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Experimental and modeling study of thermal exposure of a self-contained breathing apparatus (SCBA)☆

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ABSTRACT

An experimental apparatus designed to study firefighter safety equipment exposed to a thermal environment was developed. The apparatus consisted of an elevated temperature flow loop with the ability to heat the air stream up to 200 °C. The thermal and flow conditions at the test section were characterized using thermocouples and bi-directional probes. The safety equipment examined in this study was a self-contained breathing apparatus (SCBA), including a facepiece and an air cylinder. The SCBA facepiece was placed on a mannequin headform and coupled to a breathing simulator that was programmed with a prescribed breathing pattern. The entire SCBA assembly was placed in the test section of the flow loop for these thermal exposure experiments. Three air stream temperatures, 100 °C, 150 °C, and 200 °C, were used with the average air speed at the test section set at 1.4 m/s and thermal exposure durations up to 1200 s. Measurements were made using type-K bare-bead thermocouples located in the mannequin's mouth and on the outer surface of the SCBA cylinder. The experimental results indicated that increasing the thermal exposure severity and duration increased the breathing air temperatures supplied by the SCBA. Temperatures of breathing air from the SCBA cylinder in excess of 60 °C were observed over the course of the thermal exposure conditions used in most of the experiments.

A mathematical model for transient heat transfer was developed to complement the thermal exposure experimental study. The model took into consideration forced convective heat transfer, quasi-steady heat conduction through the composite layers of the SCBA cylinder wall, the breathing pattern and action of the breathing simulator, and predicted air temperatures from the thermally exposed SCBA cylinder and temperatures at the outer surface of the SCBA cylinder. Model predictions agreed reasonably well with the experimental measurements.

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Nomenclature

$A_{1,T}$	external heat transfer area of the SCBA cylinder, $= \pi DL$ (m^2)
c_p	constant-pressure heat capacity (J/mol K)
$c_{p,f}$	constant-pressure heat capacity of air evaluated at T_f (J/kg K)
c_v	constant-volume heat capacity (J/mol K)
D	outer diameter of the SCBA cylinder (m)
h	specific enthalpy (J/mol)
h_c	convective heat transfer coefficient (W/m^2 K)
j	index ($j = 1, 2,\ldots, J$) to represent the jth simulated breathing cycle
J	total number of simulated breathing cycles
k_{al}	thermal conductivity of aluminum alloy (W/m K)
k_{ins}	thermal conductivity of insulating layer material (W/m K)
k_{CF}	thermal conductivity of carbon fiber epoxy resin (W/m K)
k_{FG}	thermal conductivity of fiberglass (W/m K)
k_f	thermal conductivity of air evaluated at T_f (W/m K)
L	length of the SCBA tank (m)
n	amount of substance (mol)
N	amount of substance (mol)
P	pressure (Pa)
Pr	Prandtl number
Q	heat interaction (J)
$\dot{Q}$	heat transfer rate (W)
r_i	inner radius of the SCBA cylinder wall (m)
$r_{i,ins}$	inner radius of insulating layer of the SCBA cylinder wall (m)
$r_{i,CF}$	inner radius of carbon fiber epoxy resin layer of the SCBA cylinder wall (m)
$r_{i,FG}$	inner radius of fiberglass layer of the SCBA cylinder wall (m)
r_o	outer radius of the SCBA cylinder (m)
R	universal gas constant (=8.314 J/mol K)
Re_D	Reynolds number based on SCBA cylinder diameter
t	time (s)
T	temperature (K)
T_{amb}	ambient (room) temperature (K)
T_f	film temperature (K)
$T_{1,o}$	outer surface temperature of the SCBA cylinder (K)
T_∞	free stream temperature in flow loop (K)
u	specific internal energy (J/mol)
U	total internal energy (J)
$U_{1,HT}$	overall heat transfer coefficient (W/m^2 K)
v	specific volume (m^3/mol)
V	volume (m^3)
V_∞	free stream air speed at test section of flow loop (m/s)
W	work interaction (J)

Greek symbols

δ_{al}	thickness of aluminum liner (m)
δ_{ins}	thickness of insulating layer (m)
δ_{CF}	thickness of carbon fiber epoxy resin layer (m)
δ_{FG}	thickness of fiberglass layer (m)
μ_f	dynamic viscosity of air evaluated at T_f (N s/m^2)
γ	c_p/c_v
ρ	molar density of air (mol/m^3)
$\rho_{a,f}$	mass density of air evaluated at T_f (kg/m^3)
τ_{ex}	duration of exhaling phase (s)
τ_{in}	duration of inhaling phase (s)

Subscripts

1	System 1 (air in the SCBA cylinder)
2	System 2 (air in the simulated bellows)
bi	beginning of the inhaling phase of the jth breathing cycle
e	entering
ei	end of the inhaling phase of the jth breathing cycle
l	leaving
0	reference state

1. Introduction

Firefighters often face hazardous environments where breathing is difficult or impossible due to reduced oxygen levels and dangerous contaminants in the atmosphere. To enter and work under these hazardous conditions, firefighters use a self-contained breathing apparatus (SCBA), a portable device with a limited supply of breathable air. SCBAs are essential equipment for respiratory protection of emergency first responders during firefighting, search and rescue, and other hazardous operations where products of combustion, oxygen deficiency, particulates, toxic products or other immediately dangerous to life or health atmospheres exist or could exist at the incident scene [1].

Elevated temperatures are another danger typically present in a firefighting environment. The exposure of an SCBA to elevated temperatures introduces the potential for heating the breathing air provided by the SCBA. Firefighters have provided anecdotal accounts of the breathing air from their SCBA being heated to uncomfortable temperatures. Questions have been raised, based on recent Line of Duty Death incidents, of the potential for firefighters to suffer respiratory tract thermal injuries due to breathing hot air from SCBA. In a given thermal environment, the two key questions are (1) how hot the air in an SCBA becomes and (2) how quickly the air in the SCBA is heated.

Injuries can occur to the human respiratory tract due to the inhalation of hot gases [2]. When the temperature of the tissue in the respiratory tract increases above 44 °C, it can result in damage to the tissue [3] despite the fact that the mucous linings of the respiratory tract provide highly efficient heat and mass transport mechanisms to regulate the thermal environment within the respiratory tract. Temperature increases of the tissue result from complex interactions that vary based on the composition of the gas and the heat capacity of each individual's tissue. Depending on the exposure time, burns to the larynx may occur by breathing dry air at temperatures around 120 °C [4]. The addition of humidity, steam, or smoke can increase the thermal capacity or latent heat of the air. Such air at temperatures of 100 °C can cause burns if inhaled [4]. The condition of the air, including the temperature and humidity, must be sufficient to cause facial burns in order for thermal burns to the respiratory tract to occur [4].

