, met. 1 met = 58.1 W/m^2 where the area is the total skin surface area. An activity level of 1.1 met was used for this analysis. An activity level of 1.0 corresponds to sitting, awake [2]. An activity level of 1.2 corresponds to standing, or light activity while sitting. The RadTherm human model takes activity level as an input, but the metabolic heat rate is a variable that will increase as the human's core temperature rises above the set point.

The standard adult male defined by Fiala [3, 4] was used in the simulations. This corresponds to a 162lb man with 14% body fat, and closely matches a 50th percentile European male.

In conditions of high heat stress, the body's core temperature provides the "best" single physiological measure to predict the onset of heat-related medical conditions. For example, military training guidelines for work-rest cycles are based on achieving core temperatures of no more than 101.3°F for "compensated heat stress." Core temperature below these levels can be sustained with "few" persons incurring exhaustion from heat strain. "Compensated heat stress" exists when heat loss occurs at a rate in balance with heat production so that a steady-state (internal body) core temperature can be achieved at a sustainable level for a requisite activity [1]. A core temperature above 101.3°F is indicative of hyperthermia; higher core temperatures (approximately 104°F) signal the onset of heat stroke.

The 101.3°F core temperature safety limit for uncompensated heat stress is commonly employed in experimentation involving human subjects. This value is listed in the US Army and Air Force Technical Bulletin entitled: "Heat Stress Control and Heat Casualty Management" [1]. The compensated heat stress limit is typically used in the context of human simulation because, a) the environment is inherently controlled; and b) there is no danger to actual human subjects [6].

2.4 Humidity Modeling

The chambers were initially modeled with constant 90% and 100% interior relative humidity. Figure 11 shows a plot of the interior air temperature and average human core temperature for the 26 person tent. The initial mine temperature was 70°F. Constant relative humidity of 90% and 100% was modeled. At the higher relative humidity, sweating is less effective which eventually causes their core temperature to rise. Moisture content of the air inside a refuge chamber has a significant effect on the thermal comfort of the occupants.

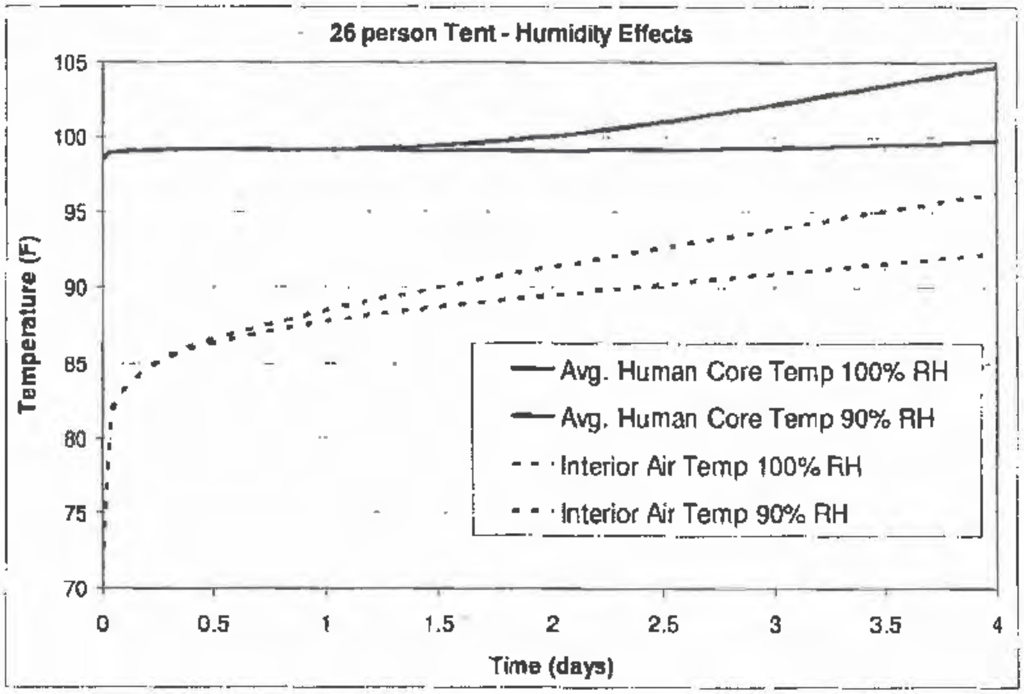

Figure 11 - Tent interior air temperature with constant 90% and 100% relative humidity (70°F initial mine temperature)

The sensitivity of the humans to humidity level suggested that it is necessary to know the humidity level inside of the refuge chambers. A custom RadTherm script was developed to model the transient changes to the absolute humidity inside the shelter so that the correct relative humidity could be applied as a boundary condition for proper respiration and sweat evaporation modeling. The inputs to the model are the shelter dimensions, ambient air pressure, and initial relative humidity. The script accounts for respiration, sweat evaporation, latent heat delivery rate provided per person by the scrubber (11.3 W) and the dry air delivery rate provided by the bottled air. The exfiltrated air mass flow rate is computed based on the dry air delivery rate and the current humidity ratio of the shelter. The bottled air mass flow rate delivery rate is approximated as a constant value based on a nominal bottled air pressure of 20MPa (typical of a 5 liter steel bottle).

Figure 12 shows predicted relative humidity in the 26 person tent. Initial temperature in the tent and mine was set to 70°F, and initial humidity was set to 40%. The model predicted the humidity to rise to 100% in 18.5 minutes. Based on this result, relative humidity was assumed to be constant 100% in subsequent models.

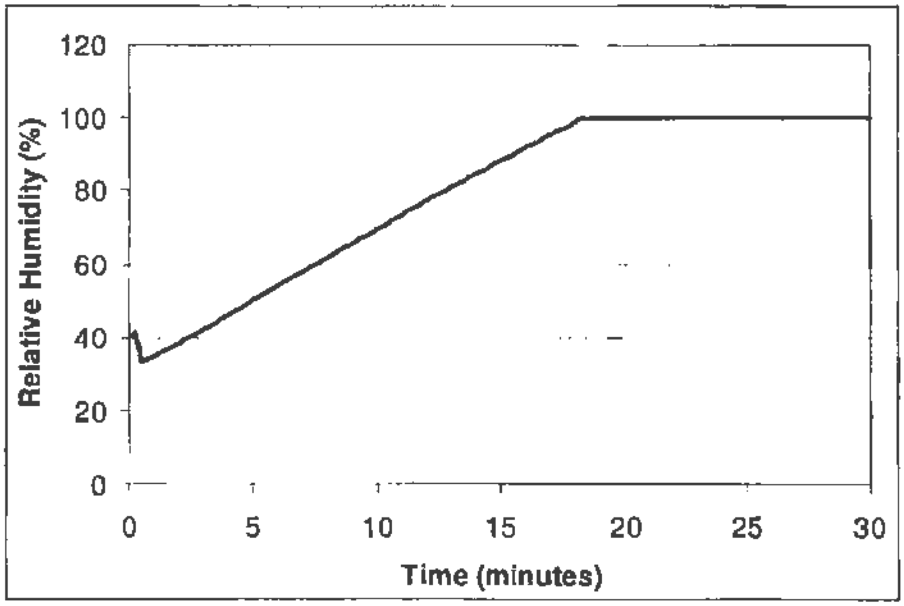

Figure 12 - Predicted interior relative humidity vs. time for 26 person tent (70°F initial mine temperature, 40% initial RH)

****Note: The humidity model described above accounted for sweat evaporation from the people, moisture output by the CO_2 scrubber, and moisture transport from the shelter. It did not account for condensation on the walls of the shelter. The relative humidity inside of the shelter may not reach 100% if some of the evaporated moisture condensed on the shelter walls.***

2.5 Coal Seam Modeling (Task 6)

Previous analyses have assumed that the mine acted like an infinite heat sink [7]. RadTherm allowed for a detailed thermal model of the mine roof, ribs and floor to test the infinite heat sink assumption. Figure 13 shows the predicted interior air temperature in the steel chamber when the thermal mass of the coal is taken into account versus when an infinite heat sink is assumed. When an infinite heat sink is assumed (pink plot), the temperature of the chamber interior air rises to a steady state value as the shelter heats up. When the temperature of the coal is calculated (blue plot), the temperature of the interior air rises as the shelter and surrounding coal absorb the heat generated by the humans.

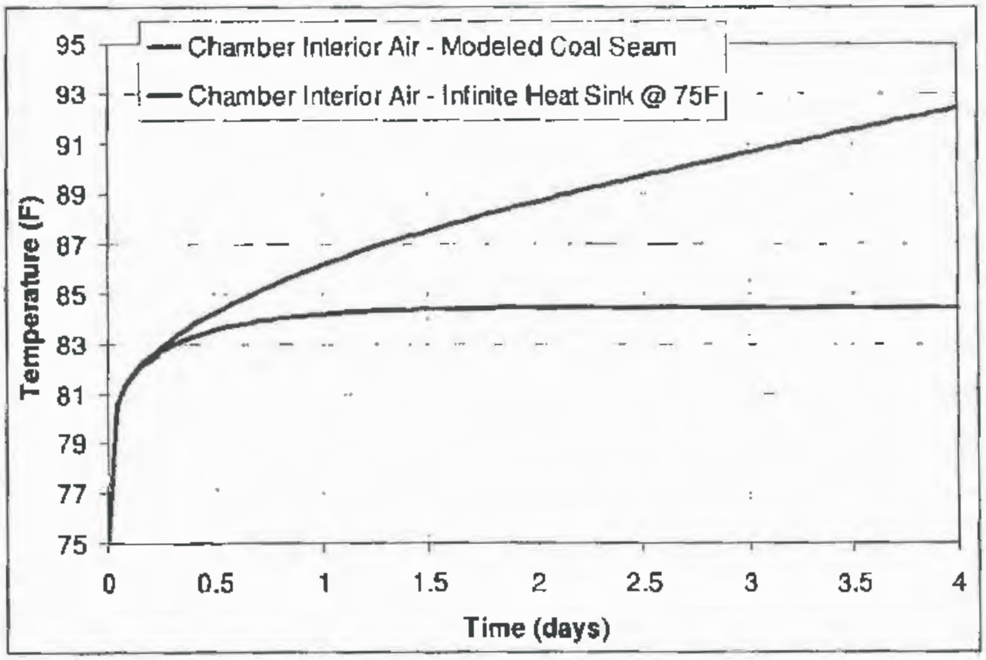

Figure 13 - Rigid shelter interior air temperature plots for calculated coal temperature and infinite heat sink assumption (75°F initial mine temperature)

Figure 14 shows a similar plot for the 26 person tent. The tent interior air reaches a steady state value much quicker than for the rigid shelter when an infinite heat sink is assumed. This is because the tent has very little thermal mass. The tent heats up very quickly when the occupants and scrubber start adding heat. The conclusion drawn from these results is that it is necessary to predict the temperature of the mine strata and account for its thermal mass. An infinite heat sink assumption would result in an 8°F error for the rigid shelter interior air temperature and a 15°F error for the inflatable tent interior air.

