University of Alberta

Development of Fabrics for Steam and Hot Water Protection

by

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ABSTRACT

Recently, use of steam and hot water in extracting and producing oil has become extensive, especially in bitumen extraction from oil sands and plants producing heavy oil. Temperatures of steam and hot water used are well above those that result in skin burns. This research reports on the development and testing of fabric systems intended for use in protective clothing to be worn by workers in the oil and gas sector for short-duration protection from both steam and hot water. To evaluate the fabrics developed, bench-scale tests were conducted with steam pressure of 210 kPa at 150 °C and hot water pressure of 0.6 kPa at 85 °C and with a flow rate of six l/min.

Results indicated that the energy transfer through the fabric systems under a jet of steam or hot water is a function of several inter-related material parameters such as mass, thickness, location of moisture barrier, fabric construction, compressibility and fabric system density. Fabric thickness and density were found to be the most important factors for steam and hot water protection.

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1. INTRODUCTION

As industrial processes evolve and new hazards are created in the workplace, there continues to be a need for high-performance advanced textile materials to keep workers safe. Depending on the workplace hazards, fabrics used for protective clothing must possess specific properties, such as heat and flame resistance (FR), or cut and abrasion resistance. The textile industry strives to develop fibres, fabrics and garment systems that will provide the needed protection for various hazardous occupations.

In the energy sectors of Alberta, especially in oil and gas industries, the use of pressurized steam and hot water has led to instances where workers have been seriously injured (Fennel, 2009). These workers were not adequately protected by the existing FR protective clothing used in these industries. At present there are no performance specifications or standard test methods for evaluating clothing for its ability to protect against pressurized steam or hot water exposure. Since 2006, research at the University of Alberta (UA) has focused on the development of a test method, test device and specifications for textile materials to be used to evaluate garments for protection against steam and hot water exposure (Ackerman, Crown, Dale, Murtaza, Batcheller, Gonzalez, 2012). The focus of this thesis is the further development of fabric systems to meet or exceed the specifications for protection against steam and hot water exposure that were established in the earlier research (Ackerman et al., 2012; Jalbani, Ackerman, Crown, van Keulen & Song, 2012). The thesis research consists of three phases. In the first phase, tests were conducted to understand the selected composite fabric systems and their performance upon exposure to pressurized steam[1]. In the second phase, based on results from phase one, fabric systems were developed to provide better steam and hot water protective properties than phase one fabrics and to provide improved protection to high pressure steam exposure. Phase three was the evaluation of prototype composite fabrics.

Problem statement

Pressurized steam, which is widely used in the oil and gas industries, is a common hazard for workers in these industries. The boilers used in the energy sector generate steam which may reach pressures as high as 4000 kPa, about 40 times atmospheric pressure (Ackerman, Crown, Dale, Paskaluk & Song, 2011). The steam is not visible and only becomes visible as it starts to condense. A jet of steam from a boiler or pipeline leak under this high pressure and temperature can travel a long way before becoming visible (Adams, 2006). The distance depends on the ambient temperature as well as the pressure and temperature of the jet of steam. Workers can accidently come into direct contact with steam and its condensate, as well as hot water and other liquids. Steam and hot water can easily penetrate the clothing system and seriously damage skin tissues. For those working in areas with high risk of steam exposure, burn injuries can lead to pain, permanent disability or even death (Fennell, 2009).

Purpose and justification

The overall purpose of this study was to design, develop and evaluate multi-component fabric systems for use in protective clothing to reduce and/or prevent burn injuries caused by steam and hot water hazards in the workplace. At

[1] Hot water protection was evaluated by Jalbani et al. (2012).

present, in the oil and gas industries and the larger energy sector, regular FR thermal protective clothing is used to protect against flash fire hazards. However, observations of workers and reports of their experiences investigated by UA researchers indicate that regular thermal protective clothing is not effective in preventing steam penetration and injury (Yu, Strickfaden, Crown & Olsen, 2012). There have been incidents documented by The Safety Association for Canada's Upstream Oil and Gas Industries (formerly known as Canadian Petroleum Safety Council), where workers have been injured by steam exposure, including one fatality (ENFORM, 2004). By understanding factors affecting heat and moisture transfer in fabrics during high pressure steam exposure, fabrics can be evaluated and improved. It was expected that this study would lead to the development of fabric systems which will improve the safety of individual workers exposed to steam and hot water hazards.

Objectives and hypothesis

In this research, fabric characteristics and properties that influence steam and hot water protection were identified. These included fabric thickness, mass, density and structure, as well as performance related properties such as heat transferred in steam and hot water testing. Fabric systems were then developed to minimize or to prevent burn injuries caused by steam and hot water. The objectives for this study were to:

1. Determine which fabric characteristics and properties contribute the most to reduced heat transfer and improved steam protection based on correlations of data from Phase I research;

2. Design a series of fabric systems for high pressure steam and hot water protection for garments that could be worn for short-term but high-risk exposure situation;
3. Develop prototype fabric systems; and
4. Test the newly developed fabric systems for energy absorption and time to reach the onset of second degree burn when exposed to steam and hot water.

To meet both objectives 1 and 4, the following null hypothesis was tested.

H_o1 – There are no significant correlations between fabric characteristics and properties and (a) steam protection parameters or (b) hot water protection parameters.

Limitations and delimitations

Limitations of this study include:

1. Only non-flame resistant insulating materials were available for testing.

The delimitations of this study are:

1. The study was limited to a small number of multi-layer fabric systems incorporating semi-permeable, polyurethane (PU) and polytetrafluoroethylene (PTFE) membranes.
2. Based on preliminary testing during Phase I, steam pressure for testing during Phase III was set at 210 kPa.
3. Testing for steam was limited to prescribed bench scale test procedures developed by UA researchers (Ackerman et al., 2012).

Definitions

Heat transfer: refers to the energy transfer from one system to another due to the temperature difference between them (Çengel, 2005, p.2). There will be an exchange of energy between the two systems until they reach an equilibrium state. Heat always flows from a high temperature system to a low temperature system. Energy in the form of heat can be transferred by three means: conduction, convection and radiation, and may also be coupled with mass (moisture) transfer. The units of measure are J/s or W.

Heat flux: is the rate of heat transfer per unit area normal to the direction of heat flow. The units for heat flux are W/m^2 (Çengel, 2005, p.10).

Moisture transfer: In this research, moisture transfer involves movement of water in the form of a vapour or liquid from a higher humidity zone to a lower humidity zone. Moisture transfer stops when the concentration gradient between the two zones becomes zero. Moisture transfer affects the heat transfer through fabrics.

Total thermal resistance (R_{ct}): is a quantity specific to textile materials or composites which determine the dry heat flux across a given area in response to a steady applied temperature gradient. It is expressed in m^2 C/W (ISO, 1993).

Total evaporative resistance (R_{et}): is a quantity specific to textile materials or composites which determine the latent evaporative heat flux across a given area in response to a steady applied water-vapour pressure gradient. It is in m^2Pa/W (ISO, 1993).

Condensation: Occurs when a vapour's temperature is reduced below its saturation temperature. It usually occurs when the vapour comes into contact with a surface with a temperature below the vapour's saturation temperature. It can also occur on the free surface of a liquid or even in a gas when the vapour is exposed to a temperature below its saturation temperature (Çengel, 2005).

First degree burn: involves the epidermis only. The skin experiences only the redness without blistering (Mosby, 2009).

Second degree burn: involves damage to the epidermis layers of the skin. The damaged site becomes red and blistered and it is also called partial thickness burn (Mosby, 2009).

Third degree burn: destroys both the epidermis and dermis layers of skin often involving subcutaneous layer and it is also called full thickness burn (Mosby, 2009).

Skin simulant sensor: in this research, sensor that absorbs energy in a manner similar to human skin absorbs the energy.

2. REVIEW OF LITERATURE

In this review, mechanisms of skin burn injuries will be discussed, followed by the heat and mass transfer theories, including the effect of water condensation on heat transfer. Most of the literature found on heat and moisture transfer through clothing discusses the movement of heat and moisture from the skin to the environment during thermal comfort research conducted at relatively low temperatures (e.g. 35 °C). In the current research, the heat and moisture transfer was considered from outside towards the body through clothing systems at high pressure and temperature (~100 °C).

Skin burn injuries

The human skin comprises three layers. The outer most layer is the epidermis followed by the dermis and finally the subcutaneous layer. The epidermis acts as a protective layer against penetration by gases and fluids. The outer most portion of the epidermis is constantly wearing off and being replaced with new cells. The cell growth occurs at the interface of the epidermis and dermis layers. Cell growth also occurs in deeper dermis layers. The dermis layer consists of blood vessels, connective tissue, lymph vessels, sweat glands, receptors and hair shafts. The subcutaneous layer consists of fatty tissues that attach the skin to underlying bones and muscles and also supply it with blood vessels and nerves (Williams, 2003).

Human skin is highly sensitive to thermal exposure over time. Skin burn injuries may occur with low heat flux exposures over long periods of time or with high heat flux exposures over short periods of time. The surface of human skin has a normal temperature range of 31 to 33 °C (Umeno, Hokoi, & Takada, 2001).

Stoll and Chianta (1969) reported that human skin experiences partial thickness or second degree burn injury when the epidermis temperature increases above 44 °C, approximately 80μm (base of the epidermis) below the surface of the skin. Burn injuries to human tissues depend on the extent of the temperature rise above the critical value (44 °C) and the duration that the temperature is above the critical value. Damage to the skin is a nonlinear function of the skin temperature. The rate at which burn injury occurs increases exponentially as skin temperature increases linearly. Stoll and Chianta further determined that at 72 °C human skin faces severe full thickness or third degree burn injury, which is irreparable.