SCBAs used by the fire service in the United States are designed to meet the standard requirements set forth by the National Fire Protection Association (NFPA). NFPA 1981 describes various design and performance requirements, including rigorous test specifications, which an SCBA must meet or exceed to obtain certification [1]. Included among the requirements are specifications for heat and flame resistance performance, detailed in NFPA 1981, Chapter 8.11 Heat and Flame Test. Test methods include subjecting the SCBA to an oven pre-heated to a temperature of 95 °C for 15 min, while operating at a ventilation rate of nominally 40 L/min. Immediately following the elevated temperature exposure, the ventilation rate is increased to 103 L/min, and the SCBA subjected to 10 s of direct flame impingement. After these exposures, "no component of the SCBA shall separate or fail in such a manner that would cause the SCBA to be worn and used in a position not specified by the manufacturer's instructions," and "no components of the SCBA shall have an afterflame of more than 2.2 s." However, NFPA 1981 does not provide any technical guidance on the temperature of the breathing air from an SCBA exposed to a given thermal environment.

This paper describes an experimental study designed to examine the air temperature of an SCBA cylinder exposed to various thermal environments under simulated breathing operations, and a thermodynamic model developed to simulate the experiments. First the experimental apparatus will be described, and then detailed model development will be presented, followed by comparisons of the model predictions with the experimental observations.

2. Material and methods

An elevated temperature flow loop is used to supply the thermal exposure environment for the SCBA equipment. Fig. 1 shows a schematic of the NIST flow loop apparatus. The arrows show the direction of the air flow. A 50 kW air duct heater located in the flow loop is used to heat the air to the desired temperature. An adjustable rate electric blower located below the heater circulates the heated air through the flow loop. The test section of the flow loop has a cross-sectional area of 0.91 m by 0.91 m. This test section provides space for the experimental package (the SCBA equipment) to be placed during the high temperature exposure experiments. Thermocouples (type-K bare-bead) and bi-directional probes located in the test section provide air temperature and velocity measurements. A return airflow duct carries the air back to the blower, where it is recirculated through the loop.

A movable platform, which forms the base of the test section when in place, is used to mount and position the experimental package in the test section. The experimental package consists of an SCBA cylinder and frame assembly, which is secured in the upright position on the movable platform, and a mannequin headform donned with an SCBA

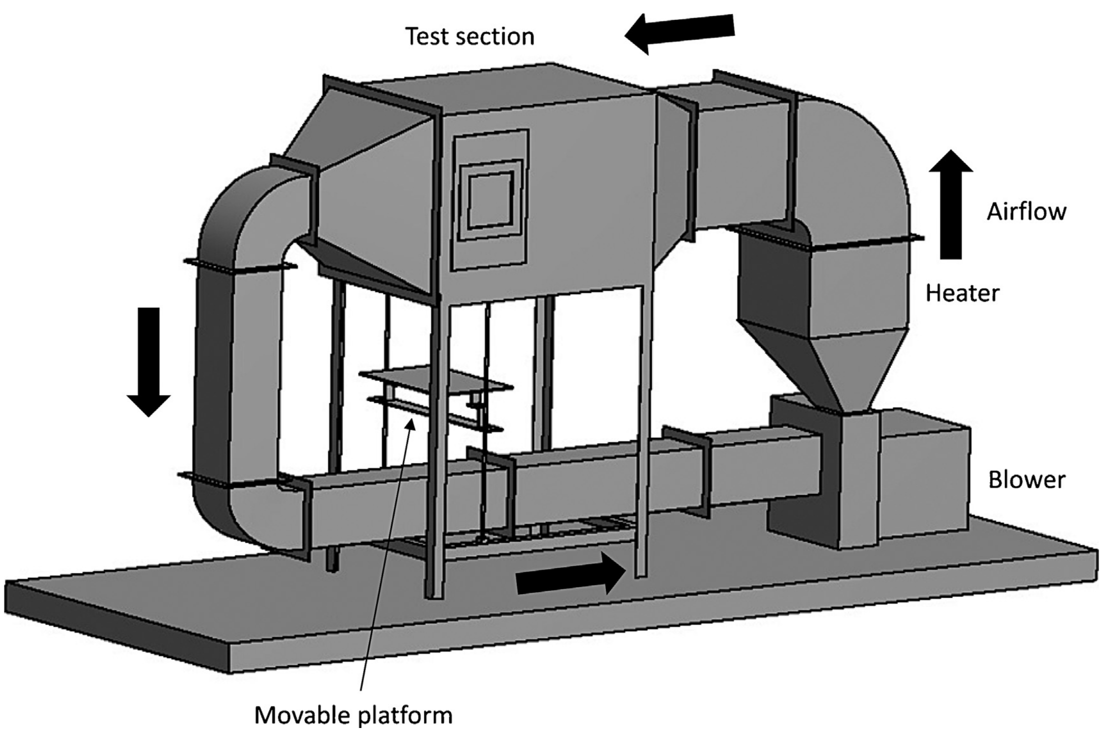

Fig. 1 – Schematic of the NIST flow loop.

facepiece. A heat-resistant firefighting hood is placed on the mannequin headform over the SCBA facepiece, as would typically be worn by a firefighter. When positioned in the test section, both the SCBA cylinder and the mannequin with the facepiece are oriented to face the oncoming airflow. Fig. 2 shows a picture of the experimental package on the movable platform retracted from the test section.

Experiments were performed using a Scott Air-Pak 75 SCBA assembly,[2] which included a carbon-fiber reinforced aluminum-lined compressed air cylinder (manufactured by Luxfer), with a maximum working pressure of 31.03 MPa, rated for 45 min, and a Scott AV-3000 facepiece. The mannequin headform used for the experiments is of the same type as specified in NFPA 1981 [1]. A photograph of the mannequin headform is shown in Fig. 3. The headform is equipped with a nominally 38 mm breathing passageway through its mouth, with an opening on the underside of the headform. This passageway may be connected to a mechanical breathing apparatus to allow for simulated breathing. When an SCBA facepiece is placed on the headform, air may be drawn through the SCBA to simulate breathing while wearing an SCBA. A static pitot tube pressure measurement probe is located in the headform, in the location of the left eye. This pressure probe is connected to a pressure transducer to monitor the pressure inside the SCBA facepiece. A thermocouple (type-K bare-bead) is also located on the outside and along the centerline at the midway point of the SCBA cylinder to record the temperature of the outer cylinder wall.