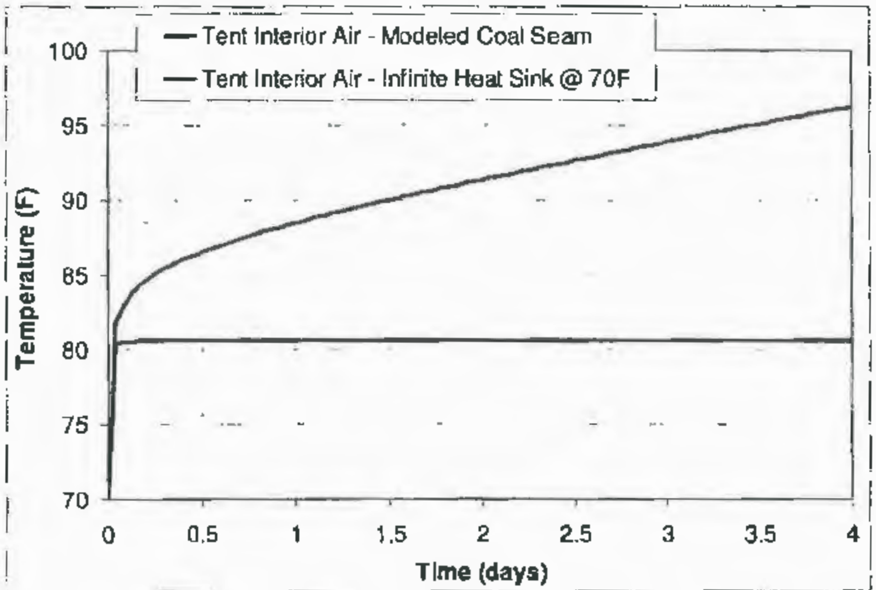

Figure 14 - Tent interior air temperature plots for predicted coal temperature, and infinite heat sink assumption (26 person tent, 70°F initial mine temperature)

The mine seam geometry was modeled a few different ways to determine the effect on shelter temperatures. Figure 15 shows two mine geometries side by side. The rigid shelter was initially modeled with rough surface geometry and steel plates on the mine ceiling. The seam model was changed to a smooth box, without steel roof bolt plates, and the results were very similar. Results in the rest of the report came from models with a smooth box seam without roof plates, for all three shelter variants.

RadTherm models surfaces using a thin shell mesh, but thickness is assigned to the mesh and modeled virtually. The mine strata was modeled as 6' thick for all models in this report. The roof, rib and floor thicknesses were initially varied to determine the effect of thickness, but 6' was determined to be enough to accurately account for the thermal behavior of the mine.

Figure 15 - Bumpy and smooth coal seam geometry

Bituminous coal was used for the baseline shelter analysis because it has the lowest thermal conductivity among typical coals, and is also the most commonly mined coal in the United States. Low thermal conductivity is worst case because less heat gets conducted into the coal and away from the refuge chamber. The thickness of coal was initially varied, but a total thickness of six feet was chosen. The total 6' depth was modeled as 24 three inch layers. This was done so that the temperature gradient into the depth of the coal could be captured. Figure 16 shows a plot of temperature vs. depth for three different locations around the 26 person tent. For this case, the heat generated inside of the tent that is transferred to the mine strata penetrates about three feet into the coal over the course of 96 hours.

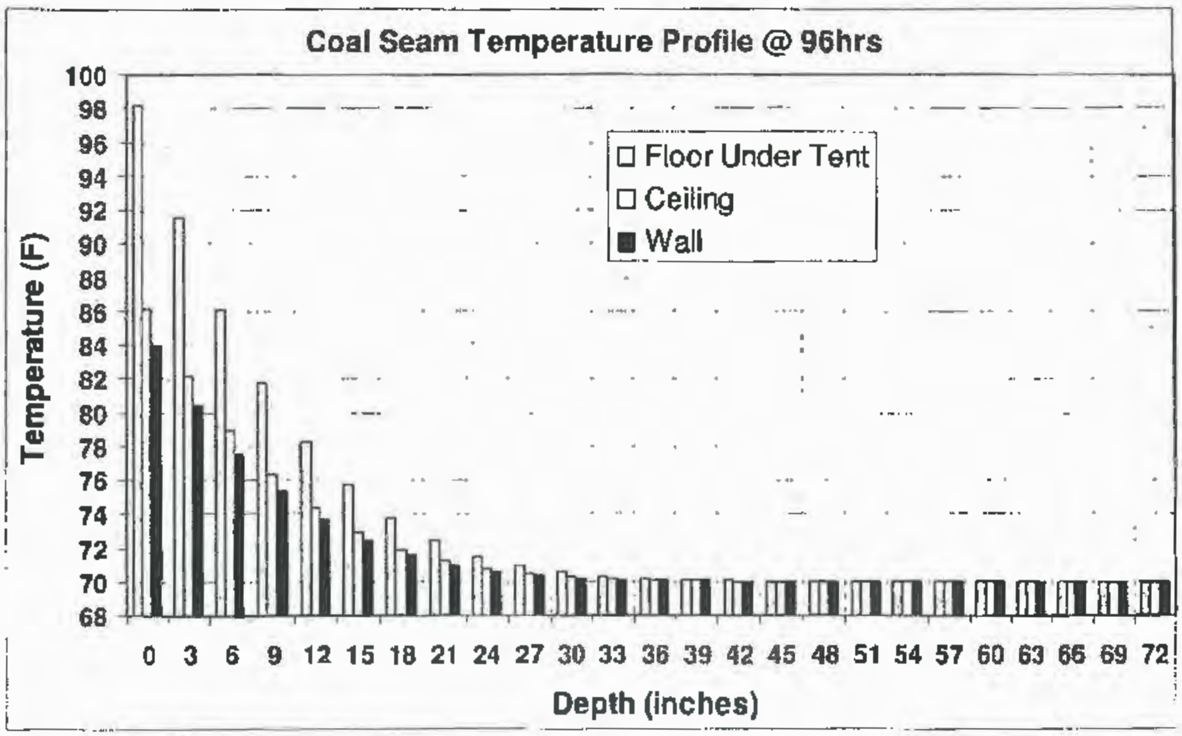

Figure 16 - Temperature profile through the depth of the coal at various locations (Bituminous coal, 26 person tent, 70°F initial mine temperature)

Section 2.5 Conclusions: It is necessary to account for the thermal mass and conductivity of the mine strata, as it does not behave like an infinite heat sink.

2.6 Air Stratification (Task 4)

The results shown in previous sections came from models where the air outside of the shelter was assumed to be uniform temperature (no air stratification). These models used RadTherm to predict the uniform air temperature in the mine. It is likely that the air in the mine will become stratified as the shelter and mine environment heat up, especially if there is no air flow through the mine. The effect of air stratification was studied using RadTherm coupled with a StarCCM+ computational fluid dynamics (CFD) model.

Figure 17 shows how RadTherm interacts with the CFD model for a coupled solution. The CFD model predicts convection coefficients on the shelter and mine surfaces, and mine air temperatures. The RadTherm model accounts for heating due to the occupants and scrubber, conduction, and radiation. Data is passed back and forth between the two models in an iterative loop. The result of the coupled simulation is shown in Figure 18. After 96 hours, there was approximately a 5°F temperature difference from the floor to the ceiling of the mine.

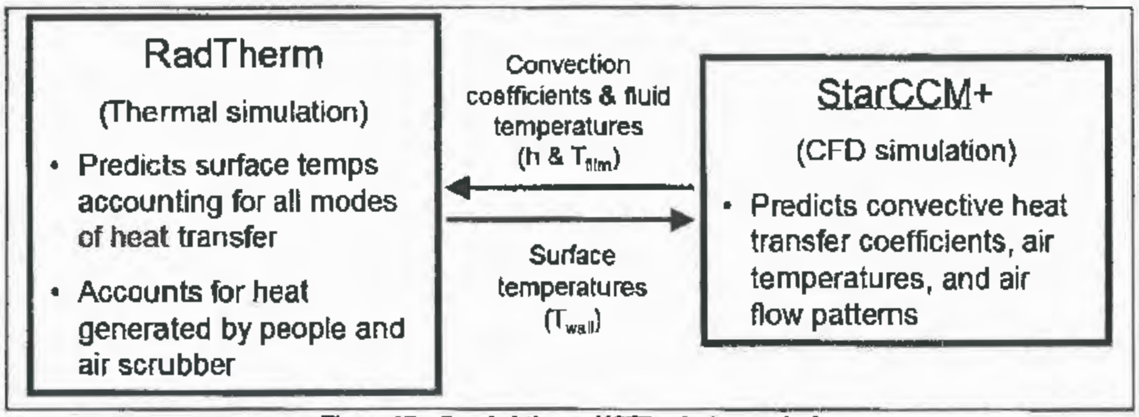

Figure 17 - Coupled thermal/CFD solution method

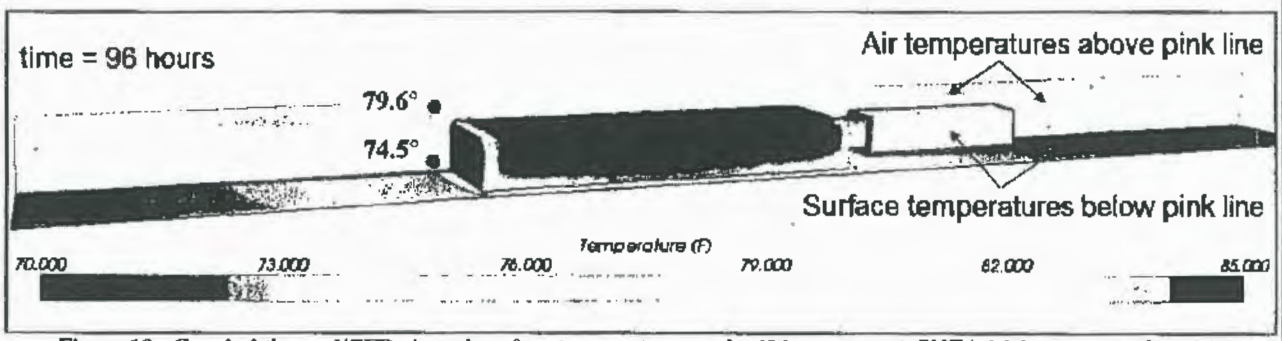

Figure 18 - Coupled thermal/CFD air and surface temperature results (26 person tent, 70°F initial, stagnant mine air)

Figure 19 shows a transient temperature plot comparing the coupled model to the RadTherm-only (no CFD) model. After 96 hours the RadTherm-only model under-predicts the tent interior air temperature by 0.9°F, when compared to the coupled model. The coupled model predicted higher air temperatures near the shelter, while the RadTherm-only model spread the heat throughout the entire mine seam volume. However, the small increase in accuracy did not justify using the more complicated and time consuming coupled model for the rest of the analyses.

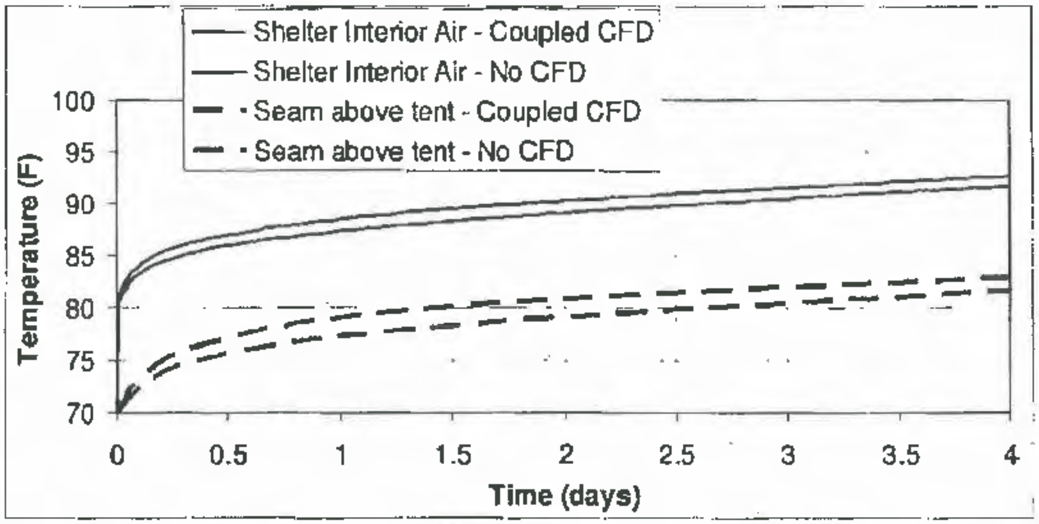

Figure 19 - Comparison of results between coupled CFD solution and simplified RadTherm solution (no CFD)

Section 2.6 Conclusions: Neglecting air stratification causes a shelter air temperature under-prediction of less than 1°F.