Figure 2.1 shows the example of the "Stoll curve" using two temperature curves from this research. The Stoll curve shows temperature over time at which the onset of a second degree burn occurs. For example, in comparing temperature rise curves to the Stoll curve, temperature curve 1 intercepts the Stoll curve at 2.7 seconds hence the criteria for the onset of a second degree burn was reached. Temperature curve 2 did not intercept the Stoll curve and did not reached the burn criteria.

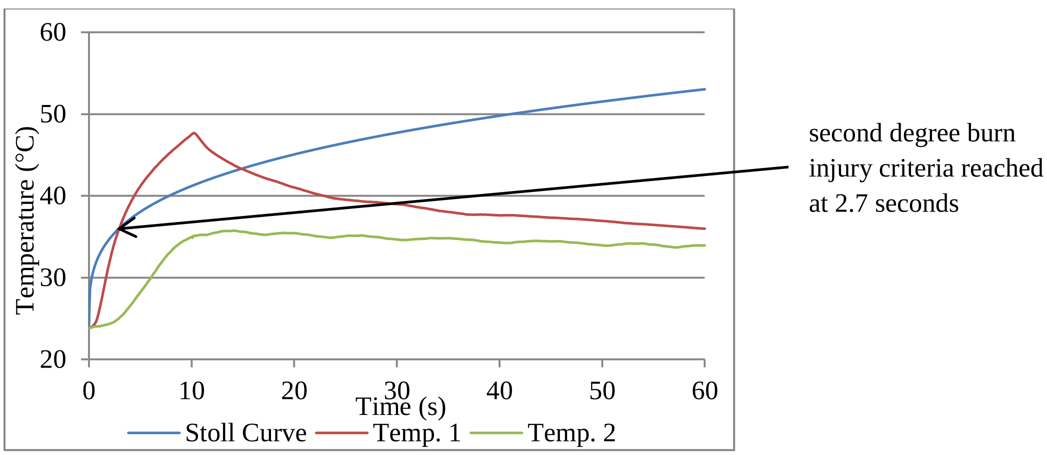

Figure 2.1. Example of Stoll curve use to predict time to reach onset of a second degree burn

Theories of heat and mass transfer in fabrics

Mechanisms of heat transfer

Heat transfer in textile fabrics/materials may occur by one or a combination of the three basic mechanisms of heat energy transfer: conduction, convection, radiation. Heat transfer through clothing systems is dependent on the intensity of the heat flux (Rossi & Zimmerli, 1996). Heat transfer through any medium is different at low and high heat fluxes (20 to 84 kW/m^2): at lower intensity heat exposure, heat is transferred to the air between the fabric layers and to the air between the skin and clothing, resulting in minimal burn injuries (Lee & Barker, 1987). Heat flows from a hot to cold substance and the greater the temperature difference that exists between the objects, the more rapid the flow of heat (Watkins, 1984).

Conduction of heat takes place when two objects or surfaces come into contact (Watkins, 1984). In the presence of a temperature gradient, energy transfer occurs in the direction of decreasing temperatures. The energy transfer is related to the random transitional motion and the internal rotational and vibrational motion of molecules. Higher temperatures are associated with higher molecular energies. Molecules collide with each other and the transfer of energy from more energetic electrons to less energetic ones occurs. In thermal protective clothing, conductive heat transfer starts when the clothing is in direct contact with both the heat source and the wearer's skin, provided that no air gap exists between the wearer's skin and the protective clothing. Conductive heat transfer can be calculated using Equation 2.1.

$$Q_{cond} = -kA\,\frac{dT}{dx} \qquad \text{.........Eq. 2.1}$$

Where

Q_{cond} = rate of heat conduction [W]

k = thermal conductivity [W/m.K]

A = heat transfer area [m^2]

dT/dx = temperature gradient [K/m]

The rate of conductive heat transfer through a medium depends on the geometry of the medium, its thickness and the thermal conductivity of the medium.

Convective heat transfer occurs by the movement of hot gases or liquids when a material is exposed to a heat source (Stull, 2000; Watkins, 1984). Watkins suggests that in thermal protective clothing, the outer layer of the clothing experiences convective heat transfer as the heat source transfers some of its energy through moving air. Convective heat transfer also occurs inside the garment when an air gap exists between the garment layers and the skin. Convective heat transfer can be calculated using Equation 2.2.

$$Q_{conv} = hA_s\,(T_s - T_\infty) \qquad \text{.........Eq. 2.2}$$

Where

Q_{conv} = rate of heat convection [W]

h = convective heat transfer coefficient [$W/m^2.K$]

A_s = convective heat transfer surface area [m^2]

T_s = surface temperature [K or °C]

T_∞ = temperature of fluid [K or °C]

Radiant heat transfer does not require air or any medium to transfer heat energy across space; however the presence of any matter may block the transfer of radiant heat (Watkins, 1984). Radiant heat transfer occurs "through space by the means of electromagnetic waves" (Geankoplis, 1993, p. 216). In thermal protective clothing, radiant heat transfer depends on the reflectivity or absorptivity of the outer surface. The surface of the outer layer is related to the properties of the textile material and the surface roughness used to construct the thermal protective clothing (Holcombe, 1981). Radiant heat transfer can be calculated using Equation 2.3.

$$Q_{rad} = \varepsilon \sigma A_s \left(T_s^4 - T_{surr}^4\right) \qquad \text{………Eq. 2.3}$$

Where

Q_{rad} = rate of heat radiation [W]

ε = emissivity of surface [dimensionless]

σ = Stefan-Boltzmann constant [$W/m^2.K^4$]

A_s = surface area [m^2]

T_s = temperature of surface [K]

T_{surr} = temperature of surrounding surfaces [K]

Mechanisms of moisture transfer in textiles

Moisture transfer in textiles includes both mass diffusion at the molecular level and bulk transport through the process of convection. The transport of one constituent, moisture, from a higher concentration region to a lower concentration region is called mass transfer. This is a diffusion process related to heat conduction. Moisture is transferred towards the lower concentration decreasing the concentration gradient. The rate of heat and mass transfer are influenced by the driving potential and the resistance (Lee, Ly & Postle, 1995). Gibson (2000) studied the water vapour transport properties of different membranes and membrane laminates with textile materials. Tests were conducted using an automated device that can test the mass transport properties of fabric specimens, membrane specimens or foams at different temperatures ranging from – 15 to 50 °C. Gibson reported that water vapour transmission proceeds purely by diffusion in nonporous materials and is driven by the vapour concentration gradient. In porous materials a vapour pressure gradient across the specimen creates a convective gas flow through the specimen which carries the water vapour with the flow. Gibson also reported that water vapour flux increased exponentially with increase in temperature. The water vapour diffusion increases at higher temperatures due to the temperature dependence of the diffusion coefficient of water vapour in air.

Coupled heat and mass transfer

Liquid water and water vapour transfer in textile materials includes water vapour diffusion, moisture absorption and capillary force effects (Li, 2001). Mass transfer occurs in the presence of a concentration gradient or pressure gradient. As energy is transferred towards the lower temperatures to decrease the temperature gradient, in the same manner, mass is transferred towards the lower concentration to decrease the concentration gradient. The rate of heat and mass transfer depends on the size of the gradient present between the two components. These transfers stop when the concentration/temperature gradient reaches zero.

Heat transferred from the environment to the body through clothing is basically governed by conduction as the air gap between the body and clothing is very small and convective heat transfer is negligible (Torvi, Dale & Faulkner, 1999). Heat transfer due to radiation from the environment to clothing is important depending on the temperature of the environment. Radiative heat transfer becomes very important when the temperature difference between the environment and the fabric, or the fabric and body is high. At room temperature, radiative heat transfer from clothing to the body is not significant and radiation contributes little towards the total energy transfer to the body. Textile sorption properties govern the evaporation process, therefore heat and mass transfer will occur by vaporization of water, diffusion of water, and condensation of water vapour (Schneider, Hoschke & Goldsmid, 1992).

Steam penetration through fabrics

Steam can easily pass through single layered fabrics because there are sufficient spaces lying between yarns and fibres for hot water vapour to enter. Rossi, Indelicato and Bolli (2004) analyzed the transfer of steam through different types of textile layers, considering specimen physical properties such as thickness and water vapour permeability. The steam utilized in their experiment was not under pressure as used in the oil and gas industry. They concluded that the materials which are impermeable to water vapour provided better protection against hot steam than the semi-permeable materials. Transfer of energy was dependent on the water vapour permeability of materials and on the thickness of the thermal insulation layer of the specimen. Desruelle and Schmid (2004) developed a procedure to study the effects of exposure to steam on the human body and to evaluate the protective capability of fabrics under steam stress. They concluded that the fabric thickness and water vapour diffusion have significant effects on protection against steam exposure. Sati, Crown, Ackerman, Gonzalez and Dale (2008) also developed a test protocol and cylindrical test device with a number of skin simulant sensors. They evaluated FR textile materials against pressurized steam exposure and concluded that fabric structure, steam pressure and distance between the jet and the surface of the fabric specimen significantly influence heat transfer upon steam exposure. They observed that the fabrics with high air permeability and very low resistance to water vapour penetration were less resistant to steam penetration. Steam easily penetrated through these fabrics and high rates of heat transfer were observed on a thermal energy sensor behind the specimen. The fabric with low air permeability showed better resistance to heat transfer.

Factors influencing thermal protection

Thermal protection provided by fabric is affected by (a) fabric properties such as thickness, fabric density, fabric mass, fabric moisture content, thermal conductivity, air permeability, air volume fraction and fabric construction (Crown, Ackerman, Dale, & Rigakis, 1993; Lee & Barker, 1987; Sun, Yoo, Zhang, & Pan, 2000; Tan, Crown, & Capjack, 1998; Watkins, 1984), and (b) fabric components such as multiple layering and coating (Crown et al., 1993; Holcombe, 1981). Crown and Dale (2005) stated that protective garments worn in the oil and gas sector should resist ignition and self-extinguish after the source is removed, should limit heat transmission during short term exposures to high heat flux and not shrink upon exposure. They also noted that protective clothing should keep its structural integrity and flexibility during exposure. For steam protection similar qualities would also be important.