Two thermocouples (type-K bare-bead) were located inside the mouth opening of the mannequin head, to measure the temperature of the airflow through the mouth. This measurement is considered to be representative of the temperature of the air breathed by a firefighter wearing an SCBA. The thermocouples inside the mannequin's mouth can be seen in the photograph of the headform in Fig. 3. The thermocouples are located at the mid-height of the mouth, 1.0 cm $\pm$ 0.2 cm in from the right and left sides, and 1.0 cm $\pm$ 0.2 cm deep inside the passageway of the mouth.

The mechanical breathing operation for the mannequin head was provided using an Active Servo Lung 5000 (ASL 5000) Breathing Simulator. The ASL 5000 is a computer controlled system designed to provide the mannequin head with precisely controlled and repeatable artificial breathing. An electronic drive motor operates a piston to control airflow into and out of a cylinder to simulate breathing. A diagram of the ASL 5000 setup is shown in Fig. 4. An Auxiliary Gas Exchange Cylinder with a bellows inside was used in line between the breathing simulator and the mannequin head to isolate and protect the internal components of the breathing simulator from possible elevated temperatures. The ASL 5000 software was used to designate a controlled breathing profile with a breathing waveform at a rate of nominally 40 L/min for all the

Fig. 2 – SCBA equipment on the flow loop testing platform.

Fig. 3 – Mannequin headform with thermocouples inside mouth.

experiments. This breathing volume work rate is the lower of the two testing work rates as described in NFPA 1981. The breathing rate for all the experiments was set at 40 breaths per every 100 s, or 2.5 s per breath. For a breath, it is the full cycle of

[2] Certain commercial entities, equipment, instruments, standards or materials may be identified in this document in order to describe an experimental procedure, equipment, or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, standards, materials, or equipment are necessarily the best available for the purpose.

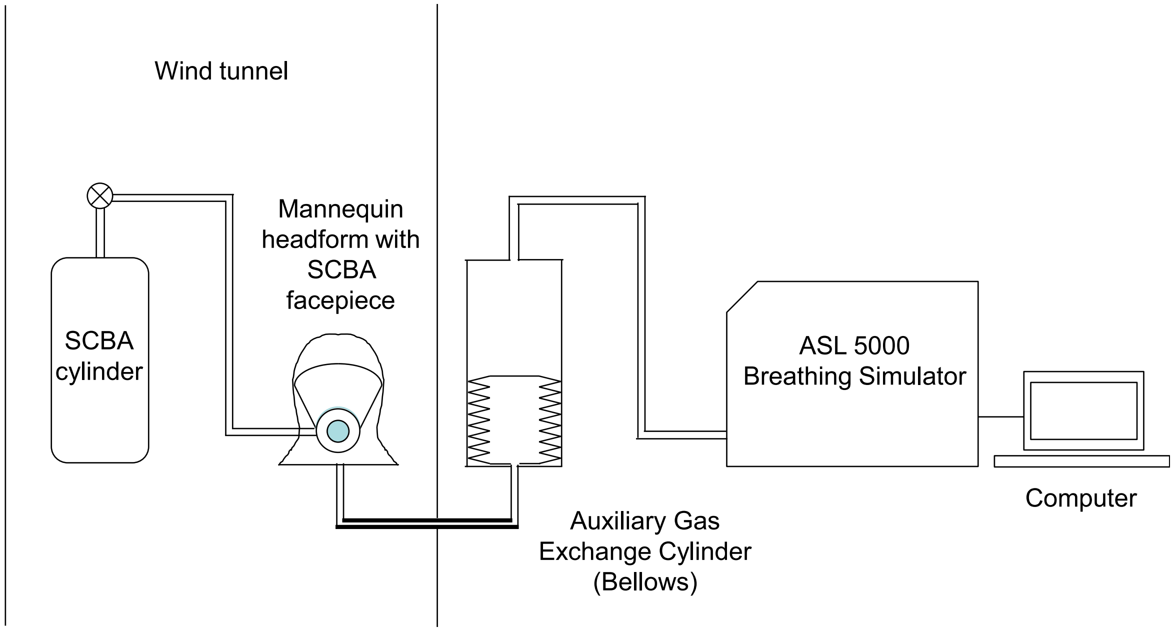

Fig. 4 – ASL 5000 Breathing Simulator System used to perform the experiments.

inhale and exhale over the 2.5 s (1.25 s for inhale and 1.25 s for exhale).

The SCBA cylinder was filled to its maximum capacity with compressed breathing air at a pressure of 31.03 MPa prior to the start of each experiment. For each test, the temperature of the cylinder was allowed to equilibrate to ambient room temperature. The full cylinder was installed in the SCBA frame assembly, and the whole SCBA assembly was secured on the platform, as shown in Fig. 2. The SCBA facepiece was positioned on the mannequin headform and secured in place with the facepiece straps. The facepiece was then connected to the rest of the SCBA assembly. Prior to each experiment, a breathing check was performed on the apparatus using the ASL 5000 breathing simulator. This check ensured that everything was properly connected, that the SCBA, mannequin, and breathing machine were operating correctly, and that there was no leakage from the SCBA or the facepiece.

For each experiment, an airflow temperature was selected, and the test section of the flow loop was pre heated to the desired temperature. Three airflow temperatures, 100 °C, 150 °C, and 200 °C, were used to conduct the thermal exposure experiments. The air speed in the flow loop at the test section was set at 1.4 m/s ± 0.3 m/s (5 km/h ± 1 km/h), which is the average human walking speed [5]. When the test section of the flow loop reached the desired temperature, the movable platform was then raised into the flow loop, exposing the entire SCBA assembly to the heated airflow, and the thermocouple outputs were recorded at 1 Hz.

A detailed description of the experimental apparatus developed to study thermal exposure of firefighting safety equipment, including SCBA, measurement uncertainties, and other measured parameters not directly pertinent to this modeling effort can be found in Donnelly and Putorti [6].