3.0 Parametric Analyses

Several parametric analyses were performed to better understand how different boundary conditions affect the refuge chamber environment. Mine strata material, mine seam size, contact resistance between the shelter and mine floor, mine ambient temperature, mine air flow, and mine shelter materials were all varied.

3.1 Mine Strata Material and Seam Size Study (Task 6)

A uniform bituminous coal seam was assumed in the baseline models described in Section 2 because it was worst case. A range of common coal mine materials were examined for task 6. Table 4 shows the mine seam materials that were examined.

Table 4 - Thermal properties of common coal mine strata materials

	Anthracite Coal	Bituminous Coal	Limestone	Sandstone
Conductivity (W/m-K)	0.49	0.33	1.3	2.3
Specific Heat (J/kg-K)	1260	1380	908	920
Density (kg/m3)	1506	1346	2300	2300

Figure 20 shows the temperature into the depth of the rock below the 26 person tent, for different mine strata compositions. For the bituminous/limestone case, the mine floor was modeled with 3" of bituminous coal then limestone for the rest of the 72" depth (same is true for Anthracite/Sandstone). The surface temperature was lowest for the anthracite/sandstone floor because sandstone has the highest conductivity which allows the heat to diffuse into the rock. Figure 21 shows a transient temperature plot for the same four cases.

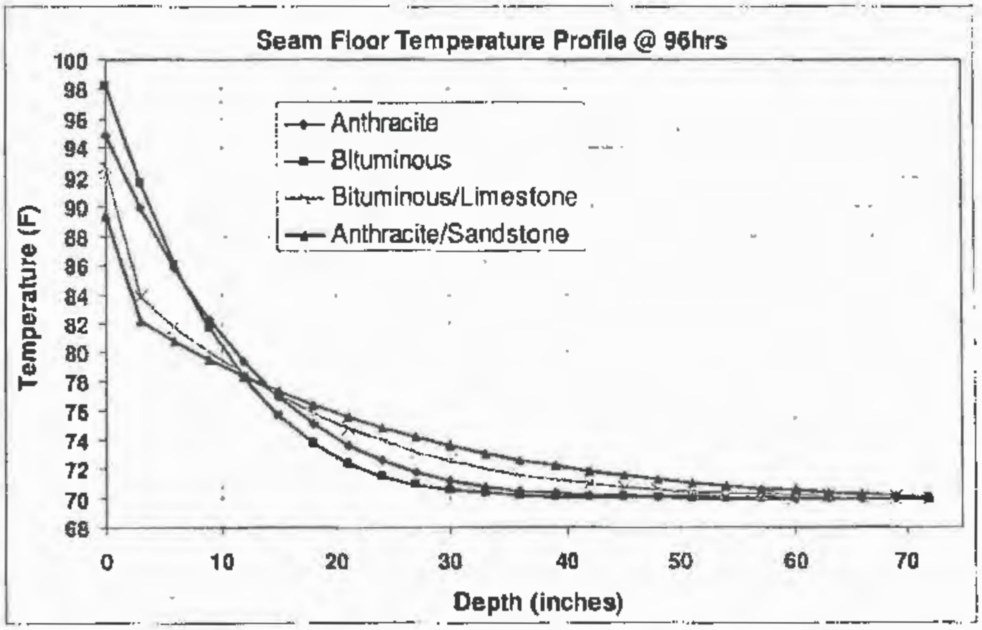

Figure 20 - Temperature profile through the depth for different mine strata compositions (70°F initial mine temperature)

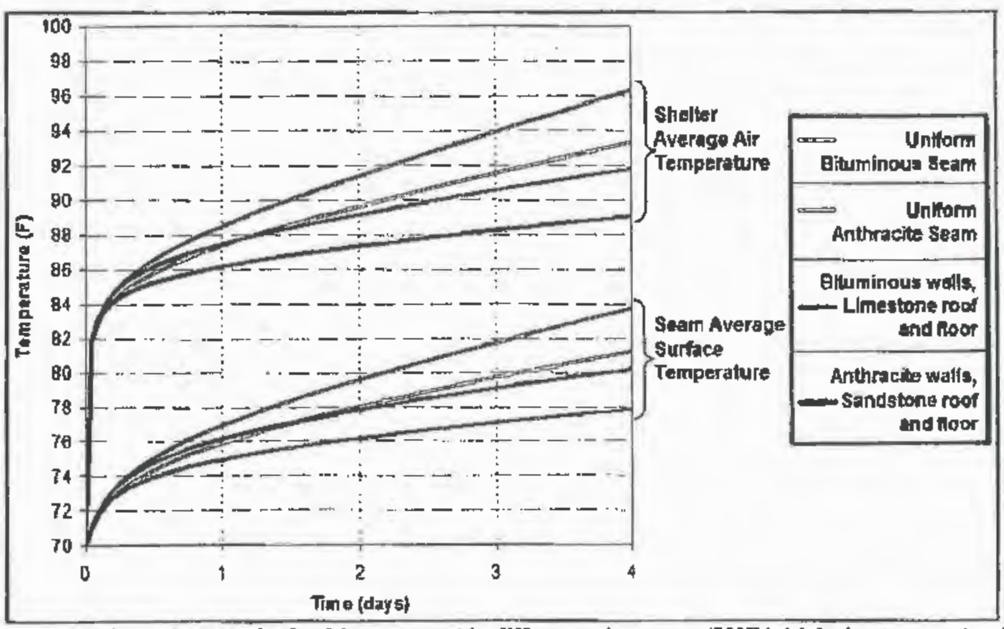

Figure 21 - Transient results for 26 person tent in different mine seams (70°F initial mine temperature)

Figure 22 shows the effects of varying the size of the coal seam. A mine seam with a larger volume will take longer to heat up because more rock surface area is available to absorb heat.

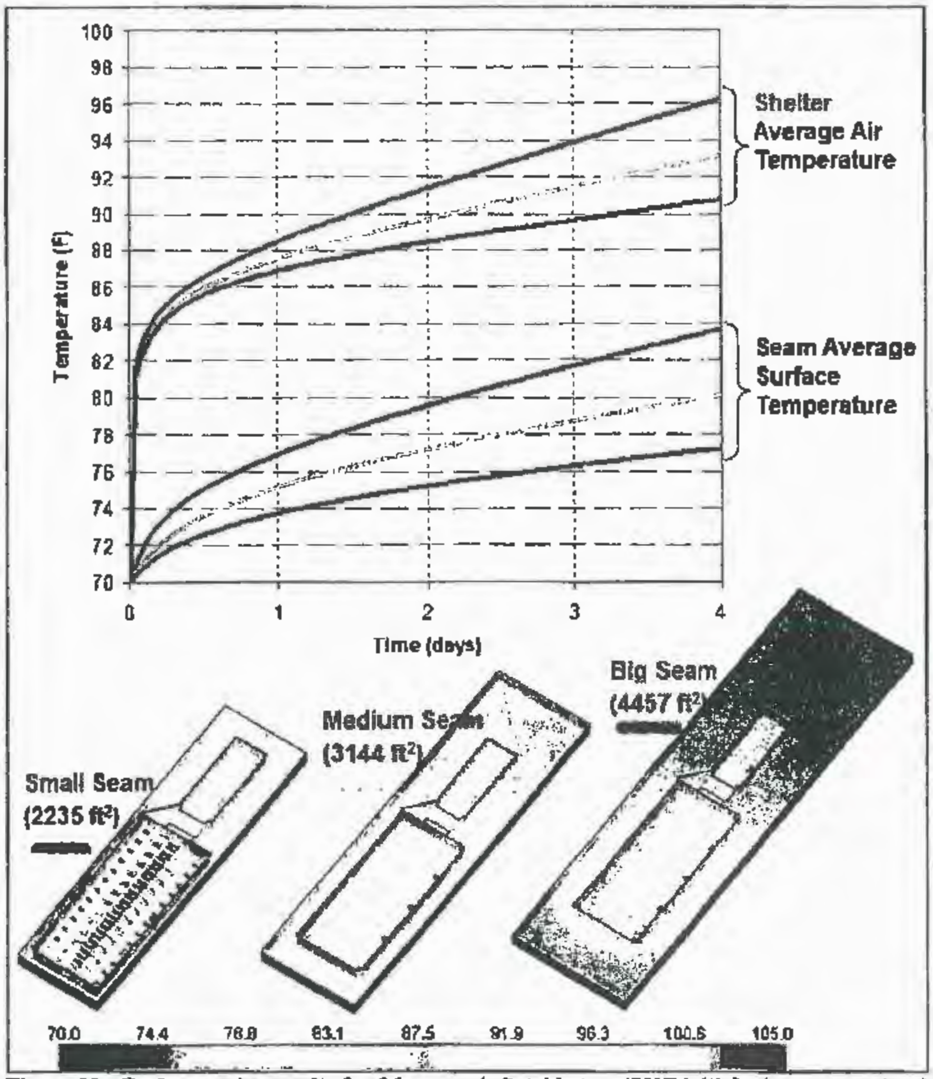

Figure 22 - Coal seam size results for 26 person inflatable tent (70°F initial mine temperature)

Section 3.1 Conclusions: A mine strata consisting of rock with higher thermal conductivity will keep the mine shelter cooler than rock with low thermal conductivity. Also, a larger mine seam will keep the shelter cooler than a small mine seam.

3.2 Mine Ambient Temperature Study (Task 3)

As shown in the task 6 results (section 3.1), the mine environment can have a significant impact on the temperature inside of a refuge chamber. The purpose of Task 3 was to determine how the ambient mine environment affects the refuge chamber environment. All three shelters were modeled in a uniform bituminous coal seam with stagnant air. The initial (ambient) temperature of the mine and shelter were varied. Table 5 summarizes the conditions that were modeled, and the results for each condition. The "Time to reach heat stress" column gives the amount of time predicted for the average human core temperature to reach 101.3°F. The core temperatures (rectal temperature) of all occupants were averaged.

Table 5 - Mine ambient temperature study summary

Shelter	Initial Temperature (mine ambient, F)	Max Shelter Air Temperature (F)	Time to reach Heat stress (days)
Rigid - 14 people	60	80.4	4+
	65	82.9	4+
	70	85.7	4+
	75	89.1	4+
	80	94.0	2.6
Tent - 26 people	60	84.7	4+
	65	87.4	4+
	70	91.7	4+
	75	97.7	1.4
	80	104.7	0.4
Tent - 36 people	60	85.3	4+
	65	88.2	4+
	70	93.0	3.5
	75	99.3	1.0
	80	106.7	0.3

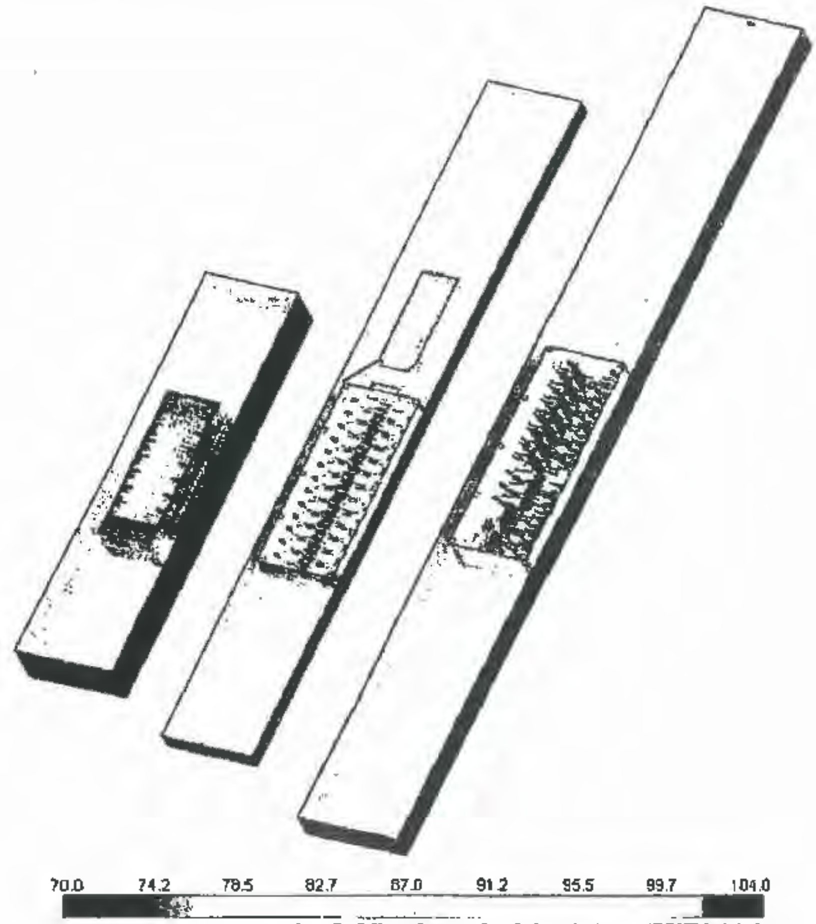

Figure 23 - Surface temperature results @ 96hrs for each of the shelters (75°F initial temperature)

Figure 23 shows surface temperature results for the three shelters after 96 hours. It also shows the relative size of the mine seam for each of the three shelters. The mine seam was scaled so that the mine seam surface area per person would be the same for each model. Section 3.1 showed that the size of the mine seam has a significant effect on the shelter interior because of the thermal mass of the mine rock. Keeping the mine surface area per person constant between the three shelters makes the results more comparable.