Fabric thickness

Sun et al. (2000) studied the radiant protection properties related to fabric thickness. They found that fabric thickness has a direct impact on radiant protection: as fabric thickness increases, protective performance improves. They also studied the structural properties of fabrics and concluded that for radiant protection, plain weave structures provide better protection than knitted structures of the same thickness. This is because a knit structure normally has bigger pores than plain weave structures. Torvi and Dale (1998) studied the effect of individual thermal properties on thermal protection by varying fabric thickness from 0.3 to 2.0 mm. They concluded that the temperature of thick fabrics increases more slowly at the back of the fabric because increasing fabric thickness increases the internal resistance to heat transfer. The increase in thickness resulted in a lower rate of energy transfer between the heat source and the sensor and hence a greater time to reach the predicted onset of a second degree burn. Thermal resistance is determined by thickness divided by conductivity so thicker materials resist the flow of energy better.

Lee and Barker (1987) studied the effect of fabric properties on thermal protection in a high intensity 84 kW/m^2 flame exposure. They found that thermal protection is directly related to fabric thickness but the relationship between time required to the onset of a predicted second degree burn and thickness is not simply linear. Holcombe (1981) also studied the relationship between the time required to the onset of a predicted second degree burn and fabric thickness. In contrast to the results of Lee and Barker, Holcombe concluded that fabric thickness has a linear relationship with time required to the onset of a second degree burn. He also concluded that fibre types have very little influence on the performance of any fabric provided that the fibres keep their physical integrity.

Fabric density

Lee and Barker (1987) reported that thermal protection increases with a decrease in fabric bulk density. An increase in bulk density increases the fraction of fibres in the fabric with similar weight, reducing the air volume and leading to more conductive energy transfer. This means that a decrease in the fabric density increases the air volume fraction and leads to a decrease in conductive transfer.

Sun et al. (2000) also studied the radiant protective properties related to fabric weight. They found that fabric mass has a direct influence on radiant protection, which means that the radiant protection improves as fabric area mass increases. They found that cotton fabrics tend to have better resistance to radiant heat transfer than synthetic fabrics of the same mass per unit area, which could be due to the structure of the cotton fibre. Lee and Barker (1987) reported that fabrics with lighter mass tend to allow penetration of convective and radiant energy through open areas in the fabric structure; hence lower mass fabrics provide lower thermal and radiant protection.

Moisture in fabric

Lee and Barker (1987) reported that moisture content and thermal protective performance correlations are not as strong when compared to fabric thickness and density effects. However moisture effects are different for convective and purely radiant heat sources. The insulative properties of fabric change significantly with moisture content. When air spaces between fibres are occupied by moisture, the fabric becomes more conductive (Watkins, 1984). Barker, Schacher, Grimes, & Hamouda (2006) studied the effect of moisture on thermal protective performance of permeable and impermeable Kevlar® PBI® fabric systems exposed to a low heat flux (6.25 kW/m^2). They reported that for both systems, thermal protection decreases with water content up to 15% of the system's weight because of a large difference in the thermal conductivity between the fabric systems and water. Beyond 15%, and up to 50%, they also found that the thermal protection increased because of a large difference in the specific heat between the fabric systems and water. With further wetting, the protection decreases. Rossi et al. (2004) determined that the impermeable fabric systems offer better protection than semi-permeable when subjected to hot steam. This is because the impermeable layer of the fabric system prevents water vapour from passing into the insulation layer, less energy is transferred to the insulation layer and later to the sensor than with semi-permeable fabric systems.

Evaporative heat transfer occurs when a liquid changes its state to a gas. Evaporative heat exchange between the human body and the environment provides a cooling effect to the body (Watkins, 1984). Energy is required to change a liquid to vapour form, so as a liquid evaporates it absorbs energy from the near environment which produces the cooling effect. However, impermeable protective clothing systems restrict the movement of water vapour from the body to the environment. Rather than getting a cooling effect with evaporation, the trapped water vapour is absorbed by the fibres within the clothing system, creating a damp environment. Schneider et al. (1992) found that heat transfer increases with increase in moisture content of fibres. As a result, the risk of burn injury will increase when protective clothing is damp.

Lawson, Crown, Ackerman, & Dale (2004) studied the effects of moisture on heat transfer in multi-layer firefighter garments exposed to a low heat flux (10 kW/m^2) and a high heat flux (83 kW/m^2). They concluded that the moisture level and the location of moisture in clothing systems affect the energy transfer. At high heat flux, moisture in the external layer of the garment generally increased the thermal protection of the garment system due to energy exchange during the evaporation process. Moisture present in the inner layer provided the lowest protection due to the water's high heat capacity. The internal moisture in the fabric system became water vapour after absorbing the thermal energy and, trapped inside the garment, it condensed on the sensor and resulted in decreased thermal protection. At low heat fluxes, internal moisture decreased heat transfer through the fabric system and increased the thermal protection. As to the effect of moisture in the external layers at low heat fluxes, no conclusions could be drawn by these researchers.

When a textile material is exposed to a high energy source, energy is absorbed and stored by the textile materials even after the energy source is removed (Stull, 2000). The energy which is absorbed by the textile material is then transferred from the textile to the wearer's skin and also back to the environment in the form of heat. Moisture present in the protective clothing system increases the amount of stored energy due to the high heat capacity of water (Mell & Lawson, 2000). Therefore, to decrease the amount of stored energy and to decrease the rate of energy transfer in steam protective clothing, the total heat capacity of the composite fabric system should be as low as possible. Stored energy in the garment system can contribute to skin burn.

Thermal conductivity

Torvi & Dale (1998) reported that thermal conductivity of a fabric has a significant influence on increasing the rate of the temperature rise on the front of the fabric and a greater influence on the back of the fabric. Increasing thermal conductivity increases the rate of heat transfer within the fabric thus causing the rise of temperature at the back of the fabric which reduces the time required to the onset of a second degree burn. They concluded that increasing the volume fraction of fibres in the fabric increases the thermal conductivity.

Air permeability

Air permeability has a negative effect on thermal protection. Increasing air permeability decreases the thermal protective performance in both convective and radiant exposures (Lee & Barker, 1987). Gibson (1993) studied the influence of air permeability on heat and water vapour transfer through woven and non-woven fabrics and concluded that fabric air permeability plays an important role in the energy transfer particularly when there is an air space between the fabric and skin. Fabrics with high air permeability allow heated gases to penetrate through them and enhance the rate of heat transfer to the skin through convection. Fabric porosity and material thickness are the key factors related to the air permeability. High porosity allows energy transfer through radiation. Gibson also stated that heat and water vapour transfer both increase greatly when air flow through fabric occurs.

Air volume fraction

The air volume fraction of the fabric structure has an influence on the thermal protective performance of a fabric. Lee and Barker (1987) reported that thermal protective performance of fabric increases as air volume fraction increases in both convective and radiant exposures. Fabric porosity is a measure of the air fraction and affects air permeability. It establishes the rate of heat transfer in intense exposures. Air and fibre conduction dominates in dense and heavier weight woven and nonwoven fabrics.

Fabric structure

Lee and Barker (1987) reported that nonwoven needle felted fabrics provide more protective insulation in comparison with the same mass of knit and woven structures. This protective insulation differs due to the air-volume fraction and porosity of different fabric constructions. Non-woven fabrics, which are composed of random fibre arrangements, may have a larger air-volume fraction than the same area mass of a woven construction. Sun et al. (2000) studied radiant protective properties of fabrics and also concluded that air permeability of fabrics depends on their structures. The air permeability of knitted fabrics is generally higher than that of woven fabrics, and plain weave structures are more air permeable than twills of the same mass. They also reported that pores within the fabric structures are influential factors in air transfer. As the fabric becomes denser, two scenarios can be observed. Convective heat transfer through the fabric decreases due to a decrease in air circulation and conductive heat transfer increases as the fibre portion increases and air portion decreases.

Multi-layering and coating

Holcombe (1981) studied the protective performance of flame resistant fabrics and reported that the thermal protection of multi-layer fabrics is far better than single layer fabric of equivalent weight or thickness. This is due to the entrapment of air between the fabric layers which increases the overall thermal protection of the assembly. He concluded that the performance of multi-layer fabric systems containing a woven outer layer of flame resistant fabric in combination with a thick, low-density insulation fabric offered significantly better thermal performance in convective heat transfer than single layer fabrics of the same mass. However, it should be noted that the benefit of the air entrapment between the fabric layers will be lost if the multi-layers are laminated together into a single composite.

Baitinger and Konopasek (1986) studied the thermal insulative performance of single-layer and multi-layer fabric assemblies and reported that multi-layering provides not only an increase in thickness but also incorporates an air layer between the two fabric layers improving insulation. Spaces between multi-layers of clothing significantly affected the heat transfer rate, time to reach maximum heat transfer rate and the total energy transfer (Crown, Ackerman, Dale, & Tan, 1998).

Summary

In the current research, the transfer of heat and moisture through clothing systems toward the body under steam and hot water exposure are considered. After considering the literature reviewed, few references were found regarding steam permeability of thermal protective clothing. Rossi et al. (2004) determined that the impermeable fabric systems offer better protection than semi-permeable fabrics when subjected to hot steam. Temperature has a significant influence on water vapour transfer through fabric systems because of the temperature dependence of the diffusion coefficient of water vapour in air. Fabric system properties such as fabric thickness, fabric structure, air permeability and water vapour permeability influence the rate of heat transfer during steam exposure (Gibson, 2000). The structural stability of fabric is an important factor in steam protective clothing: fabric should keep its structural integrity and flexibility during exposure to high pressure steam jets. In this research some of the important effects of fabric characteristics such as mass, thickness, thickness under pressure, density and density under pressure will be investigated for both steam and hot water exposures.