3. Theory and calculations

For each breathing cycle, the modeling processes are divided into two stages: (a) the inhaling phase and (b) the exhaling phase. Fig. 5 shows the idealized representations of the model used to simulate the thermal exposure experiments during the inhaling and exhaling phases of a breathing cycle. The pressure reducer is used to decrease the high cylinder pressure to an intermediate pressure. The facepiece mounted pressure demand breathing regulator further reduces the intermediate pressure to ambient pressure for breathing. The bellows in the actual auxiliary gas exchange cylinder connected to the breathing simulator used in the experiments is modeled as a rigid hollow cylinder with a moving piston with the same displacement volume as the bellows driven by a direct drive motor of the breathing simulator. The air in the SCBA cylinder and the simulated bellows is assumed to be ideal, and there is no heat interaction between the surroundings and the tubing connecting the SCBA cylinder and the simulated bellows. The SCBA cylinder is modeled as a regular cylinder with the same length, outer diameter, and internal volume. The thickness of the cylinder wall (information considered proprietary) is estimated using the internal volume and the outer diameter of the simulated regular cylinder. The convective heat transfer to both ends of the simulated cylinder is assumed to be negligible.

3.1. *During the inhaling phase of the jth breathing cycle*

For the jth breathing cycle, the following time interval encompasses the inhaling phase with an inhaling duration τ_{in}:
$(j-1)(\tau_{in}+\tau_{ex}) \le t < j\tau_{in}+(j-1)\tau_{ex} \quad j = 1, 2, \ldots$

During this phase, the SCBA cylinder (System 1) and the simulated bellows (System 2) are coupled.

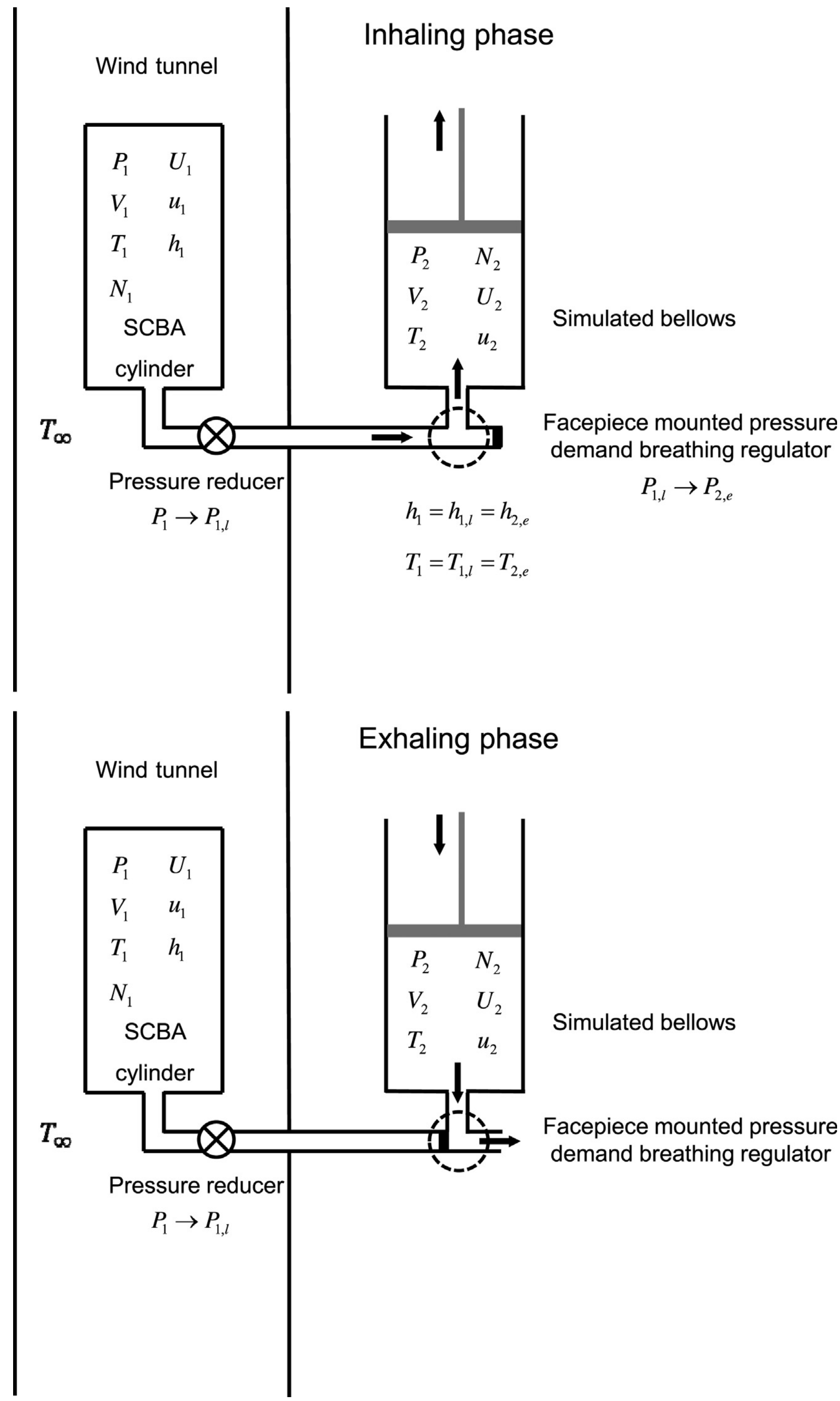

Fig. 5 – Model representation of the inhaling and exhaling phases of a breathing cycle.

3.1.1. *SCBA clinder*

The system (designated as System 1) under consideration is breathing air in the SCBA cylinder. From the first law of thermodynamics for a simple open system[3] [7],

$$dU_1 = \delta Q_1 - \delta W_1 - h_{1,l} dn_{1,l} \quad (1)$$

With $\delta W_1 = 0$ and taking the time derivative, Eq. (1) can be written as

$$\frac{dU_1}{dt} = \frac{\delta Q_1}{dt} - h_{1,l} \frac{dn_{1,l}}{dt} \quad (2)$$

Eq. (2) can be expressed in terms of molar internal energy, u_1, and the total number of moles in the system, N_1.