Figure 24, Figure 25, and Figure 26 show transient plots of occupant core temperature and shelter interior air temperature for the three shelters. For a given initial temperature, the rigid steel shelter kept its occupants under the heat stress limit longer than either of the inflatable tents. The main reason for the rigid shelter providing a safer thermal environment is its thermal mass. The heavy steel construction of the rigid shelter means it has a lot of thermal mass, which takes longer to heat up than a lightweight tent.

The core temperature plot for the 80°F case in Figure 24 has a steep slope because the shelter environment reaches a temperature where the occupants are no longer able to get rid of excess body heat.

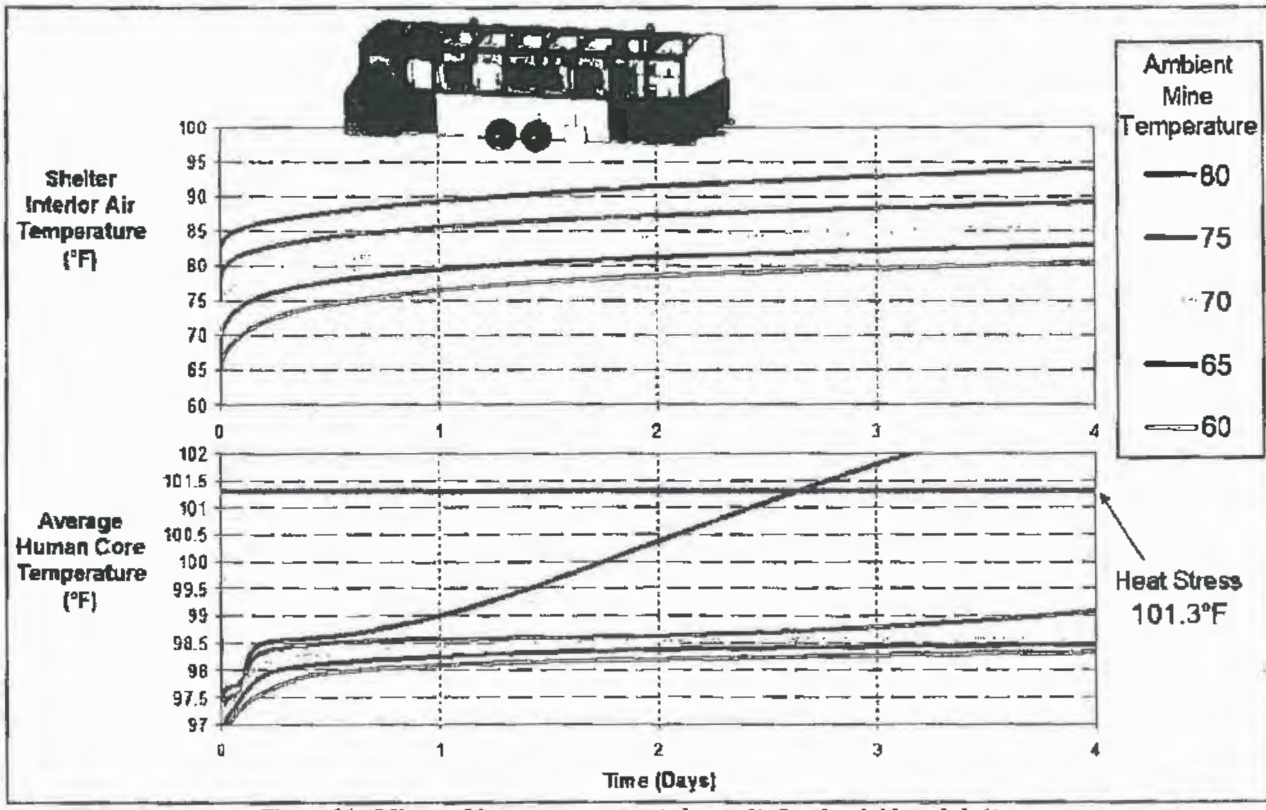

Figure 24 - Mine ambient temperature study results for the rigid steel shelter

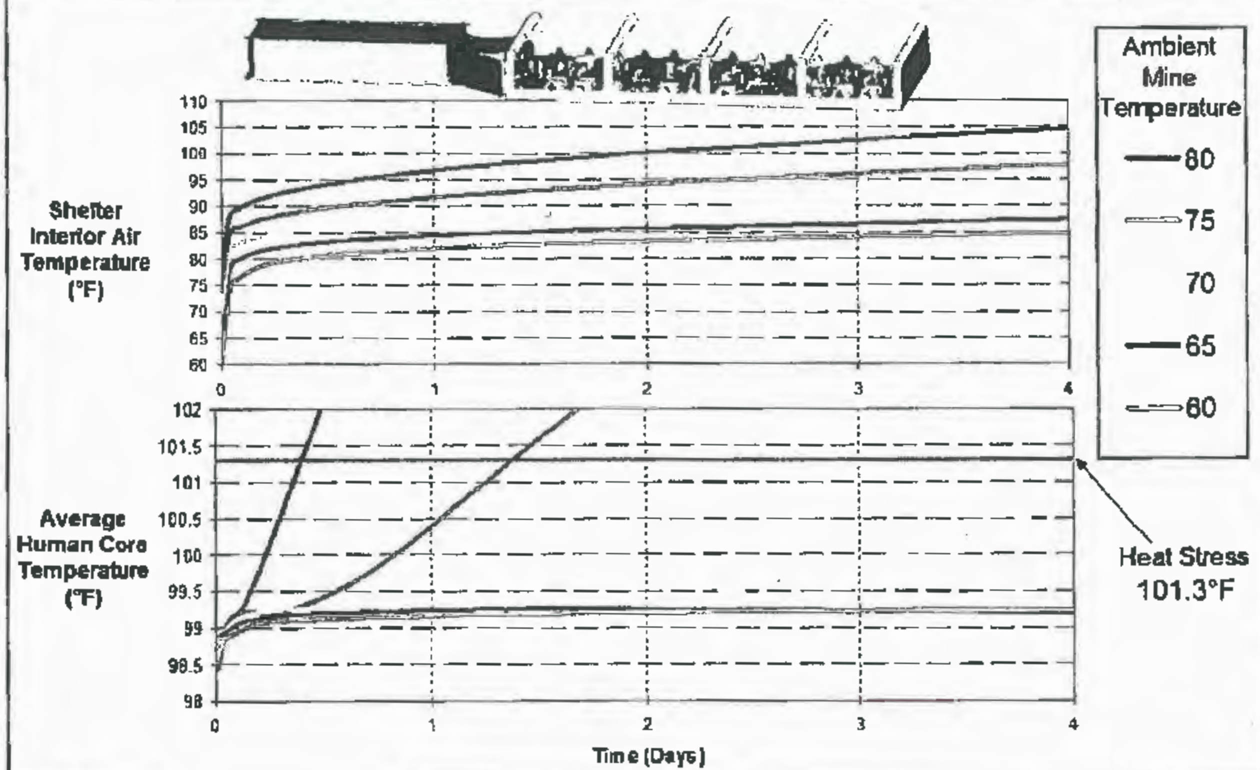

Figure 25 - Mine ambient temperature study results for the 26 person inflatable tent

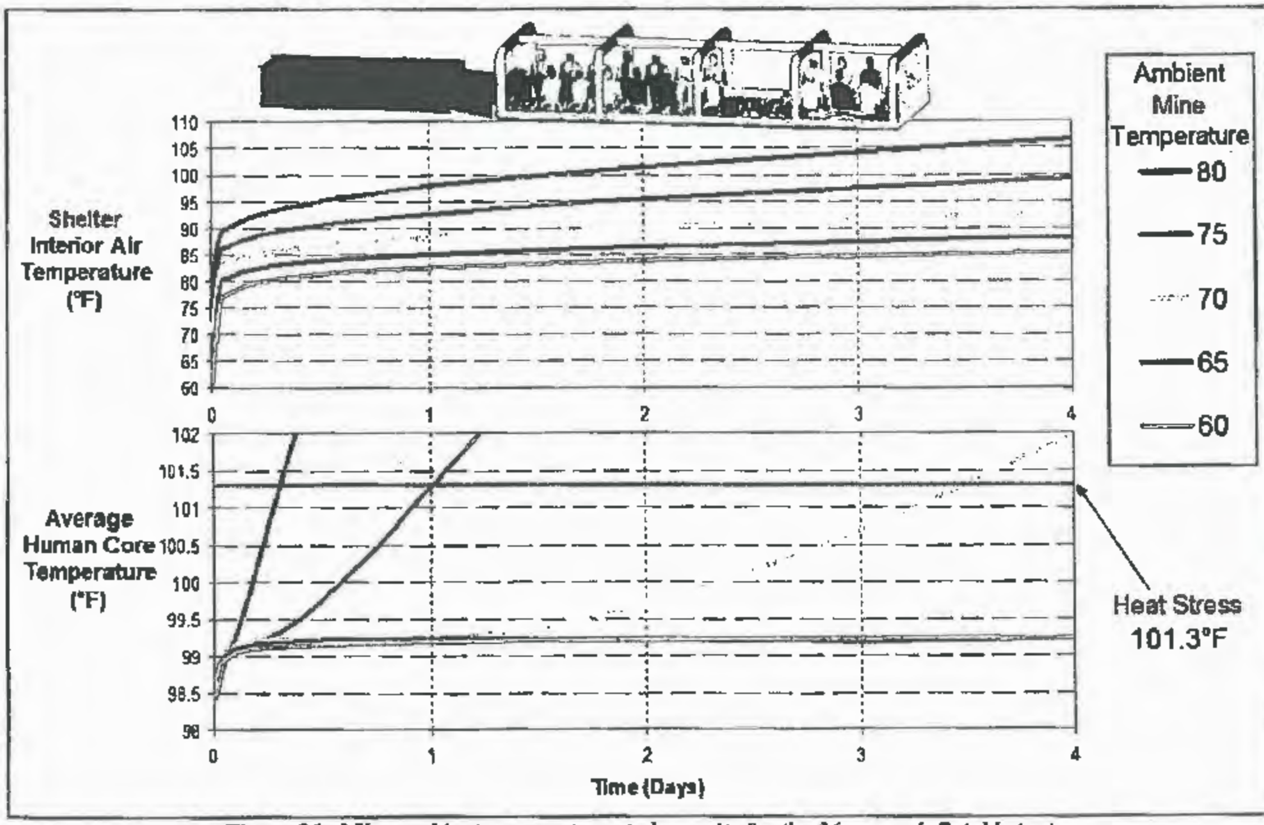

Figure 26 - Mine ambient temperature study results for the 36 person inflatable tent

Section 3.2 Conclusions: Ambient mine temperatures greater than 70°F may cause extreme physiological stress to the shelter occupants. The rigid steel shelter was predicted to maintain a cooler thermal environment than either of the inflatable tents.