3. PHASE I RESEARCH[2]

Tests were conducted in Phase I of this research to understand selected composite fabric systems and their performance upon exposure to pressurized steam. An experimental design was used to determine the effect of fabric characteristics on energy absorption and time to reach the onset of a second degree burn under small-scale steam testing. The independent variables were the mass, thickness, density and evaporative resistance of the fabric systems.

Fabrics for evaluation in Phase I were selected from the larger group of fabrics used for the initial steam project at University of Alberta. A series of semi-permeable, permeable and impermeable fabrics (Table 3.1) were supplied by several manufacturers. It was attempted to find fabrics in each category that varied systematically on area mass and thickness, and for thick fabrics, on compressibility. One permeable, six semi-permeable and two impermeable fabric systems with different structures were tested.

In the preliminary work, it was found that permeable fabrics were not able to provide any protection from steam exposure and so only one of these (Fabric A2) fabrics was considered here. The other fabrics selected were either semi-permeable or impermeable to water vapour and consisted of two or more components. Semi-permeable fabric systems (coded B) consisted of two layers or three layers (tri-laminate) with a semi-permeable membrane laminated between an outer fabric and a lining or insulation layer. The impermeable fabric systems (coded C) were coated/laminated fabrics. Table 3.1 provides the component details of each fabric systems.

[2] A version of this chapter has been published as part of Ackerman et.al (2012)

Table 3.1. Fabric description

Fabric code	Description	Outer layer	Middle layer	Inner layer
Permeable				
A2	Quilted thermal liner	woven aramid	none	non-woven reprocessed aramid felt
Semi-permeable				
B9	Tri-laminate	fleece aramid	PU membrane	fleece aramid
B9/10	Quilted thermal liner	woven aramid	non-woven reprocessed aramid felt	PU membrane as inner most layer
B10	Tri-laminate	woven aramid with water replant finish	PTFE membrane	fleece aramid
B11	Tri-laminate	woven aramid	PTFE membrane	jersey aramid
B12	Two-layer laminate	woven aramid with fluorocarbon finish	PU membrane	none
B15/16	Tri-laminate	jersey aramid	FR PU membrane	jersey aramid
Impermeable				
C18	Two-layer coated	silicone coating	none	woven aramid
C20	Two-layer laminate	chemical barrier laminate	none	non-woven aramid

The permeable fabric, A2, consisted of a plain-woven aramid face next to a non-woven fabric followed by a felt and finally a non-woven layer. Fabric A2 was included because it was the same as B9/10, except that B9/10 included a semi-permeable PU membrane on the "back" of the fabric. One semi-permeable fabric, B9, consisted of an aramid/carbon blended fleece on both the face and the back of the fabric with a semi-permeable PU membrane between. Fabric B10 consisted of an aramid/carbon blended, plain-woven fabric on the face followed by a semi-permeable PTFE membrane and an aramid fleece fabric on the back. The outer layer of the B10 fabric had a water repellent (WR) finish. The B11 fabric consisted of an aramid/carbon blended twill-woven fabric on the face followed by a semi-permeable PTFE membrane with an aramid single jersey fabric on the back. The B12 fabric consisted of two layers with an aramid fabric twill-woven fabric on the face with a semi-permeable PU membrane on the back. This fabric also had a fluorocarbon water repellent finish. The B15/16 fabric is tri-laminate. Both sides of the fabric consisted of an aramid single jersey with a semi-permeable PU membrane laminated between. One impermeable fabric, C18, consisted of an aramid twill-woven fabric with an impermeable silicone coating on the face side of the fabric. The other impermeable fabric, C20, consisted of an aramid/carbon blended non-woven with an impermeable chemical barrier laminated on the face side of the fabric.

Methods

Fabric sampling and preparation

Fabrics were not laundered as fabrics were received in dyed and finished form. Specimens were cut from twenty metre rolls that were supplied by several manufacturers. Five large samples were cut from each roll. Specimens for two replications of fabric characteristic, performance properties and small scale steam testing and hot water testing were cut from two of the samples. Individual fabric specimens were cut in such a manner that, for any test, each specimen contained a different set of warp and weft yarns. The remaining three samples were used for cutting of large specimens for full-scale validity testing.

All fabric specimens were conditioned at a relative humidity of 65 ± 2% and temperature of 20 ± 2 °C for 24 hours according to CAN/CGSB-4.2 NO.2-M88 (CGSB, 1988). Fabric characteristics such as thickness, mass and performance properties such as air permeability, evaporative resistance and thermal resistance were determined following CGSB and ISO standard test methods, as follows.

Fabric characteristics

Mass. The conditioned mass of each fabric was determined according to CAN/CGSB-4.2 No.5.1 – M90. The mass was calculated in grams per unit area (g/m^2) (CGSB, 2004a).

Thickness. The thickness of each fabric was determined according to CAN/CGSB-4.2 No. 37-2002 and was reported in millimeters at 1 kPa applied pressure (CGSB, 2002a).

Thickness under pressure. The thickness under pressure was determined according to CAN/CGSB-4.2 No. 37-2002 and was in millimeters (CGSB, 2002a). Maximum compression was achieved at a pressure of ~ 11.6 kPa.

Density. Fabric density (g/m^3) was calculated from fabric mass per unit area and the fabric thickness using equation 3.1.

$$\rho = \frac{m}{t} \qquad \text{.......Eq. 3.1}$$

Where,

ρ = density (kg/m^3)

m = mass per unit area (kg/m^2)

t = thickness (mm)

Thickness change. Thickness change (%) was calculated from the fabric thickness at 1 and 11.6 kPa, using equation 3.2.

$$\Delta t(\%) = \frac{t - tp}{t} \times 100 \qquad \text{......Eq. 3.2}$$

Where,

Δt = Thickness change (%)

t = thickness (mm)

tp = thickness under pressure at 11.6 kPa (mm)

Performance properties of fabrics

Air permeability. The air permeability of each fabric was determined according to CAN/CGSB-4.2 No. 36-2002, using Frazier high-pressure air permeability apparatus with the differential between the air pressure on opposite sides of the fabric equal to 12.7 mm of water. Air permeability was reported in *l*/cm^2/sec (CGSB, 2002b).

Evaporative resistance (R_{et}). The water-vapour resistance of each fabric was determined according to ISO 11092, using a sweating guarded-hotplate apparatus. R_{et} was reported in m^{2}Pa/W (ISO, 1993).

Thermal resistance (R_{ct}). The thermal resistance of each fabric was determined according to ISO 11092, using sweating guarded-hotplate apparatus. R_{ct} was reported in m^{2}C/W (ISO, 1993).

Water-vapour permeability. Based on water-vapour resistance and thermal resistance of each fabric, water-vapour permeability was calculated according to ISO 11092. It was reported in g/m^{2}Pa·h (ISO, 1993).

The fabric characteristics and performance related properties are reported in Table 3.2 and 3.3, as mean values of 10 specimens, except mass, which is the mean of 25 specimens.

Table 3.2. Fabric characteristics

Fabric code	Mass[1]	Thickness[2]	Thickness under pressure[3]	Density[4]	Density under pressure[5]
A2	350	4.8	2.0	73	173
B9	481	5.0	2.4	95	202
B9/10	423	4.6	2.1	91	203
B10	507	2.5	1.6	201	307
B11	273	0.9	0.7	303	409
B12	261	0.7	0.5	389	540
B15/16	203	0.9	0.6	223	320
C18	776	1.2	0.9	656	909
C20	273	1.7	0.8	165	333

[1] *g/m^2, following CAN/CGSB-4.2 No.5.1 – M90*
[2, 3] *mm, following CAN/CGSB-4.2 No. 37-2002*
[3, 5] *at 11.6 kPa*
[4, 5] *reported in kg/m^3*

Table 3.3. Fabric performance properties

Fabric code	Air permeability[1]	Thermal resistance[2]	Evaporative resistance[3]	Water-vapour permeability[4]
A2	46.0	0.20	Not tested	Not tested
B9	0.22	0.17	32	0.05
B9/10	0.00	0.19	26	0.06
B10	0.26	0.12	32	0.05
B11	0.18	0.09	16	0.10
B12	0.00	0.25	22	0.07
B15/16	0.20	0.10	36	0.05
C18	0.00	0.10	628	0.00
C20	0.00	0.10	591	0.00

[1] *l/cm^2/s, following CAN/CGSB-4.2 No.36-2002*
[2] *m^{2}C/W, following ISO 11092:1993*
[3] *m^{2}Pa/W, following ISO 11092:1993*
[4] *reported in g/m^{2}Pa·h*

In Phase I research the dependent variables, absorbed energy and time to reach the onset of a second degree burn were determined using a laboratory test device developed by UA researchers (Ackerman et al., 2012). The laboratory test device was used to test two replications of five specimens of each fabric type. B9/10 fabric was tested with both the face and membrane (B9/10M) facing the steam exposure. Only one replication of A2 and B9/10M was tested. The small scale testing device measures the energy transfer through the fabric when exposed to high pressure steam. A skin simulant sensor is used to measure the heat transfer through the fabric. This sensor is connected to a data acquisition system that records the temperature as a function of time. The pressure during these tests was 210 kPa, the steam exposure time was 10 seconds and the temperature of the steam was 150 °C. The temperature and time data were collected for 60 seconds, which includes 10 seconds exposure time and 50 seconds post exposure to incorporate any effects of stored energy. Heat flux data were determined and were used to calculate the total absorbed energy. The heat flux history was used in a multi-layer skin model to determine the time required to the predicted onset of second or third degree burn. The test procedure for steam exposure has been validated by UA researchers through field trials (Ackerman et al., 2012).