[3] The symbol δ is used here to denote a differential change of a path function, whereas d is for a differential change of a state function.

$$\frac{d(N_1u_1)}{dt} = N_1\frac{du_1}{dt} + u_1\frac{dN_1}{dt} = \frac{\delta Q_1}{dt} - (u_{1,l} + P_{1,l}v_{1,l})\frac{dn_{1,l}}{dt} \quad (3)$$

A balance of the amount of air in the system is

$$-\frac{dN_1}{dt} = \frac{dn_{1,l}}{dt} \quad (4)$$

If the gas is treated as ideal, then the molar internal energy of an ideal gas can be expressed as

$$u_1 = u_0 + c_v(T_1 - T_0) \quad \text{and} \quad u_{1,l} = u_0 + c_v(T_{1,l} - T_0) \quad (5)$$

Substituting Eq. (5) into Eq. (3) results in

$$c_vN_1\frac{dT_1}{dt} + \frac{dN_1}{dt}[u_0 + c_v(T_1 - T_0)] = \dot{Q}_1 + \frac{dN_1}{dt}[u_0 + c_v(T_{1,l} - T_0)] + \frac{dN_1}{dt}RT_{1,l} \quad (6)$$

where $\dot{Q}_1 = \delta Q_1/dt$ is the heat transfer rate to the system from the surroundings. Treating the pressure reducer (regulator) and facepiece mounted pressure demand breathing regulator as a constant enthalpy process [8] ($h_1 = h_{1,l} = h_{2,e}$) and assuming negligible heat loss from the connection between the SCBA and the simulated bellows, it can be shown that for an ideal gas $T_1 = T_{1,l} = T_{2,e}$. Eq. (6) can be further simplified to

$$c_vN_1\frac{dT_1}{dt} = \dot{Q}_1 + \frac{dN_1}{dt}RT_1 \quad (7)$$

Since the cylinder inner diameter is much larger than the composite wall thickness, it is reasonable to assume the heat transfer process through the composite wall to be quasi-steady, and the $\dot{Q}_1$ term in Eq. (7) can be conveniently expressed in terms of an overall heat transfer coefficient, $U_{1,HT}$, the outer heat transfer area of the cylinder, $A_{1,t}$, the thermal resistances for conduction and convection, and the temperature difference between the surrounding (free stream) temperature, T_∞, and the cylinder temperature, T_1 [9].

$$\dot{Q}_1 = U_{1,HT}A_{1,t}(T_\infty - T_1) \quad (8)$$

Based on the product literature provided by the SCBA cylinder manufacturer [10], the wall of the cylinder is composed of four layers: the innermost wall layer, a thin-walled aluminum alloy (AA 6061) liner, followed by a thin layer of insulating material, a layer of over-wrapping of carbon fiber in an epoxy resin and a layer of over-wrapping of fiberglass as the outermost layer to provide additional impact and abrasion resistance to the cylinder.[4] Fig. 6 shows a schematic of a cross section of the SCBA cylinder and the associated equivalent thermal circuit for the composite cylinder wall. For a four-layer composite wall, the overall heat transfer coefficient based on the external surface area of the SCBA tank can be expressed by [9]

$$U_{1,HT}A_{1,t} = \frac{1}{1/(A_{1,t}h_c) + [\ln(r_o/r_{i,FG})]/2\pi k_{FG}L + [\ln(r_{i,FG}/r_{i,CF})]/2\pi k_{CF}L + [\ln(r_{i,CF}/r_{i,ins})]/2\pi k_{ins}L + [\ln(r_{i,ins}/r_i)]/2\pi k_{al}L} \quad (9)$$

In writing Eq. (9), the innermost wall surface is assumed to be in thermal equilibrium with the air in the cylinder. The convective heat transfer coefficient h_c at the outermost wall is estimated using the Churchill and Bernstein forced convective heat transfer coefficient correlation for a cylinder in cross flow under the condition of $Re_DPr > 0.2$ with all the thermophysical properties of air evaluated at the film temperature [9], $T_f = (T_\infty + T_{1,o})/2$.

$$\frac{h_cD}{k_f} = 0.3 + \frac{0.62\sqrt{Re_D}Pr^{1/3}}{[1 + (0.4/Pr)^{2/3}]^{1/4}}\left[1 + \left(\frac{Re_D}{282\,000}\right)^{5/8}\right]^{4/5} \quad (10)$$

where

$$Re_D = \frac{\rho_{a,f}DV_\infty}{\mu_f} \qquad Pr = \frac{c_{p,f}\mu_f}{k_f}$$

Under a quasi-steady process, the heat transfer rate through the overall composite wall, convection, and each of the three layers will be the same, and the outer surface temperature of the SCBA cylinder can be estimated using Eq. (11).

$$\dot{Q}_1 = h_cA_{1,t}(T_\infty - T_{1,o}) = U_{1,HT}A_{1,t}(T_\infty - T_1)$$
$$T_{1,o} = T_\infty - \frac{U_{1,HT}}{h_c}(T_\infty - T_1) \quad (11)$$

Substituting Eq. (8) into Eq. (7) results in

$$\frac{dT_1}{dt} = \frac{U_{1,HT}A_{1,t}}{c_vN_1}(T_\infty - T_1) + \frac{RT_1}{c_vN_1}\frac{dN_1}{dt} \quad (12)$$

3.1.2. *Simulated bellows*

In this case, the system (designated as System 2) is the air in the cylinder at any time, which is an open simple system. Applying the first law of thermodynamics to the system,

$$dU_2 = \delta Q_2 - \delta W_2 + h_{2,e}dn_{2,e} \quad (13)$$

For the simulated bellows, $\delta W_2 \neq 0$ because there is work interaction between the system and the surroundings due to the displacement of the piston. If we assume the moving piston is frictionless and the process is reversible, $\delta W_2 = P_2dV_2$, and Eq. (13) becomes

$$dU_2 = \delta Q_2 - P_2dV_2 + h_{2,e}dn_{2,e} \quad (14)$$

Given a very short residence time of the inhaling air in the bellows of the breathing simulator before it is exhaled, it is reasonable to assume $\delta Q_2 \approx 0$. Taking the time derivative, Eq. (14) then becomes

$$\frac{dU_2}{dt} = -P_2\frac{dV_2}{dt} + h_{2,e}\frac{dn_{2,e}}{dt} \quad (15)$$

Following the same procedure described above, Eq. (15) can be re-written as

$$c_vN_2\frac{dT_2}{dt} + [u_0 + c_v(T_2 - T_0)]\frac{dN_2}{dt} = -P_2\frac{dV_2}{dt} + [u_0 + c_v(T_{2,e} - T_0) + RT_{2,e}]\frac{dn_{2,e}}{dt} \quad (16)$$

[4] In the Luxfer 2003 User Manual, Toray T-700 and S2 Glass were described as the carbon-fiber and the fiberglass used in the fabrication of the SCBA cylinders; however, the types of carbon-fiber and fiberglass are not specified in the most recent version of the User Manual (2011).