3.3 Mine Shelter Conduction Study (Task 5)

Conduction from the bottom of the shelter to the mine floor can account for a significant portion of the heat loss. Modeling the conduction in RadTherm requires knowledge of the contact resistance between the shelter and mine. The purpose of task 5 was to quantify the contact resistance and run the model with a realistic range of values. Table 6 summarizes the contact resistances that were used for the 26 person tent. A contact resistance of 0.01 m^2-K/W was used in the baseline models (nominal resistance in Table 6) as the lower limit for a compliant material in contact with a rough surface. Figure 27 shows the tent interior air temperature calculated when the contact resistance was varied. Varying the contact resistance was found to have very little impact on the thermal environment inside of the tent.

Table 6 - Contact resistance variations for inflatable tent

Baseline: 100% of floor area in contact @ nominal resistance	R"=[1.00/R"nom]-1=R"nom	0.010 m2-K / W
Alt 1: 25% of floor area has 1mm air gap	R" = [.25/R"gap + .75 / R"nom]-1	0.012 m2-K / W
Alt 2: 100% of floor has 1 mm air gap	R"=[1.00/R"gap]-1	0.040 m2-K / W

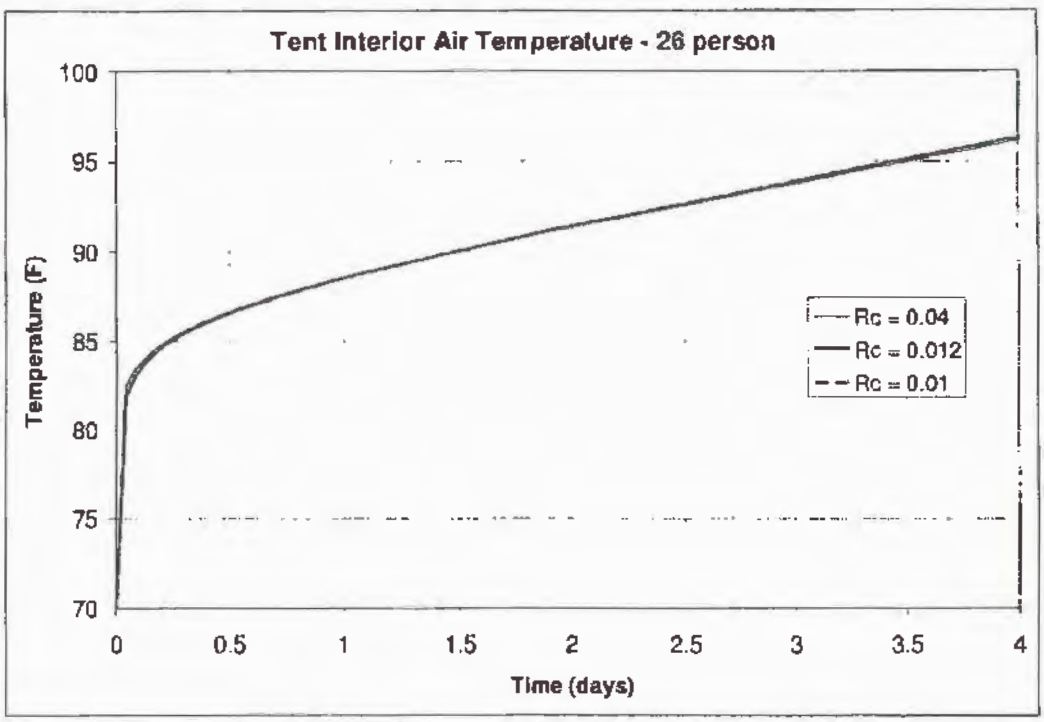

Figure 27 - Tent interior air temperature calculated with three tent to mine floor contact resistances (70°F initial mine temperature)

The rigid steel shelter geometry received from Strata Products had wheels, which lift the bottom face of the shelter about 6" off of the mine floor. There is effectively no conduction to the mine floor when the shelter has wheels, but there is convection to the air and radiation to the mine floor. If the wheels were removed, the bottom of the steel structure would contact the mine floor. A contact resistance of 0.01 m^2-K/W was assumed for this case. Figure 28 shows the interior air temperature calculated for these two cases. These results show that conduction to the floor when the shelter does not have wheels removes about the same amount of heat from the shelter as convection and radiation for the case with wheels.

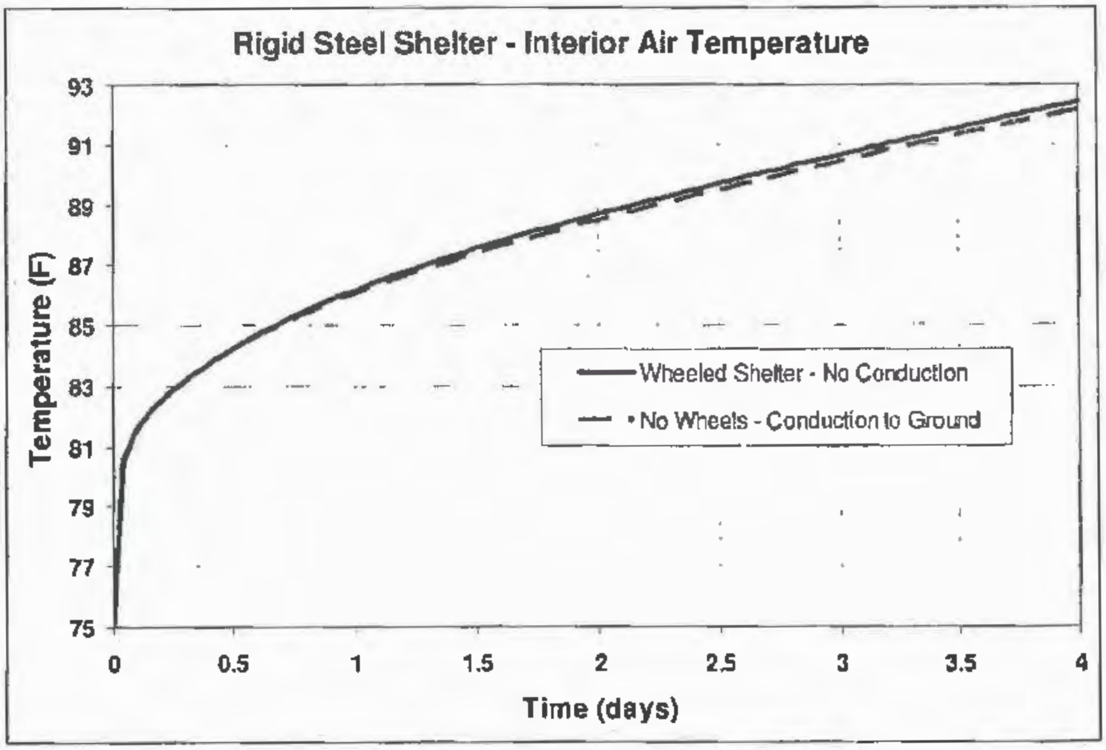

Figure 28 - Rigid shelter interior air temperature for a shelter with wheels (no conduction) and no wheels (conduction from shelter to mine floor)

Section 3.3 Conclusions: Changes in contact resistance between the inflatable tent and mine floor was shown to have very little effect on the interior environment. Contact between the bottom of the rigid shelter and the mine floor (no wheels) resulted in a similar shelter interior air temperature to the case where the bottom of the shelter was lifted off of the floor (with wheels).

3.4 Mine Air Flow (Task 4)

All models shown previously have assumed stagnant mine air because that is likely worst-case from a thermal perspective. Forced air flow through the mine was modeled in Task 4 to quantify its thermal effects on an inflatable tent. The effect of air flow through the mine seam was first predicted using RadTherm coupled with a CFD model. The initial mine, shelter, and upstream air temperatures were modeled as 70°F. Figure 29 shows surface and air temperatures predicted by the coupled model for 7150 cfm of air flow through the mine. Figure 30 shows a plot comparing tent interior air temperatures for varying levels of air flow through the mine seam. Mine air flow keeps the shelter much cooler than the stagnant air case because heat generated in the shelter gets transported away (advection), and the mine seam near the tent is kept cooler. An air flow of 1430cfm through the mine kept the shelter interior air 6°F cooler than stagnant mine air. Figure 30 also compares the coupled model to the RadTherm-only (no CFD) model. As shown in section 2.6, the RadTherm-only model under-predicts the tent interior air temperature by a small amount (0.7°F in this case).

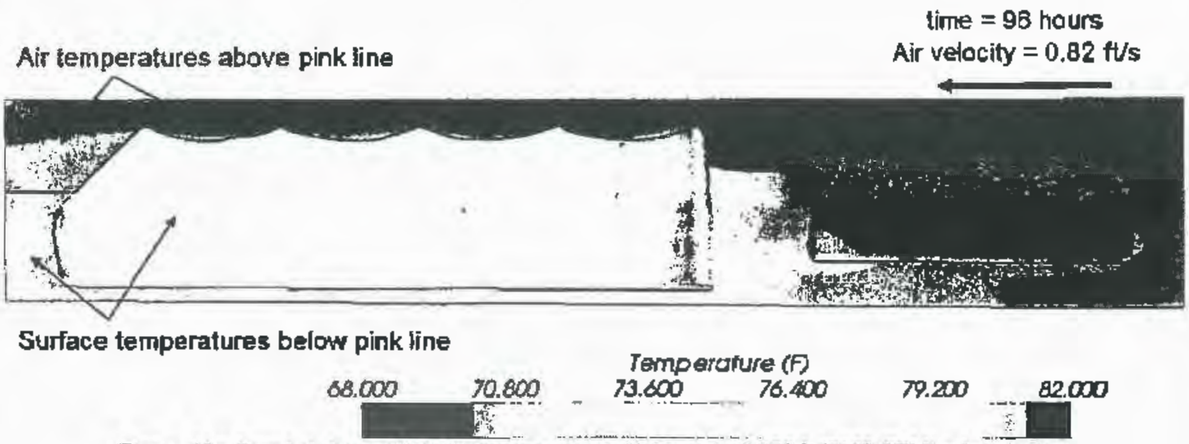

Figure 29 - Coupled thermal/CFD temperature predictions for 0.82ft/s (7150 CFM) mine air flow

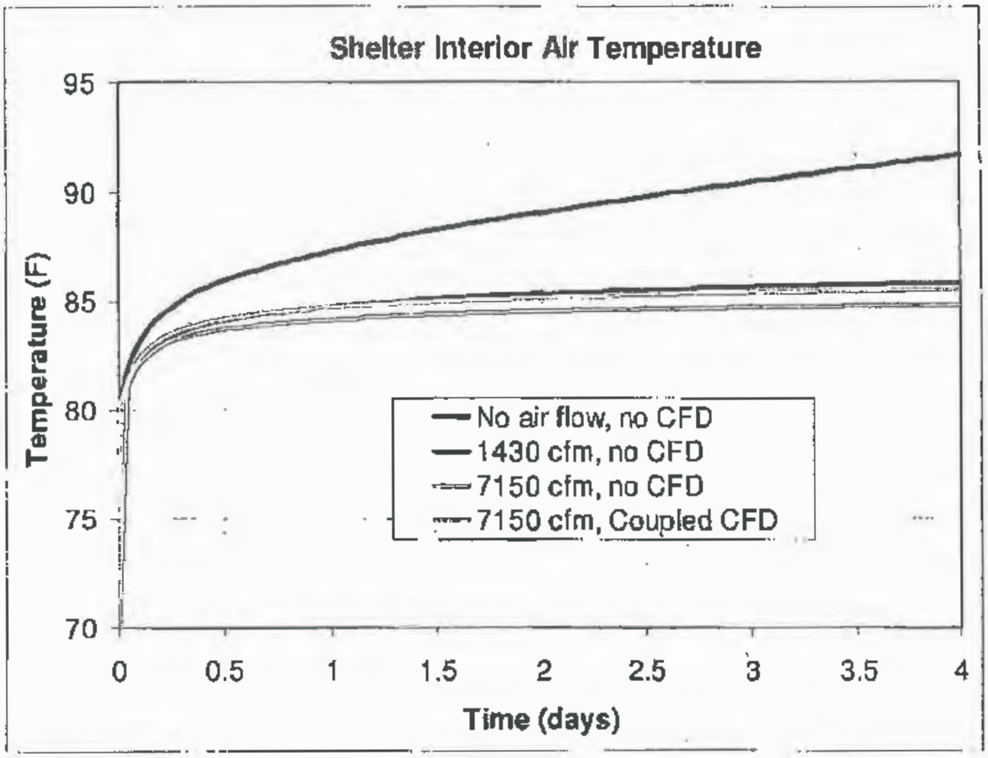

Figure 30 - Mine air flow effect on tent interior air temperature (26 people, 70°F initial temperature)

Section 3.4 Conclusions: Air flow through the mine was predicted to keep the shelter interior cooler by approximately 7°F.