Statistical analyses

Statistical analyses were conducted using PASW (SPSS) software version 18 (PASW, 2009). Descriptive statistics were calculated for each dependent variable for each fabric type. Two-way analyses of variance (ANOVA) of fabrics by replication on the absorbed energy data established no significant difference between replications 1 and 2, so pooled data were used in one-way ANOVA with Duncan's post-hoc test performed to determine the differences among fabric systems on absorbed energy. Correlations between absorbed energy and fabric characteristics and properties were also determined.

Results: Phase I experiments

Test results are summarized in Table 3.4.

Table 3.4. Steam test results

Fabric code	Replication	Time to second degree burns[1]	Time to third degree burns[2]	Absorbed energy[3]
A2	1	0.3	11.7	571
B9	1	25.9*	>60	173
B9	2	22.7*	>60	179
B9/10	1	1.0	14.9*	381
B9/10	2	1.0	14.4	430
B9/10M	1	8.3	>60	177
B10	1	>60	>60	137
B10	2	>60	>60	143
B11	1	5.0	46.7*	288
B11	2	5.1	46.2*	273
B12	1	1.3	15.3	404
B12	2	1.2	14.9	410
B15/16	1	6.5	>60	220
B15/16	2	5.9	>60	226
C18	1	>60	>60	161
C18	2	47.9*	>60	176
C20	1	>60	>60	80
C20	2	>60	>60	84

[1, 2] *seconds*
[3] *kJ/m*^{2}.
[1, 2, 3] *are means of 5 specimens*
** indicates that one or more of the five specimens in the set did not show a burn injury within the data collection period.*
If no predicted second or third degree burn injury occurred within the 60 seconds data collection time period the result is indicated as >60 seconds.

The results of one-way ANOVAs for the absorbed energy data (Table 3.5) indicated that the fabrics differed significantly from each other. Duncan's post-hoc test results (Table 3.6) indicated that the steam test was able to differentiate the fabrics into six distinct groups.

Table 3.5. ANOVA: fabric effect on absorbed energy

		Sum of squares	d.f.	Mean square	F	p
Steam absorbed energy	Between groups	1029245	8	128656	176.9	0.000
	Within groups	55267	35	727		
	Total	1084512	84			

Table 3.6. ANOVA with Duncan's post-hoc test: fabric effect on steam absorbed energy

Fabric code	Steam absorbed energy (kJ/m^2)
C20	82
B10	140
C18	169
B9	176
B9/10M	177
B15/16	223
B11	281
B9/10	406
B12	407

means grouped by vertical lines are not significantly different at $p<0.05$ when tested by Duncan's post-hoc test. A2 fabric was not included in ANOVA analysis because no protection was provided and the second degree burn time was similar to bare sensor test.

Table 3.7 shows the correlations between absorbed energy and the fabric characteristics and properties. The results showed strongest correlations with density, density under pressure (at 11.6 kPa) and thickness under pressure (at 11.6 kPa). Density under pressure and thickness under pressure are inter-related as mass and thickness under pressure are used to calculate the density under pressure.

Table 3.7. Pearson correlation (r^2) for steam absorbed energy and fabric characteristics and properties.

Fabric characteristics and properties	r^2 steam absorbed energy
Density	0.856**
Density under pressure	0.887**
R_{ct}	0.038
R_{et}	-0.492
Water vapour permeability	0.438
Mass	-0.697**
Thickness	-0.641**
Thickness under pressure	-0.730**
Thickness change	-0.440**

** *Correlation is significant at the 0.01 level*

Conclusion: Phase I

Phase I results indicated that a fabric system for steam protection and hot water protection should have at least a semi-permeable or impermeable barrier. The permeable fabric system, A2, performed very poorly in comparison to the fabric systems with semi- and impermeable barriers. Examination of the tested specimens from two fabrics with non-woven felt insulation layers, A2 and B9/10, showed displacement of the fibres in the location of the steam jet upon pressurized steam exposure. These easily deformed fabrics also performed poorly suggesting that the fabric system must retain its structural integrity upon exposure to pressurized steam to provide the best protection. It was noted that fabric B10, C18 and C20 had times to onset of a second degree burn greater than 60 seconds. The structure of B10 fabric suggests that fabric systems with an insulation layer underneath the semi-permeable or impermeable membrane performed better than other semi-permeable fabric systems. It should also be noted that fabrics B9 and B9/10M which also have an insulation layer beneath a semi-permeable membrane are not significantly different from C18 impermeable fabric, while other semi-permeable fabrics without an insulation layer provided less protection. This indicates that it is not necessary to have an impermeable water vapor barrier to achieve a specified level of protection, but an insulation layer is required.

4. **METHODS**

This research was conducted in three phases. Phase I, part of a larger study, was completed and published (Ackerman et al., 2012) and described in Chapter 3. In Phase II, based on results from Phase I, multi-layer prototype fabrics were developed that are intended to have better steam and hot water protective properties than the fabrics selected in Phase I. Phase III was the evaluation of the developed prototype fabrics.

Phase II: Fabric design and prototype development

Phase I work suggested that for the fabrics to protect against steam and hot water they needed certain characteristics. First, fabrics that allow liquid water penetration cannot protect against steam and hot water hazards (Ackerman et al., 2012). Second, the position of the membrane relative to the wearer's skin in semi-permeable fabric systems is an important factor in providing protection against steam and hot water hazards. The membrane should be placed farthest from the wearer's skin. Third, the insulation underneath the semi-permeable membrane is necessary to minimize the heat transfer through the fabric system to the skin. Results of Phase I research also suggested that it is not necessary to have an impermeable water vapor barrier to achieve a specified level of protection (e.g. fabric B10). Garments incorporating semi-permeable membranes allow water vapour from the body to escape through the clothing and hence should provide better physiological comfort for the wearer. Observations suggested that the semi-permeable membrane must be protected with a fabric to prevent rupture or damage of the membrane upon pressurized steam exposure and from abrasion in use. Therefore it was concluded from Phase I that a suitable fabric system might consist of three components: an outer fabric, a semi-permeable membrane and an insulation fabric. It was also noted during Phase I testing that the fabric system should maintain its structure and should not compress upon exposure to pressurized steam.

It was apparent from materials tested in Phase I that existing liquid moisture barrier material in the market place and outer layers performed well and provided protection from steam. Therefore this research focused on the development of the insulation layer. Based on Phase I observations, the following criteria were established for the insulation layer.

- low density (high thickness/mass ratio)
- flexible
- minimum compressibility
- retain structural integrity

Three woven structures (A, B and C) were developed for the insulation layer. Each of these three fabrics was prepared in a towel manufacturing unit in Karachi, Pakistan. Thus, only cotton fabrics could be produced. Three different corrugated structures were woven on terry looms from cotton yarn (single, ring-spun, ~37 tex for warp and weft). These fabrics were woven on a loom in continuous operation with the existing warp beams used for towel production. Thus, because very short portions (3 metres) were woven the warp yarn of the developed prototype insulation fabrics could not be specified but had to be the existing yarn on the looms. Rather than producing pile loops, the fabrics were woven with ridges in the horizontal direction creating a corrugated structure. Three sets of yarns are used on the terry looms. Two sets are warp: a ground warp and a pile warp. The third set of yarns is weft or filling yarns. The ground warp set was used to make the body of the fabric while the pile warp set was used to make the corrugated ridges on the surface of the fabric. Ten weft yarns were inserted into the pile shedding and loosely laid before being beaten into the fell of the fabric to form the ridges. The slack in the pile warp yarns was pushed up by a final weft shot interlacing with both the pile and ground warp yarns and became a corrugation (as shown in Figure 4.1). Fabric A was prepared with face-side ridges with a height of 3mm and the back flat for potential lamination to a semi-permeable membrane and outer fabric. Fabric B was prepared with both sides having ridges with a height of 1.5mm on each side. Fabric C was prepared with face-side ridges with a height of 2mm and the back flat as in fabric A. However, the ridges of fabric C were wider than those of fabric A.

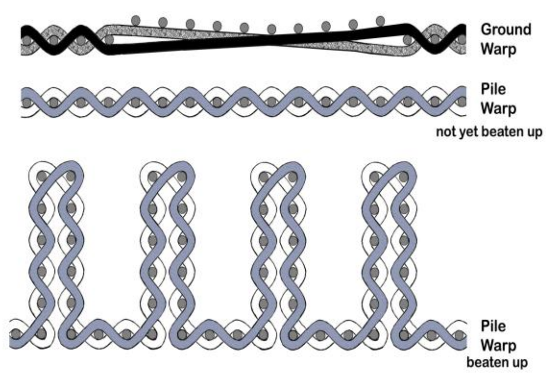

Figure 4.1. Cross-section of fabric A

Once the first three fabrics were received, it was apparent that the yarn was heavy. For this reason a lighter woven fabric was purchased. This fourth fabric (D) also had corrugated structure but incorporated lighter yarns than were used in the first three fabrics. This fabric was also made from cotton yarns (single, ring-spun, ~30 tex for warp and weft).

Three knit fabrics were also prepared (E, F and G). Two of these (E and F) were weft knits, double sided single rib and flat-back single rib using cotton yarns (single, ring-spun, ~20 tex). The third fabric was warp knit terry using polyester filament yarns (multi-filament, ~56 dtex/100). Although polyester is not ideal for steam protection, polyester has low moisture absorbency and to check the effect of low absorbency on steam protection this fabric was included. Each of these three fabrics was prepared and finished in a knit manufacturing unit in Karachi, Pakistan.

Rib knit constructions are most commonly used for sleeve cuff and neckbands (garment trim) because of their elasticity and ability to retain their shape. The single rib knit structure results from the alternate positioning of the knit loop on the face and reverse of the fabric. This structure produces raised ribs alternating with a flat space on each side of the fabric. The ribs are formed in the length-wise dimension. In single rib the two sides of the knit fabric look identical (Figure 4.2) while single flat back rib has ribs only on the face of the fabric, with the back being flat (Figure 4.3). Flat back rib fabric is potentially useful for bonding to a semi-permeable membrane and outer fabric.