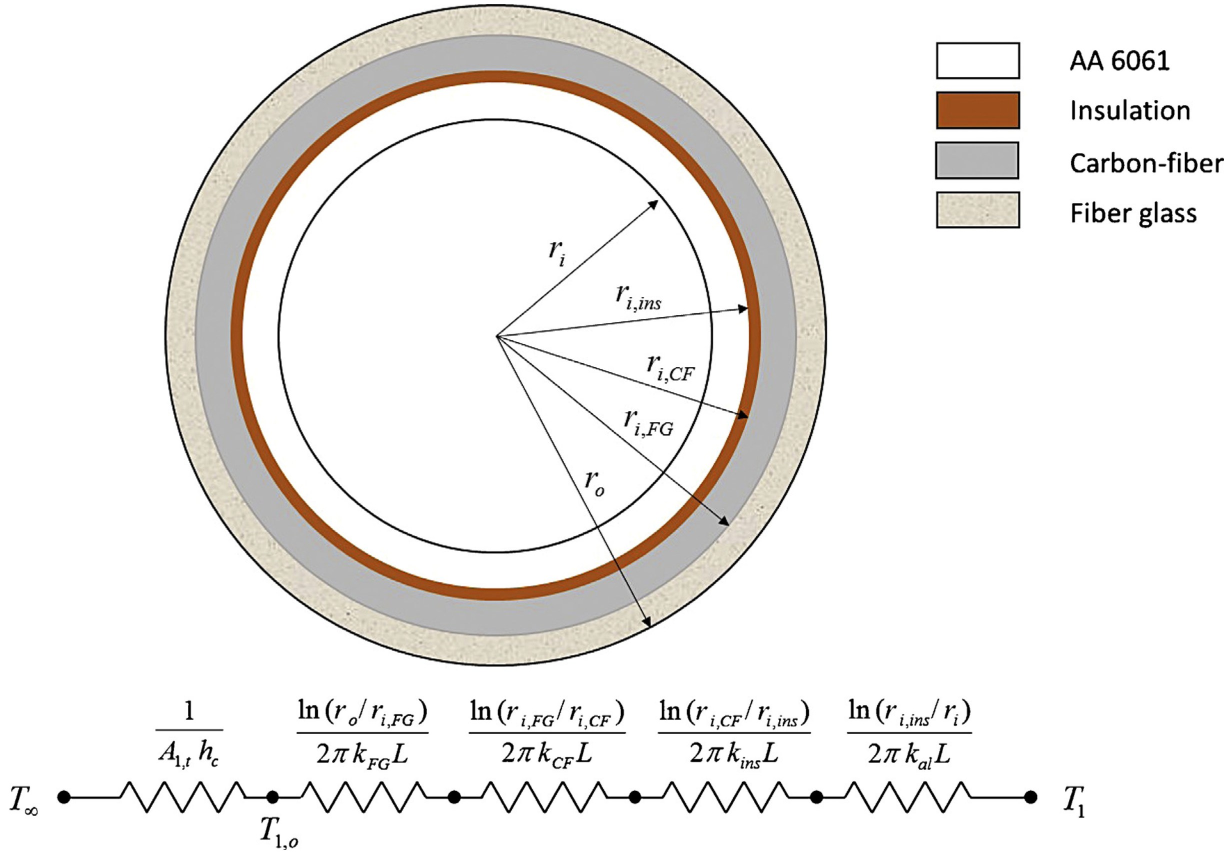

Fig. 6 – Schematic of a cross section of the SCBA cylinder with the associated equivalent thermal circuit for the composite cylinder wall.

A balance of the amount of air in the system gives

$\frac{dN_2}{dt} = \frac{dn_{2,e}}{dt}$

In addition, the accumulation rate of air in the breathing simulator (System 2) is balanced by the depletion rate of air in the SCBA cylinder (System 1) and is given by

$$\frac{dN_2}{dt} = \frac{dn_{2,e}}{dt} = -\frac{dN_1}{dt} \tag{17}$$

In the experiments, the air from the SCBA cylinder was pulled (inhaled) into the bellows by the breathing simulator at a time-varying inspired volumetric flow rate as prescribed in NFPA 1981. In the model, the air from the SCBA cylinder is drawn into the hollow cylinder through the action of the expanding piston to simulate the process following the same inhaling pattern. The mass inflow to the cylinder can then be expressed as:

$$\frac{dN_2}{dt} = \frac{dn_{2,e}}{dt} = \rho_{2,e}\frac{dV_2}{dt} = \frac{P_{2,e}}{RT_{2,e}}\frac{dV_2}{dt} \tag{18}$$

With $T_{2,e} = T_1 = T_{1,l}$ and using Eq. (18), it can be shown that Eq. (16) becomes

$$\frac{dT_2}{dt} = \left[\frac{(\gamma T_1 - T_2)}{N_2}\frac{P_{2,e}}{RT_1} - \frac{RT_2}{c_v V_2}\right]\frac{dV_2}{dt} \tag{19}$$

A quadratic polynomial was used to best-fit the tabulated temporal volume-change data for the lung breathing (inhaling) waveform for 40 L/min volume work rate prescribed in NFPA 1981, resulting in the following equation.

$$\frac{dV_2}{dt} = a_0 + a_1 t + a_2 t^2 \tag{20}$$

where $a_0 = -8.58 \times 10^{-5}$ m^3/s, $a_1 = 6.5 \times 10^{-3}$ m^3/s^2, and $a_2 = -5.1 \times 10^{-3}$ m^3/s^3. Eq. (20) can be integrated using the initial conditions at the beginning of the inhaling phase in the jth breathing cycle, $t = (j-1)(\tau_{in} + \tau_{ex})$, $V_2 = V_{2,bi}$ for $j = 1, 2, 3, \ldots, J$. For $j = 1$, $V_{2,bi} = V_{2,initial}$, which is the initial volume of the cylinder at the start of the experiment. Based on the estimation of the initial volume of the actual bellows used in the experiments, a value of 0.0005 m^3 for $V_{2,initial}$ is ascribed. For $j > 1$, $V_{2,bi}$ is the volume of the simulated bellows at the end of the exhaling phase of the $(j-1)$th breathing cycle.