3.5 Mine Shelter Material Study (Task 2)

Material properties of the rigid shelter and inflatable tent were varied with the goal of reducing the maximum interior temperatures in the shelter.

The inflatable tents were constructed of 0.5mm thick polyurethane in the baseline models. The material was changed to pvc and aluminum to determine whether the thermal properties of the tent material had any effect on the interior environment. Aluminum is not a realistic material for an inflatable tent, but it was simulated because it has a very high thermal conductivity. Figure 31 shows the interior air temperature in the 26 man tent for the three different tent materials. After 96 hours, the interior air temperature difference between the three materials was only 0.23°F. The thermal conductivity had very little effect because the temperature changes slowly over the four day period. Also, the difference in thermal capacitance of the three materials had very little effect because the tent is thin and doesn't have much thermal mass.

75°F was used as the initial mine and tent temperature because that case was shown to be stressing for the occupants (Section 3.2, Figure 25). A thermally stressing case was chosen so that differences in shelter construction materials would have a more significant impact on the shelter temperatures.

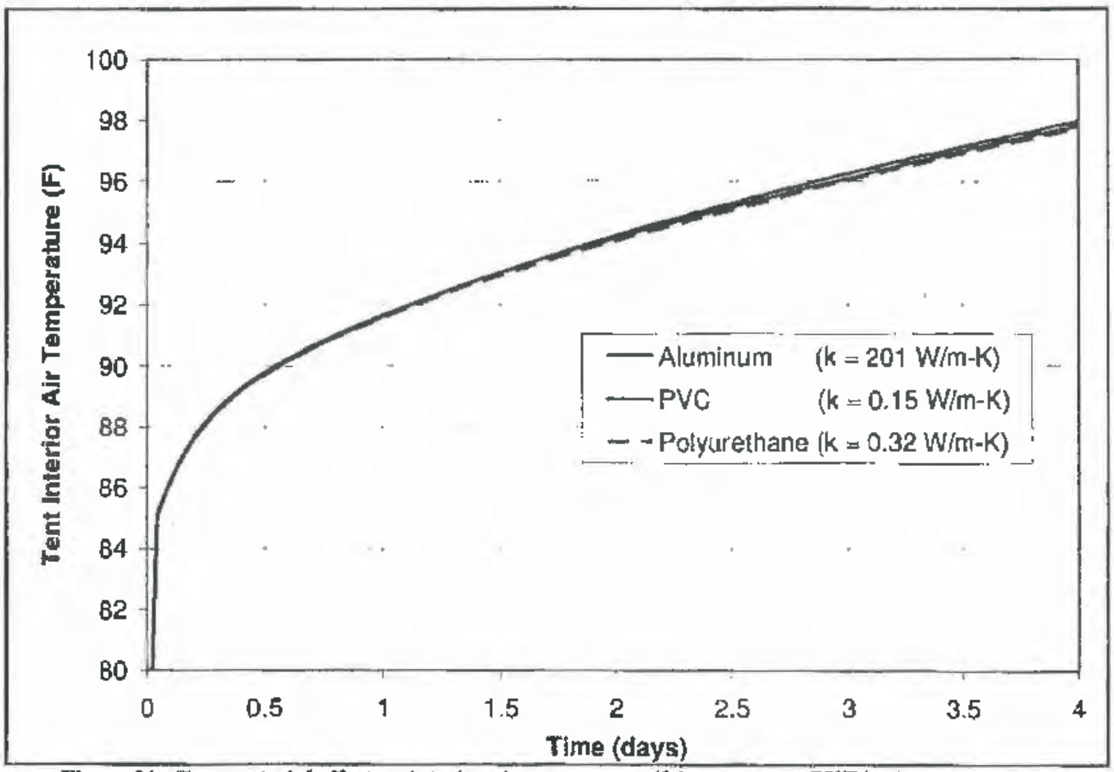

Figure 31 - Tent material effect on interior air temperature (26 person tent, 75°F initial temperature)

It was predicted by the models in Task 3 that the rigid steel shelter provides a safer thermal environment than the inflatable tents because it takes more energy to heat up. The thickness (thermal mass) of the steel shelter was varied in order to gain a better understanding of the thermal behavior. Figure 32 shows the results of varying the thickness of the steel shelter. For the "thin steel" case, all frame and sheet metal parts of the shelter were changed to 1/16" thick, reducing the total shelter weight from 21,277lbs to 6318lbs. The "thick steel" shelter had the same frame as the baseline shelter, but all sheet metal parts were twice as thick as baseline. As expected, the thick steel shelter stayed cooler because of the extra thermal mass. Figure 33 shows the shelter thermal mass effect on occupant core temperature, while Figure 34 shows surface temperatures for the thin steel and thick steel cases.

The "high emissivity" case in Figure 32 used the baseline shelter, but the thermal emissivity of the surfaces was raised from 0.9 to 0.95. This was a small change with a small effect on interior air temperature, but in general a higher thermal emissivity will allow more heat to radiate to the mine seam.

80°F was used as the initial mine and shelter temperature because that case was shown to be stressing for the occupants (Section 3.2, Figure 24). A thermally stressing case was chosen so that differences in shelter construction would have a more significant impact on the shelter temperatures.

Model	Shelter Material	Shelter Weight (lb)	Frame Thickness	Skin Thickness	Surface Emissivity	Interior Air Temp @ 96hrs
Baseline	Steel	21,277	¼"	¼" to ½"	0.9	94.00
High Emissivity	Steel	21,277	¼"	¼" to ½"	0.95	93.88
Thin Steel	Steel	6,318	1/16"	1/16"	0.9	95.41
Thick Steel	Steel	26,686	¼"	½" to 1"	0.9	93.68

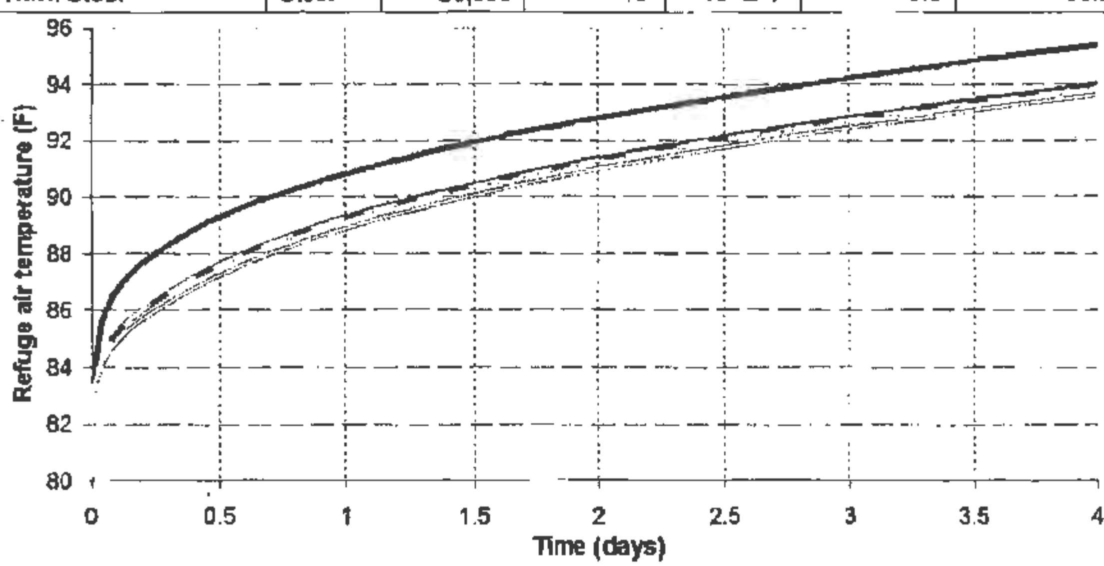

Figure 32 - Material effects on the rigid shelter interior air temperature (14 people, 80°F initial temperature)

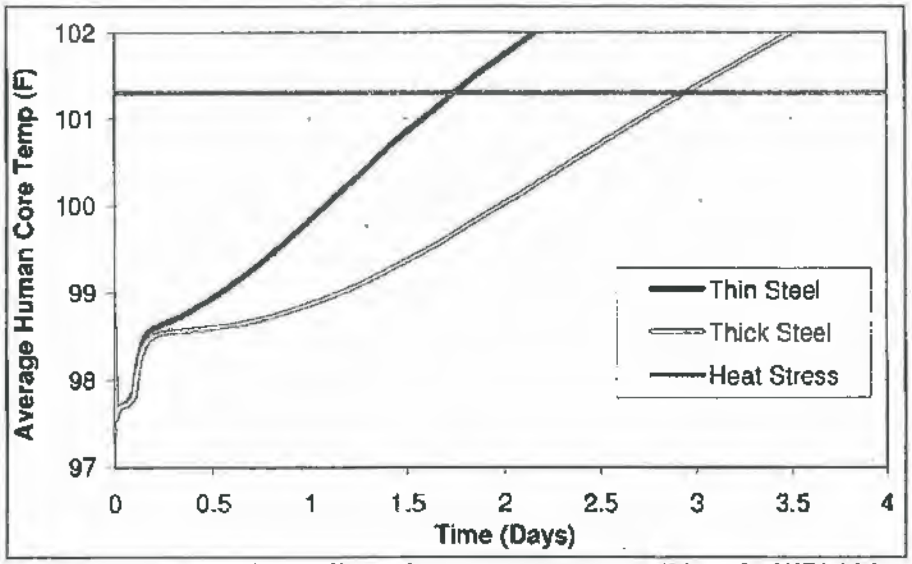

Figure 33 - Shelter thermal capacitance effect on human core temperature (14 people, 80°F initial temperature)

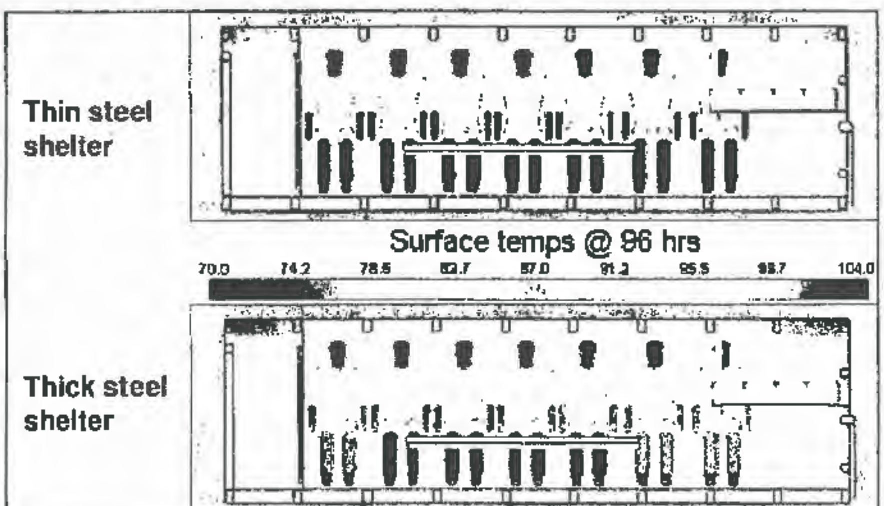

Figure 34 - Surface temperatures after 96 hours for thin and thick steel shelters (14 people, 80°F initial temperature)

The previous two plots showed that additional thermal mass provides a thermal benefit to shelter occupants. Table 7 compares the thermal capacitance of steel to aluminum. Aluminum has a higher specific heat value than steel. This means that if the mass of an aluminum and steel part were the same, it would take more energy to raise the temperature of the aluminum part. Aluminum is also less dense, so it takes more material volume to achieve the same mass. The baseline steel shelter was changed to aluminum, and the thickness of the frame and sheet metal were increased to get the same overall shelter weight. Figure 35 shows the resulting interior air temperatures and occupant core temperatures. For the same shelter weight, the aluminum shelter keeps the occupant core temperatures below the heat stress limit (101.3°F) for the full four days, while the occupants in the baseline shelter exceed the limit at 2.6 days.