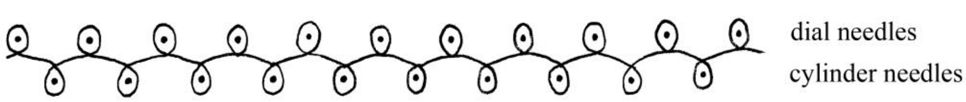

Figure 4.2. Single rib knit structure

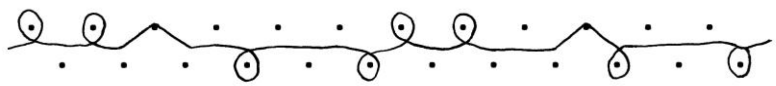

Figure 4.3. Single flat back rib knit structure (one repeat)

The warp terry knit fabric was produced with the ridges in the width-wise dimension of the fabric. The warp terry knit machine had a three bar warp with a set of pile yarns fed from the bottom bar, a set of ground yarns fed from the top bar and set of float yarns fed from the middle bar. Pile yarns were over fed by 2.5 times relative to the ground yarns to form the loops on both sides of the fabric. Lengthwise stability was achieved by the loops knitted from the middle bar. Figure 4.4 shows the warp terry knit fabric structure.

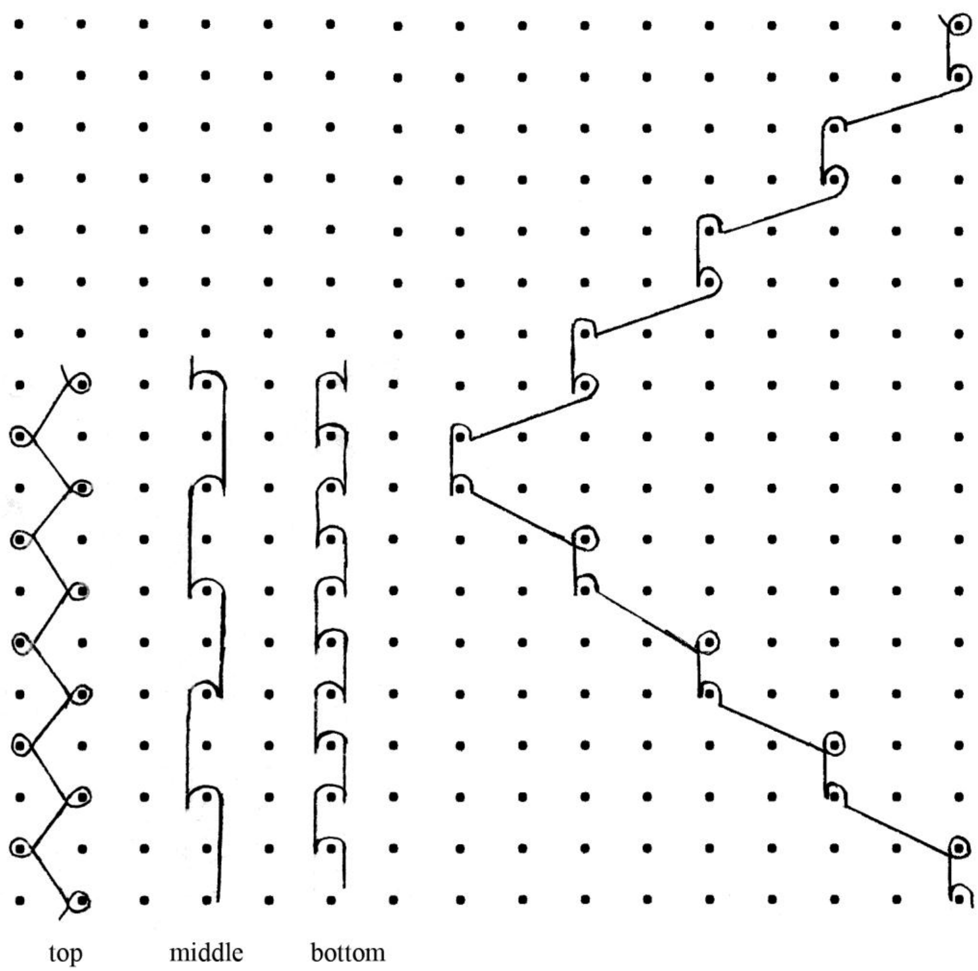

Figure 4.4. Warp terry knit structure

It should be noted that the developed fabrics were not flame resistant, but will need to be. These fabrics will be used to construct garments for oil and gas sector workers where flash fire hazards exist. Garments for these workers require flame resistance as specified in standards such as CGSB-155.20-2000 (CGSB, 2000). Steam protective material must therefore meet the criteria set out for flash fires in order to meet the protective work wear standards. Flame resistance was desirable for the fabric developed but it was not possible in this research to arrange the weaving and knitting of fabric from flame resistant synthetic yarns[3]. Flame resistant finishes were not applied to the developed fabrics[4]. The short pieces of fabric were received unfinished from the mill as greige goods[5].

To evaluate and characterize the developed fabrics for steam and hot water protection, it was necessary to have an outer layer and semi-permeable membrane material. As it was not practical to laminate small prototype insulation fabrics, it was decided to use one of the fabrics (B12) from Phase I. This fabric consisted of an outer woven aramid fabric bonded to a semi-permeable PU membrane.

Determination of fabric characteristics

For each fabric system, thickness, thickness under pressure, mass, density, and density under pressure were determined according to CGSB standard test

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[3] The factories developing the prototype (short run) fabric were using cotton yarns in their normal production process. The introduction of synthetic yarns would contaminate their production.
[4]The developed fabrics were too short (3metres) for flame resistant finishing to be applied after weaving.
[5] A minimum of thirty metres of fabric is required for routine finishing (eg. de-sizing, bleaching etc...) before sending for an additional processing for the application of a flame resistant finish. An attempt was made to finish the first three woven fabrics, by stitching to a running lot of fabric and exposing to routine finishing procedures, on half of the sample (1.5 metre), to perform the finishing. However, some of the fabric was lost therefore further finishing on the short pieces not attempted.

methods. These methods are reported in Chapter 3. Fabric system thickness change percent was calculated using Equation 3.2.

To determine the pressure required to obtain the maximum compression of each fabric system to use in the measurements of thickness under pressure and density under pressure, thickness values were recorded at increasing levels of pressure. The results were plotted (pressure vs. thickness). Figure 4.5 shows how each fabric system compresses differently under the range of pressures. However, it also shows that each of the fabric systems has reached its maximum compression at a pressure of ~ 13.8 kPa.

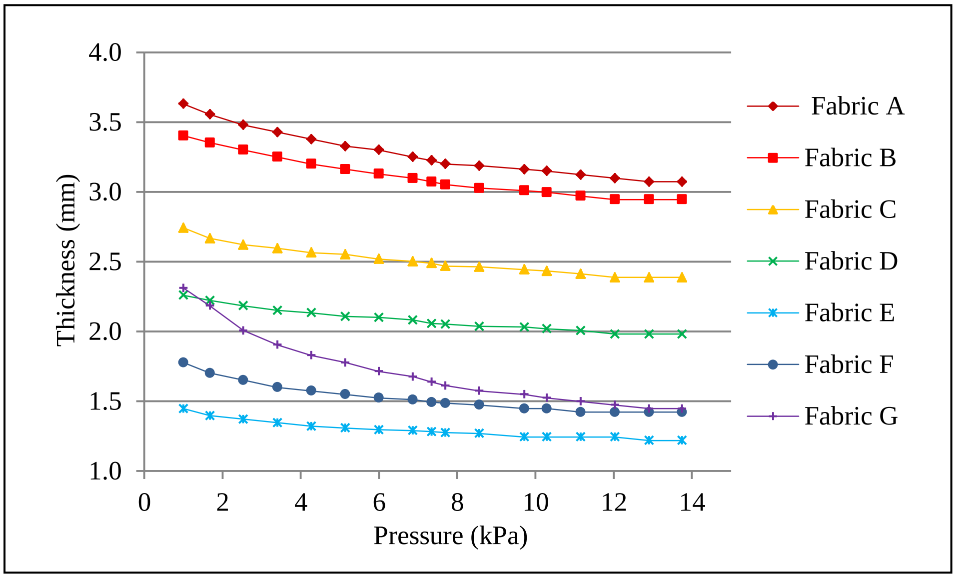

Figure 4.5. Effect of pressure on fabric system thickness

It should be noted that the variables in this study are not entirely independent of each other. Mass and thicknesses are used to calculate the density and density under pressure, while thickness and thickness under pressure are used to calculate the thickness change.

Prior to all testing, the woven fabrics (A, B and C) were laundered once to remove the sizing from the manufacturing process because, as mentioned previously, these three fabrics could not be put through the de-sizing process in the factory. The laundering process was in accordance with procedure III C of CGSB-4.2 No. 58-2004 (CGSB, 2004b). The wash process had moderate mechanical action and the temperature was 50°C using a synthetic detergent (Tide). To minimize shrinkage, fabrics were pinned out onto a flat horizontal surface during drying. Fabric D was purchased from the local retailer in a finished and dyed form. Three knitted fabrics (E, F and G) were also received in finished and dyed form as these are typical products of the knitting mill producing the sample fabrics. These four fabrics were not laundered.

Fabric specimens were cut from the fabric in such a manner that each specimen had different warp and weft yarns or course and wale. Before testing the specimens were conditioned for 24 hours at a relative humidity of 65± 2% and temperature of 20 ± 2 °C in accordance with CAN/CGSB-4.2 NO.2-M88 (CGSB, 1988). Detailed data for both woven and knit fabric systems are provided in Appendix 1, Tables A.1 and A.2. A summary of all the fabrics used in the study are summarized in Table 4.1.

Table 4.1. Fabric descriptions.