Given the inhaling and exhaling durations τ_{in}, and τ_{ex} and the initial conditions of $T_{1,bi}$, $T_{2,bi}$, T_∞, V_1, $V_{2,bi}$, $N_{1,bi}$, and $N_{2,bi}$, the conditions (T_1, T_2, N_1, and N_2) of the SCBA cylinder and the simulated bellows during the inhaling phase of the jth breathing cycle can be determined by simultaneously solving Eqs. (12), (17), (18), and (19) coupled with Eqs. (10) and (20) using a fourth order Runge–Kutta method [11].

3.2. *During the exhaling phase of the jth breathing cycle*

For the jth breathing cycle, the following time interval encompasses the exhaling phase with an exhaling duration τ_{ex}:

$$j\tau_{in} + (j-1)\tau_{ex} \le t < j(\tau_{in} + \tau_{ex}) \quad j = 1, 2, \ldots, J$$

During this phase, the SCBA cylinder (System 1) and the simulated bellows (System 2) are de-coupled.

3.2.1. SCBA cylinder

During the exhaling phase, there is no air flowing out of the air cylinder, and the system (System 1) is closed. The first law of thermodynamics becomes

$$dU_1 = \delta Q_1 \tag{21}$$

Taking the time derivative with $N_1 = N_{1,ei}$ (closed system, $dN_1/dt = 0$) and following the derivations described above, it can be shown

$$\frac{dT_1}{dt} = \frac{U_{1,HT}A_{1,t}}{N_{1,ei}c_v}(T_\infty - T_1) \tag{22}$$

where $N_{1,ei}$ is the total amount (mol) of air in the cylinder at the *end* of the inhaling phase of the jth breathing cycle. The initial condition, $t = j\tau_{in} + (j-1)\tau_{ex}, T_1 = T_{1,ei}$, for Eq. (22) corresponds to the time at the end of the inhaling phase of the jth breathing cycle or the beginning of the exhaling phase of the jth breathing cycle, and $T_1 = T_{1,ei}$ is the temperature of the air in the cylinder at the end of the jth inhaling cycle.

3.2.2. Simulated bellows

During the exhaling phase of the jth breathing cycle and with $\delta Q_2 \approx 0$ and $T_2 = T_{2,l}$, the first law of thermodynamics applied to the simulated bellows cylinder yields

$$c_v N_2 \frac{dT_2}{dt} = -P_2 \frac{dV_2}{dt} + RT_2 \frac{dN_2}{dt} \tag{23}$$

Similar to the approach used in the inhaling phase, the rate of air exhaling from the cylinder can be expressed as

$$-\frac{dN_2}{dt} = \frac{dn_{2,l}}{dt} = -\rho_2 \frac{dV_2}{dt} = -\frac{N_2}{V_2}\frac{dV_2}{dt} \tag{24}$$

Substituting Eq. (24) into Eq. (23), it can be shown that $dT_2/dt = 0$, and $T_2 = T_{2,ei}$, that is the air temperature in the cylinder remains constant during the exhaling phase.

As with the approach used in the inhaling phase, a quadratic polynomial was also used to best-fit the tabulated temporal volume-change data for the lung breathing (exhaling) waveform for 40 L/min volume work rate prescribed in the NFPA 1981, resulting in the following equation.

$$\frac{dV_2}{dt} = a_0 + a_1 t + a_2 t^2 \tag{25}$$

where $a_0 = 10^{-4}$ m^3/s, $a_1 = -6.6 \times 10^{-3}$ m^3/s^2, and $a_2 = 5.2 \times 10^{-3}$ m^3/s^3. Eq. (25) can be integrated using the initial conditions at the end of the inhaling phase in the jth breathing cycle, $t = j\tau_{in} + (j-1)\tau_{ex}$, $V_2 = V_{2,ei}$, where $V_{2,ei}$ is the volume of the cylinder at the end of the inhaling phase of the jth breathing cycle for $j = 1, 2, \ldots, J$.

Given the inhaling and exhaling durations τ_{in}, and τ_{ex} and the initial conditions of $T_{1,ei}$, $T_{2,ei}$, T_∞, V_1, $V_{2,ei}$, $N_{1,ei}$, and $N_{2,ei}$ the conditions (T_1, T_2, N_1, and N_2) of the SCBA cylinder and the cylinder during the exhaling phase of the jth breathing cycle can be determined by Eqs. (22) and (24) coupled with Eqs. (10) and (25), $T_2 = T_{2,ei}$ and $N_1 = N_{1,ei}$.

Table 1 – Input parameters used for the model simulations.

$A_{1,t}$	$= \pi DL$
c_p	Using correlation from DIPPR [12]
D	0.16002 (m)
J	600
k	Using correlation from DIPPR [12]
k_{al}	167 W/m K (assuming aluminum alloy AA6061)
k_{ins}	0.03 W/m K (considered a representative value)
k_{CF}	0.71 W/m K (assuming carbon-fiber Toray T-700®)
k_{FG}	1.45 W/m K (assuming fiberglass S-2® Glass)
L	0.51816 m
$P_{1,initial}$	31.02×10^6 Pa
$P_{2,e}$	101×10^3 Pa
T_{amb}	296 K
T_∞	373 K, 423 K, or 473 K
V_1	6.85×10^{-3} m^3
$V_{2,initial}$	5×10^{-4} m^3
V_∞	1.4 m/s
δ_{al}	3.175×10^{-3} m (considered nominal value)
δ_{ins}	Calculated (based on the overall wall thickness, δ_{al}, δ_{CF}, and δ_{FG})
δ_{CF}	6.35×10^{-3} m (considered nominal value)
δ_{FG}	Assumed to be $3\delta_{CF}/4$
γ	1.4
μ	Using correlation from DIPPR [12]
ρ	Using correlation from DIPPR [12]
τ_{in}	1.25 s
τ_{ex}	1.25 s

The simulation starts in the inhaling phase of the 1st breathing cycle ($j = 1$) with the given initial conditions. The calculated conditions in the SCBA cylinder and the simulated bellows at the end of this inhaling phase are then used as the initial conditions for the simulation of the exhaling phase in the same breathing cycle. The calculated conditions in the SCBA cylinder and the simulated bellows at the end of this exhaling phase are used as the initial conditions for the inhaling phase simulation in the 2nd breathing cycle ($j = 2$), and the cyclic breathing processes continue until the Jth breathing cycle ($j = J$) is completed. Table 1 lists the input parameters used in the model calculations.