Table 7 - Steel and aluminum thermal capacitance

Material	Specific Heat (J/kg-K)	Shelter Mass (kg)	Thermal Capacitance (J/K)
Steel	461	9660	4.5×10^6
Aluminum	884	9660	8.5×10^6

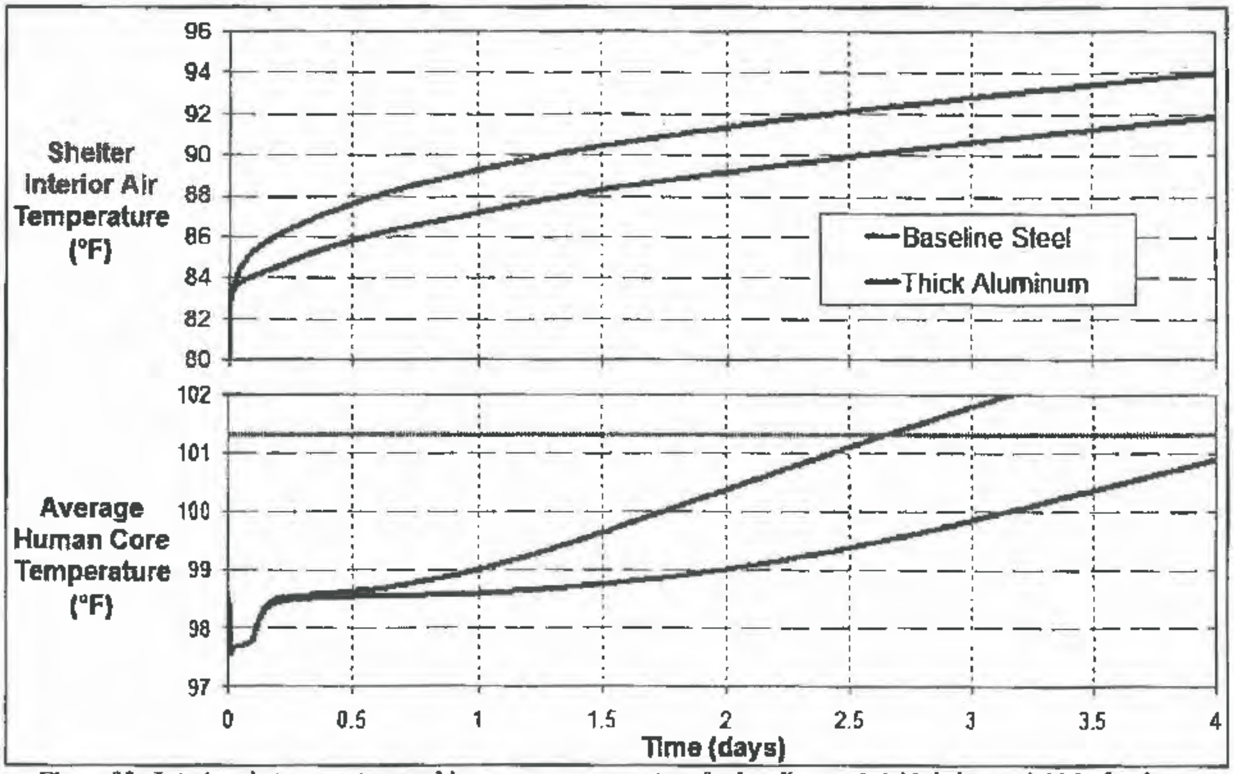

Figure 35 - Interior air temperature and human core temperature for baseline steel rigid shelter and thick aluminum rigid shelter (14 people, 80°F initial temperature)

Section 3.5 Conclusions: Thermal properties of the inflatable tent material have very little impact on interior temperatures. Thermal capacitance does have an effect on the interior temperatures in the rigid shelter because there is significantly more thermal mass than the inflatable tents. Increasing thermal mass will benefit the shelter environment for the mine conditions that were simulated.

4.0 Conclusions

The preceding report summarizes thermal analyses conducted with an objective of quantifying the thermal environment of underground refuge shelters. The scope of the work has taken into account a number of variables, including type of mine shelter, number of human occupants, and size and ambient temperature of the coal seam.

The analysis has resulted in several high-level observations that relate directly to the original objectives of this work:

- The analysis indicates that certain thermal conditions can cause extreme physiological stress to miners over a four-day period within a refuge chamber (Section 3.2)
- The mine seam cannot be assumed to behave as an infinite heat sink (Section 2.5)
    - Mine seam size affects shelter temperatures. A larger mine seam has more thermal capacitance, and takes longer to heat up than smaller seam (Section 3.1)
    - A mine consisting of more conductive rock will keep the shelter cooler (Section 3.1)
- Air flowing through the seam at the location of the occupied shelter can significantly affect its temperature, either positively or negatively depending on the temperature of the air (Section 3.4)
- Shelter thermal mass benefits the occupants by absorbing energy and keeping the occupants cooler (Section 3.5)

The thermal environment of the refuge has been characterized by its ambient temperature over a 96-hour duration, and also through human core temperature predictions for simulated mine workers occupying the shelter. The outcome of the work has shown that conditions inside a refuge can cause occupants physical sensations ranging from mild discomfort to extreme physiological stress, depending on the ambient temperature of the seam.

Our intent as authors was not to assess the relative safety of a mine refuge under any of the specific conditions we analyzed. Rather, our objective has been to accurately quantify the heat transfer mechanisms affecting the refuge environment, and to determine the effect those mechanisms have on the thermal environment of the refuge and on the physiology of a mine worker occupant.

5.0 References

1. "Heat Stress Control and Heat Casualty Management," Technical Bulletin (TBMED) 2003; 507/AFPAM (I), U.S. Army Research Institute of Environmental Medicine.
2. "Thermal Comfort", Fundamentals Handbook, Chapter 8, American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE), 2005.
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4. Fiala, D., K.J. Lomas and M. Stohrer. 2001 Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. Int. J. Biometeorol 45: 143-159.
5. Curran, A.R., M.A. Hepokoski, J.S. Curlee, D.A. Nelson and A. Biswas, "Adapting Segmental Models of Human Thermoregulation and Thermal Sensation for use in a Thermal Simulation of a Vehicle Passenger Compartment" (F2006D129T), FISITA Transactions 2006, International Federation of Automotive Engineering Societies, London, 2006.
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7. Gillies, A.D.S., Wu, H.W., Rau, J., "Design Aspects of Underground Rescue Chambers", SME Annual Meeting, Seattle, WA, 2012.

Bauer, Eric R. (CDC/NIOSH/OMSHR)

From:	Pete Rynes <plr@thermoanalytics.com>
Sent:	Friday, July 13, 2012 10:54 AM
To:	Bauer, Eric R. (CDC/NIOSH/OMSHR)
Subject:	Re: Abstracts for SME Annual Meeting

Eric,

If you can stay till the afternoon of the 16th (~2pm), there would be time to visit the Quincy Mine:

http://www.keweenawheritagesites.org/site-quincy_mine.php

It's a pretty interesting place to visit.

Pete

On 7/10/2012 11:07 AM, Bauer, Eric R. (CDC/NIOSH/OMSHR) wrote:

Gentlemen,

As I believe we have discussed previously, I would like each of you to consider submitting an abstract for the Society of Mining Engineers (SME) Annual Meeting, Feb. 24-27, 2013, to be held in Denver, CO. I am co-chair of a refuge session. The abstract should be 150 to 200 words that describes the research you have completed, or expect to complete, under the contracts with NIOSH. If accepted, I would hope that you can provide a paper and then attend and present at the meeting.

Please note that any travel expenses will be your responsibility.

All abstracts must be submitted by August 16 so the sooner you can get me a Word document the better. I believe that as the session co-chair I must submit the abstracts.

Give me a call to discuss.

Thanks, Eric

Eric R. Bauer, PhD, PE, Mining Engineer
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AB79-COMM-107

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Pete Rynes
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10:05 AM

A Comparison of Photogrammetry and Laser Scanning for Deformation Monitoring in Underground Mines

B. Fahrman[1], E. Westman[1] and M. Golparvar-Fard[2]; [1]Mining Engineering, Virginia Tech, Blacksburg, VA and [2]Civil Engineering, Virginia Tech, Blacksburg, VA

Regular measurement of deformation in underground mine openings can reveal potential ground control hazards. Traditional deformation monitoring instruments give only point measurements. Photogrammetry and laser scanning, however, both allow for quick, accurate determination of spatial coordinates over a wide area. Analysis of successive point clouds generated from photogrammetry or laser scanning can provide an effective means of widespread deformation monitoring. This paper presents a comparison between photogrammetry and laser scanning by analyzing 3D point clouds taken before and after a series of progressively larger rib excavations in an entry at an underground coal mine in the eastern US. Discussion includes the time and financial resources required for each method as well as the ability to be certified as MSHA-permissible.

10:25 AM

Practical UAV Applications for Mining and Minerals Exploration

M. Bartlett; Newmont Mining Corporation, Greenwood Village, CO

Mining and exploration have used aerial photogrammetry for years to map mining operations, explore for mineral deposits, and evaluate the environment. Unmanned aerial vehicles are becoming more common outside of the defense industry and new platforms offer the opportunity to quickly collect high quality, aerial photos at a fraction of the cost of satellite or standard commercial data. An evaluation of a fixed-wing UAV indicates that this platform can provide aerial photo coverage over a 2 to 6 km2 area per flight with a spatial resolution of approximately 5 to 20 cm from a flight elevation of 150 to 500 m AGL. Data can be easily resolved to a GIS map provided suitable ground control points are incorporated. Newmont can successfully use the data to provide quick volume calculations for tailing dam and mineral stockpiles, land use surveys, disturbance mapping and area calculations, environmental remediation surveys, and provide high-quality mapping photos for new exploration area. We envision the use of UAV data to supplement existing commercial and satellite photogrammetry where detailed information is required quickly and where cloud cover prevents timely photo missions.