Fabric code	Description
A	Cotton, pile woven, one side corrugated (3 mm height)
B	Cotton, pile woven, both side corrugated (1.5 mm height)
C	Cotton, pile woven, one side corrugated (2 mm height)
D	Cotton, pile woven, both side corrugated (1.5 mm height)
E	Cotton, weft knit 1x1 rib knit
F	Cotton, weft knit flat back rib knit
G	Polyester filament, warp knit two sided ribbed terry pile

Phase III: Evaluation of the prototype fabrics

Each fabric system was evaluated for steam and hot water protection using equipment developed in Phase I.

Procedure for steam testing

Fabric system specimens were taken in a sealed plastic bag from the conditioning room to the lab where the testing was performed. Mounting of the specimens in preparation for testing was completed within 45 seconds of removal from the plastic bag (conditioned environment). A laboratory test apparatus (Figure 4.6) developed by UA researchers (Ackerman et al., 2012) was used to measure heat transfer through fabrics when exposed to high pressure steam.

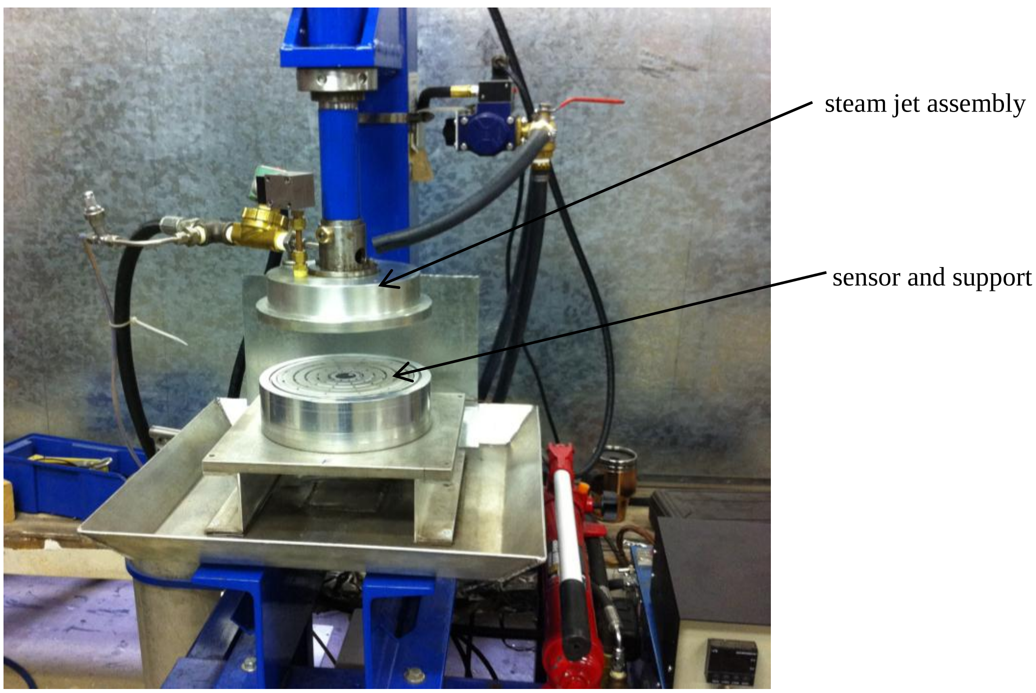

Figure 4.6. Steam and hot water test apparatus with steam testing attachment

The conditioned specimen was placed horizontally below the steam jet and rested on a skin simulant sensor (heat flux transducer) mounted in a perforated PTFE support. The perforated PTFE support below the specimen allows vapour to pass through, preventing steam from being pressurized above the specimen, and allowing condensate to drain from the bottom of the specimen. The specimen is held in place during the test with a PTFE spacer 9.5 mm thick. The spacer restrains the test specimen and also prevents pressure build-up on top of the specimen allowing blowing steam to escape and condensate to drain from the top of the specimen (Figure 4.7).

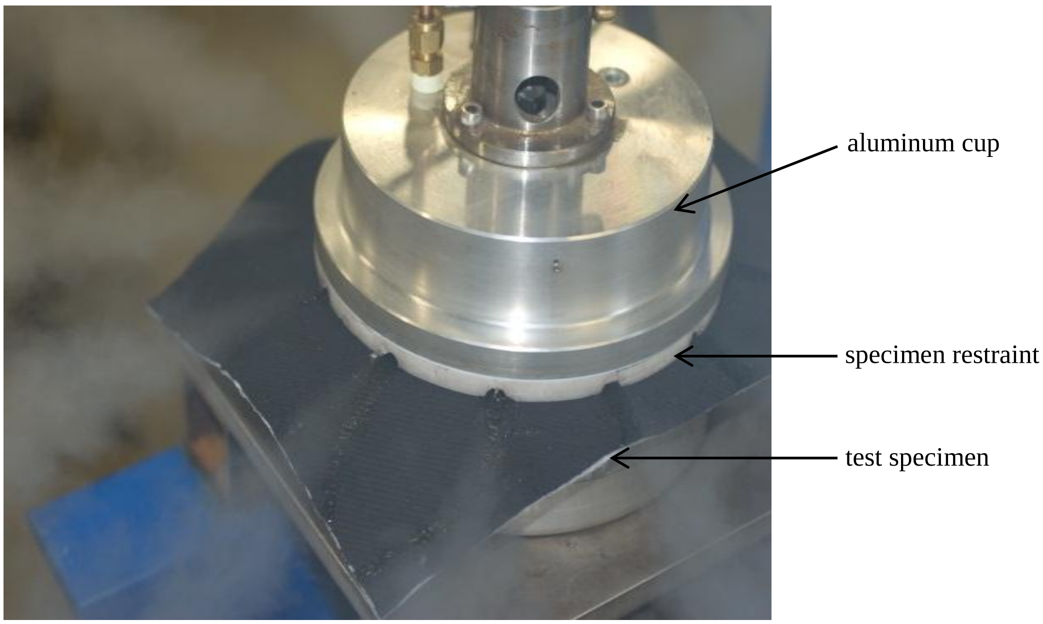

Figure 4.7. Steam exposure during test

A skin simulant sensor was used to measure the heat transfer through the specimen. This sensor is connected to a data acquisition device that records the temperature as a function of time. Each specimen was exposed to a steam jet for 10 seconds. The exposure steam pressure and temperature were 210 kPa and 150 °C respectively. The jet was positioned 60 mm from the face of the fabric. Temperature vs. time data were collected for 60 seconds, which includes 10 seconds exposure time and 50 seconds post exposure to incorporate any effects of stored energy. Temperature data were used to calculate the heat flux and the total absorbed energy. The heat-flux history was used in a multi-layer skin model to determine the time required to predict the onset of second or third degree burn and absorbed energy. This method of heat flux measurement and burn injury prediction is similar to that used in flash fire testing using an instrument mannequin (Crown et al., 1993). Skin properties used in the calculation for burn injuries are provided in Appendix 1, Table A.3. Following steam exposure, the aluminum cup was lifted so that the specimen could be removed. Observations were made regarding the structural integrity, stability, and flexibility of the test specimen and the presence of moisture on the surface of the sensor.

Procedure for hot water testing

The same laboratory test apparatus was used with a water jet attachment instead of steam jet attachment (Figure 4.8) to measure heat transfer through the specimen when exposed to a jet of hot water.

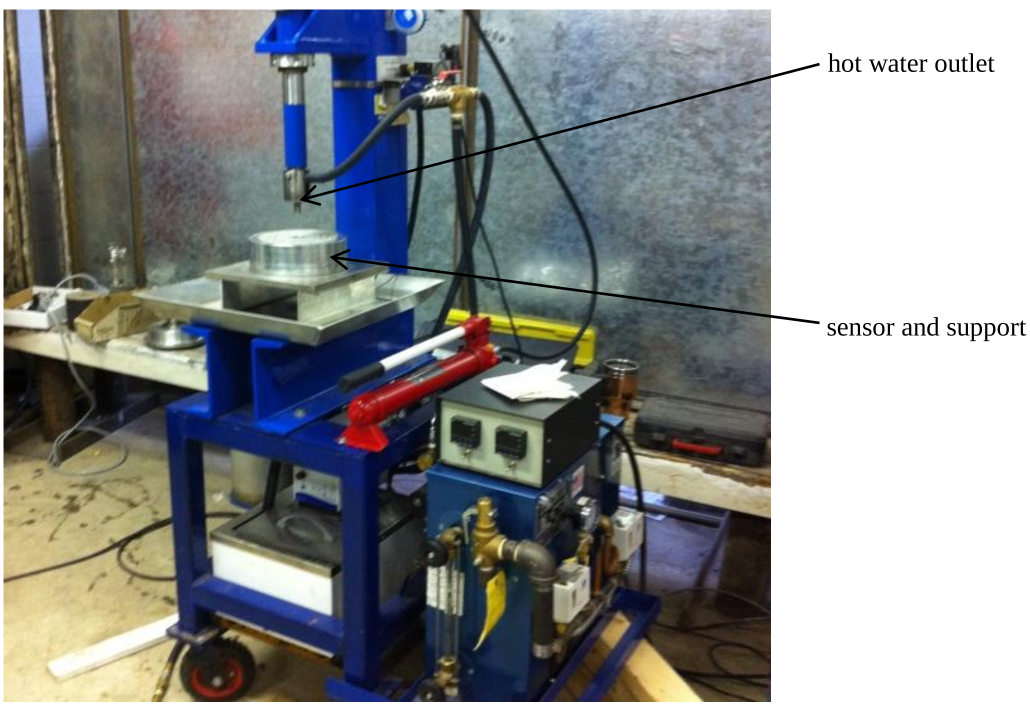

Figure 4.8. Steam and hot water test apparatus with hot water testing attachment

A conditioned specimen was placed below the water stream and resting on a skin simulant sensor (heat flux transducer) mounted in a perforated PTFE support. The specimen was held in place with a tripod metal stand (Figure 4.9). Each specimen was exposed for 10 seconds to a stream of hot water at 85 °C. The water nozzle was positioned 50 mm from the surface of the specimen and allowed the hot water to flow onto the specimen at a rate of six litres per minute. This was determined in earlier research to be an appropriate flow rate (Jalbani et al., 2012). Water ran off the specimen and collected in a tray which drained to the hot water bath and was recycled in the system for further testing. Data collection and calculation of the onset of second or third degree burn and absorbed energy was the same as in steam testing procedure. Following hot water exposure, observations were made regarding structural integrity, stability, and flexibility of the test specimen and the presence of moisture.