4. Results and discussion

A total of seven thermal exposure experiments were performed on the SCBA: one at 100 °C for 1200 s, two at 150 °C for 900 s, two at 150 °C for 1200 s, and two at 200 °C for 1200 s. The current NIST flow loop is limited to a maximum operating temperature of 200 °C. When multiple experiments were conducted at the same air flow temperature, the results were very repeatable, and the measured temperatures were within ±5 °C.

The results of the temperature measurements taken on the outside surface of the SCBA cylinder and model predictions are shown in Fig. 7. Comparing with the experimental

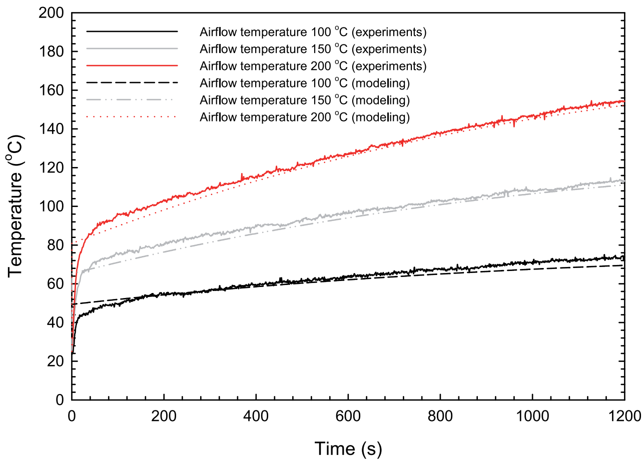

Fig. 7 – Temporal variations of the average SCBA cylinder outer face temperatures under the three airflow temperatures.

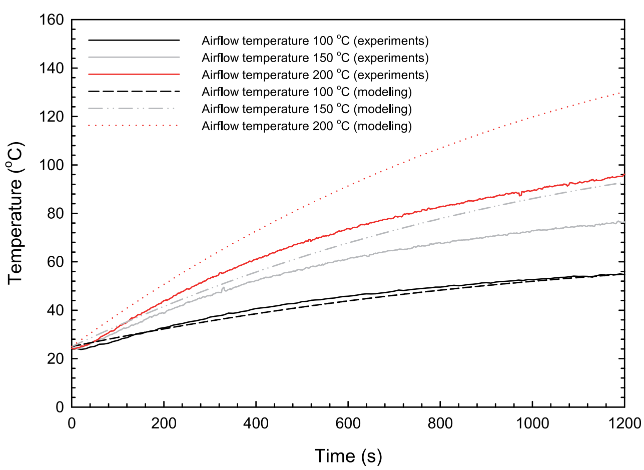

Fig. 8 – Temporal variations of average temperatures measured at the mouth of the mannequin headform under the three airflow temperatures.

measurements, the quasi-steady assumption used in the model to describe the heat transfer processes through the SCBA cylinder composite wall provides reasonable estimates of the cylinder outer surface temperatures except the initial sudden jump of the external wall temperature, which is the result of the assumption of instantaneous attainment of quasi-steadiness used in the conduction heat transfer calculations within the composite wall.

The temperatures measured at the left and right mouth of the mannequin headform under the same thermal exposure condition differ by less than 5 °C for all the experiments. In most cases, the differences were found to be 2 °C or less. Fig. 8 shows the temporal variations of the averages of the temperature measurements at the two mouth locations for the three air flow temperatures. The cyclic nature of the experimental data and calculations during the inhaling and exhaling phases is not apparent due to the time scale used in the figure. In addition, the experimental results were smoothed. The experimental measurements indicate that before the SCBA cylinder runs out of its air supply (about 45 min), the breathing air could reach temperatures above 50 °C or higher, depending on the thermal environment.

Fig. 8 also shows the model predictions of the temperatures of the air coming out of the SCBA cylinder for the three thermal exposure temperatures (i.e., T_∞ = 100 °C, 150 °C, and 200 °C). Given the large uncertainties in the convective heat transfer coefficient correlation, uncertainties due to thermal losses to the SCBA tubing, valves, and other components not included in the model, and the imprecise values used for the ill-defined thicknesses of the SCBA cylinder wall layers and the thermal conductivities of the carbon-fiber epoxy-resin composite, insulating, and fiberglass layers, the model performs satisfactorily well and captures the phenomenological processes in the thermal exposure experiments. Since carbon-fiber composite SCBA cylinders are not recommended be left in a fire or high-heat environment for a prolonged period [10], the model provides a useful tool to examine other extreme thermal exposure conditions under which experimental data are currently lacking or may be difficult to obtain. In addition, various breathing patterns (e.g., under duress during firefighting) can be easily incorporated into the model to study their effects on the thermal exposure processes.

5. Conclusions

An experimental elevated temperature flow loop was developed to study the thermal exposure of firefighter safety equipment up to 200 °C. This study focused on a full SCBA assembly. Wind tunnel air temperatures at 100 °C, 150 °C, and 200 °C were the three thermal exposure conditions used in the experiments. The average air speed of 1.4 m/s was set at the test section to simulate normal walking speed for humans. Experiments were conducted with thermal exposure durations up to 1200 s (20 min). Breathing was simulated using a mannequin headform donning a facepiece and a breathing simulator programmed with a breathing pattern prescribed by NFPA 1981. Measurements were made using type-K bare-bead thermocouples placed at the mannequin's mouth and on the outer surface of the SCBA cylinder. The experimental results indicated that increasing the thermal exposure severity and duration increased the breathing air temperatures supplied by the SCBA. Temperatures of breathing air from the SCBA cylinder in excess of 60 °C were observed over the course of the thermal exposure conditions used in most of the experiments.

A thermodynamic model was developed to describe the physical processes of the thermal exposure experiments. Other than the initial brief highly transient duration and given the uncertainties associated with the thicknesses and thermal conductivities of the composite layers of the tank wall, the model provided satisfactory predictions of the outer cylinder surface temperatures and the temperatures of the air leaving the SCBA cylinder and before inhalation by the mannequin headform.

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