WEDNESDAY, FEBRUARY 27 **AFTERNOON**

Coal & Energy: Coal Preparation

2:00 PM • Wednesday, February 27

Chair: **D. Tao**, University of Kentucky, Lexington, KY

2:00 PM

Introductions

2:05 PM

Nanobubble Column Flotation for More Efficient Coal Recovery

A. Sobhy, R. Honaker and D. Tao; Mining Engineering Department, University of Kentucky, Lexington, KY

Froth flotation is a widely used, cost effective coal cleaning process. However, its high process efficiency is limited to a narrow particle size range between approximately 10 and 100 µm. Beyond this range, the efficiency of froth flotation decreases sharply, especially for difficult-to-float coal fines of weak hydrophobicity (e.g., oxidized coal). This study was aimed at enhancing recovery of an Illinois fine coal sample using a flotation column featuring a hydrodynamic cavitation nanobubble generator. nanobubbles that are mostly smaller than 1 µm can be formed selectively on hydrophobic coal particles from dissolved air in fine coal slurry. Results indicate that combustible recovery of a -100 mesh coal was increased by 20-50% for different size fractions and that flotation rate was increased by at least 41% in the presence of nanobubbles. Other major advantages of the nanobubble process include lower collector dosage and air consumption since nanoobubbles are produced from air naturally dissolved in water and they act as a secondary collector on particle surfaces, thereby resulting in considerably lower operating costs.

2:25 PM

Use of Fatty Acids in Oxidized Coal Flotation

R. Dube and R. Honaker; Univ. of Kentucky, Lexington, KY

Oxidized coals are generally difficult to float using conventional aliphatic hydrocarbons such as diesel fuel oil. The formation of carboxyl, carbonyl and hydroxyl oxygen groups on the coal surface decreases the hydrophobic character of the coal surface. A flotation study was conducted on a naturally oxidized bituminous coal to identify chemicals and process conditions providing acceptable recovery and selectivity performances. Laboratory tests revealed that fatty acid collectors blended with standard fuel oil provided the desired performances. The operating conditions including slurry pH, flotation time and reagent dosage levels were studied to identify the conditions providing the optimum results. Compared to the typical chemical use and operating conditions, the fatty acid and fuel oil blend provided an increase in combustible recovery that exceeded 30 absolute percentage points while achieving an acceptable selectivity.

2:45 PM

Commercial Application of Dry Cleaning of a High Sulfur Coal

B. Parekh[1], R. Tschantz[2] and J. Pilcher[3]; [1]FGXSepTech, LLC, Lexington, KY; [2]Imperial Technology, Canton, OH and [3]Eagle River Mining, Harrisburg, IL

Dry separators for coal cleaning have a long history of application in the coal.. The dry coal cleaning processes typically has lower capital and operating costs, required no waste water treatment or fine waste impoundment, provided lower product moistures and needed less stringent permitting requirements. A commercial unit capable of processing up to 250TPH was installed in 2011 at the Eagle River Mining located at the Harrisburg, Illinois. The plant flowsheet involves feeding the ROM coal to an Accelerator set to reject mineral matter large than 3-inch size particles. Minus 3 inch particles are processed using the FGX Dry Coal separator. The feed containing about 16% ash and 6% total sulfur produces a clean coal with 8% ash and 3.2% sulfur at a yield of 70% and combustible recovery of 90%. The rejects from the Accelerator and FGX separator has more than 15% sulfur. The paper will present an economical data on the process.

3:05 PM

Ultrafine Spiral Separator Circuit Performance Evaluations for Bituminous Coal

F. Peng and M. Yang; West Virginia Univ., Morgantown, WV

Most of coal preparation plants, flotation circuit is used for ultrafine cleaning. The flotation process requires reagents which increase operating costs and may cause contamination for tailings underground injection. As an alternative, spiral separator, a gravity based concentrator, has been applied for ultrafine cleaning using lower flowrate than that of fine spiral separator. To evaluate the ultrafine spiral performance, in-plant coal samples are collected from processing medium volatile bituminous coal. Particle sizing and float-sink analysis are conducted at various size intervals. Size effects on the performance of ultrafine spiral are evaluated. The characteristic parameters of the distribution functions include probable error and specific gravity separation were derived by curve-fitting to the separation performance data. The parameters values, Ep~0.47-0.12 at SG50~2.1-1.5 for clean coal, and Ep~0.44-0.12 at SG50~2.50 -1.52 for clean coal+middlings for ultrafine spiral separator are obtained. To maintain the high quality of products from ultrafine spiral separation circuit is presented and discussed.

Coal & Energy: Refuge Alternatives

2:00 PM • Wednesday, February 27

Chairs: **N. LaBranche**, NIOSH, Pittsburgh, PA
E. Bauer, NIOSH, Pittsburgh, PA

2:00 PM

Introductions

2:05 PM

Physiological Analysis of Human Generated Heat n a Refuge Alternative

T. Bernard; College of Public Health, Univ. of So. Florida, Tampa, FL

Heat and sweat generation by occupants in a refuge alternative (RA) may be a limiting factor in demonstrating design capacity. In the final MSHA rule, an environmental limit based on the Steadman Apparent Temperature was specified. An analysis of potential limiting thermal conditions was undertaken. The major conclusion was that an occupant surrogate would be an effective testing vehicle to demonstrate RA capacity and that a thermal limit is not necessary. In summary, the following recommendations were made for testing an RA: (1) heat generation at 115 W per occupant; (2) reasonable surrogate occupant can be achieved using a standard drum with a wetted surface to represent sweating; (3) an upper limit skin temperature of 95 ∞F (35 ∞C) for a surrogate occupant (this decision is independent of a limit on the RA environment) and (4) a limit based on the Steadman Apparent Temperature limit can be set higher (e.g., 105 to 115 ∞F).

2:25 PM

Detailed Thermal Analysis of an Underground Mine Shelter to Evaluate Thermal Burden on Mine Workers

M. Klein, M. Hepokoski and P. Rynes; Thermal Modeling Group, ThermoAnalytics, Inc, Calumet, MI

Mine refuge shelters are designed to protect mine workers from hazardous environmental conditions after a mine disaster. These shelters primarily provide clean air and sustenance until conditions within the mine either become safe for human occupation or an evacuation is feasible. Prolonged exposure to elevated temperature and humidity levels can result in a heat stress condition in which the human body is unable to maintain its core temperature. Consequently, thermal conditions within the shelter itself can pose a risk to human safety over time. A detailed thermal model of a mine refuge shelter was created to evaluate the thermal burden imposed on a group of mine workers over an extended period of time. A moisture model was developed to track the transient changes in humidity within the chamber, including evaporation from sweat and respiration; moisture from the air cleaning equipment; and condensation on the walls. An integrated thermoregulation model was used to simulate the humans and to provide a measure of the degree of heat stress in terms of their core temperature.

2:45 PM

Three-dimensional CFD Modeling of Purging From Refuge Chamber

L. Wang, M. Thiruvengadam, J. Tien and Y. Zheng; Missouri S&T, Rolla, MO

The MINER Act of 2006 mandated that all underground coalmines must install and maintain refuge chambers. They are also commonly used in metal and nonmetal mines. Refuge chambers serve as a temporary shelter in case of emergency. Several factors affect the performance of a refuge chamber: heat production inside the chamber and introduction of CO when chamber doors are opened. This study examines the CO purging process and to determine total air quantity and time necessary to lower the CO concentration to safe levels for different inlet/outlet configurations using three-dimensional simulation technique. The study uses Reynolds Averaged Navier Stokes and continuity equations along with the species transport model assuming uniform air-CO mixing initially in the refuge chamber. The heat transfer of any kind is neglected and the purging process is assumed to take place isothermally. The standard k-∞ model is utilized for simulating turbulence in the flow field. This research provides useful guidelines in developing an efficient strategy for purging refuge chamber

3:05 PM

Refuge Chambers in US Coal Mines

C. Slaughter, L. Wang and J. Tien; Missouri S&T, Rolla, MO

With the passage of the Mine Improvement and New Emergency Response Act of 2006 (MINER Act of 2006) and the Mine Safety and Health Administrations Refuge Shelter Final Rule, coal mines were required to have available Refuge Alternatives for emergency situations. These alternatives have been in place for 5 years and many valuable insights have been gained in their use, design and location underground. This paper will conduct a preliminary survey of refuge chamber use in the coalfield and lessons learned by coal companies and give some general consensus guidelines for the practical use of Refuge Chambers.

3:25 PM

Innovations In Cryogenic Breathing Technologies

C. Blalock; BCS Life Support, LLC, DeLand, FL

For a number of years the state-of-the-art for breathing technology in mine rescue, and self-rescue has been open-circuit compressed air, or closed circuit rebreathers. While there have been improvements made to these devices, there are still significant limitations, mostly concerning heat, and duration. The advent of the refuge alternative echoed the same limitations, and then some. Limited space for air supply systems forced the use of compressed oxygen, introducing a new set of hazards. And, heat elimination is still a nagging problem. The use of cryogenic liquid air has long been seen by some as a pie-in-the-sky solution to many of these issues. In fact, NASA has been using liquid air for decades, but for a few nagging technical issues, LAir has not been adopted for widespread use. Recent developments have begged a new look at Cryogenic Life Support, triggering a joint research project between NASA and NIOSH to develop these innovations.

Coal & Energy:
Surface Mining II

2:00 PM • Wednesday, February 27

Chair: **G. Buchan,** Alpha Natural Resources, Waynesburg, PA

2:00 PM

Introductions

2:05 PM

Fatigue Failure Modeling of Cable Shovel Dipper

M. Raza[1] and S. Frimpong[2]; [1]Mining Engineering Dept., Missouri S&T, Rolla, MO and [2]Mining Engineering Dept., Missouri S&T, Rolla, MO

Cable shovels are the primary excavation units for many surface mining operations. Modern cable shovels can scoop 100+ tons per pass. During the excavation operation the shovel front-end assembly is subjected to considerable stresses resulting in stress loading and failure. Further, the repeated loading and unloading cycles cause the fatigue failure in cable shovel components, specially the front-end components (i.e. teeth, dipper-n-teeth assembly, and dipper). The stress and fatigue failure of shovel components result in reduced efficiency, increased downtime, and higher operating costs for the shovel. This research, after modeling the stress loading of the shovel, models the fatigue behavior and crack propagation life of the cable shovel dippe. The fatigue behavior is modeled in MSC ADAMS/FATIGUE software and the fatigue-life for different crack lengths, at the critical parts of the dipper, is estimated for dipper. The research is critical to enhance the health and longevity of the cable-shovel and is expected to contribute towards better understanding of the shovel failure, resulting in improved economic lives of the front-end components.

2:25 PM

The Economic and Technical Aspects of Material Handling Methods in Taft Copper Project

B. Asi; Mining Industry, Kavoshgaran Consulting Engineers Co., Tehran, Islamic Republic of Iran

Focusing on reducing costs by providing the best solutions and increasing the production rate with the most advanced automation techniques will get a high profitable operation. Taft Copper Complex is located in Yazd province,IRAN. TCP consists of two copper mines are about 11km apart, concentrator plant and leaching plant. Plants feed will be supplied from both deposits. In this research handling methods and their synthesis in a handling system of TCP for transporting the crushed ore from mines to concentrator plant have been assessed. Then engineering and economical calculations of a material flow have been done. The conceptual design for alternative handling systems has been done. The costs for alternative systems have been compared to those developed for traditional methods Consequently the best practical technology to move the material has been chosen. After analyzing truck versus belt haulage, it has been shown turning to overland belt conveyor systems are more profitable The results show belt haulage equipment, maintenance and power costs are lower, ton-for-ton, than other methods of moving bulk materials.

2:45 PM

Green Field Project Surface Coal Mine in Mississippi

V. Lund, M. Jones and D. Bogunovic; North American Coal Corporation Liberty Mine, Bailey, MS

Over the past 15 years, the challenges facing the mining industry have changed significantly. North American Coal developed a green field lignite surface mine in central Mississippi in the late 1990's and is currently in the process of developing its second greenfield operation in south-eastern Mississippi. This newest operation is currently in the first year of development and is scheduled to go into production in the third quarter of 2013. This paper highlights the challenges and differences mine management encountered throughout the development phase of the mine and the expected pressures of a new surface lignite mine.