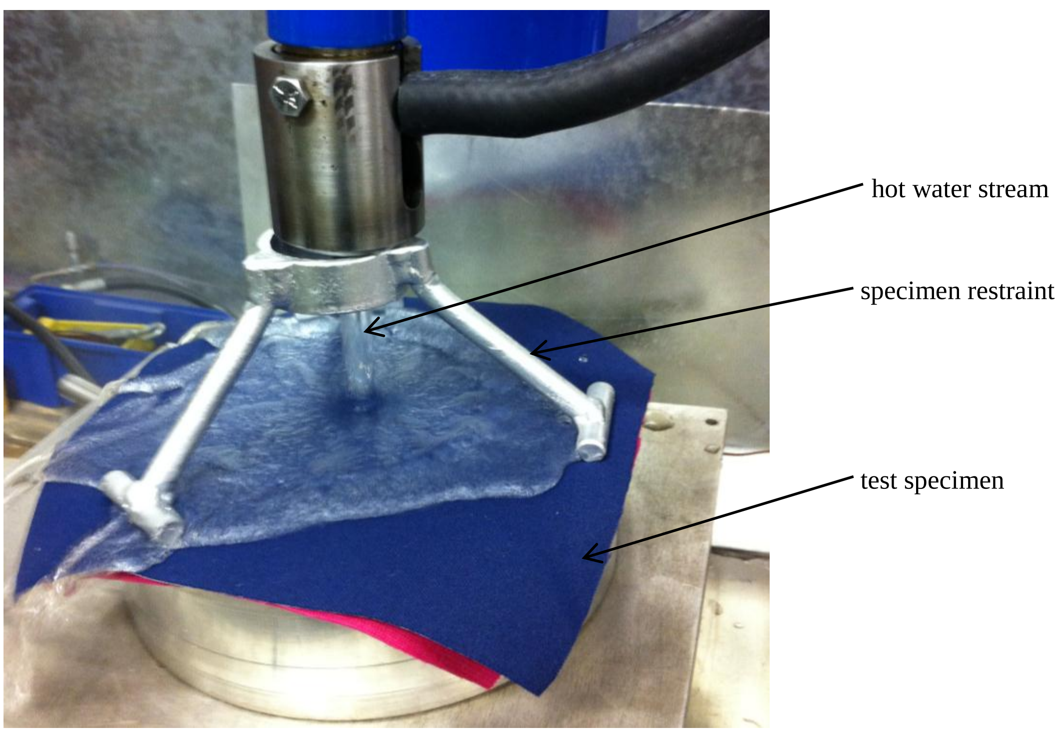

Figure 4.9. Hot water exposure during test

It was apparent from preliminary hot-water testing on the test apparatus that the absorbed energy results strongly depended on the initial sensor temperature for both blank tests and tests with a specimen on top of the skin simulant sensor. If the initial sensor temperature is high at the start of the test, the total absorbed energy recorded over the test period is less than when the initial sensor temperature is low. Therefore, it was decided to control the initial sensor temperature at 30 ± 1°C. This setting was chosen as it is close to human skin temperature. As well, this temperature can be achieved in successive specimen tests without extensive cooling of the apparatus.

At the start of a testing period, the temperature of the whole assembly in which the skin simulant sensor is mounted was raised to 30 ± 1°C by application of hot water from the nozzle. Between specimens the sensor requires cooling and this was done by wrapping the assembly with a wet towel and blowing air over the apparatus using a table fan.

In preliminary testing it was observed that the applied water was sitting in the form of a pool on the surface of the specimen after the 10 seconds of hot water exposure. This hot water on the surface of the specimen leads to a higher level of stored energy than would occur from the specimen alone. Therefore, before running the experiment, it was decided to incline the sensor mounting assembly for hot water testing so that water could run off the surface of the specimen. A maximum possible angle of six degrees was adopted for the testing. This angle was restricted by the design of the test apparatus.

Statistical analysis

Statistical analyses were performed using PASW (SPSS) software version 18 (PASW, 2009). Descriptive statistics such as mean and coefficient of variation were calculated for dependent variables for each fabric system. One way analysis of variance (ANOVA) with Duncan's post-hoc tests were performed to determine the differences in absorbed energy among the fabrics. For ANOVA calculations fabric types (A to G) were used as the independent variables and the absorbed energy was the dependent variable. The null hypothesis was tested using a significance level of $p<0.05$. Pearson correlations (r^2) and regressions were performed to determine relationships between absorbed energy and the independent variables of fabric mass, thickness, thickness under pressure, density, density under pressure and thickness change.

5. RESULTS AND DISCUSSION

In this chapter the results of the steam and hot water tests are presented followed by a discussion of the temperature, heat flux and absorbed energy curves. ANOVA results and correlations are presented, followed by a discussion of the differences among the fabric systems for each dependent variable. Finally, a discussion of the study's objectives is presented.

Observations during both steam and hot water tests

In the steam test, the specimen was covered by an aluminum cup during pressurized steam exposure. The specimen was therefore not visible during the period of test and only condensate and steam flowing off the surface of the test specimen through PTFE restraint holes could be observed. Pressurized steam through a jet impinged for ten seconds on the surface of the specimen, a large portion of which turned into liquid water condensate and ran off the surface of the specimen with the steam through the holes of the PTFE restraint. However, some of the steam vapour passed through the semi-permeable membrane of the fabric system and through the insulation layer and was seen as water droplets condensed on the surface of the skin simulant sensor and on the PTFE support. This condensing water vapour was also absorbed by the insulation layer, making it wet. An attempt was made to quantify the transmitted moisture during the steam exposure. However, some of the condensate running off the surface of the specimen was absorbed by the edges of the specimen making it impossible to record only the moisture that passed through the semi-permeable membrane during the test. This problem could be resolved by altering the specimen size to have a larger outer layer and smaller insulation layer. It was also observed that some of the condensing water was still lying on top of the test specimen after the end of the test when the upper cap of the tester was lifted to remove the specimen. Energy contained by condensed water would have transferred to the sensor during the post exposure data collection time period. A vertical orientation of specimens, or an angle to the horizontal surface, might resolve this problem but the tester is built for horizontal testing because in a horizontal direction it can simulate the most severe actual steam exposure hazard.

Some water condensation occurred on the surface of the skin simulant sensor during the steam exposure tests. Figure 5.1 shows the typical appearance of this condensed water droplet with the test specimen just removed.

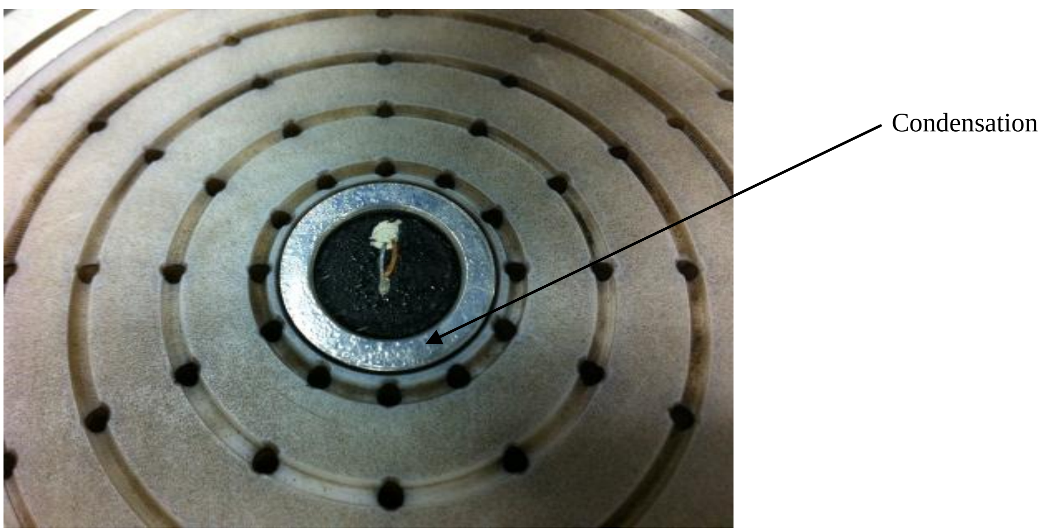

Figure 5.1. Condensation of water on the sensor following steam exposure

In the hot water test the specimen was restrained with a tripod stand and was not covered by the aluminum cup during exposure. The specimen was visible during the test period and hot water flowing off the surface of the test specimen was also observed. After exposure to hot water, some water pooling on the surface of the specimen creates a noticeable effect on the absorbed energy. Although the specimen mounting assembly was tilted slightly (by an angle of six degrees), pooling was still noted. Whether or not the water will sit on the surface is unpredictable and affects the reproducibility of the results. When one specimen with no water repellent finish was exposed to the hot water jet as a trial, it was observed that all the water ran off the surface leaving the outer surface completely wet, with no water pooling on the specimen surface. It seems that "water pooling" phenomena occurred only on fabrics with a water-repellent finish. The hot water stream diminishes the repellency of the water-repellent finish only on the spot of jet impingement (on top of the sensor), allowing water to stay there, while the areas around that spot with intact water-repellant finish push water toward that spot resulting in a pool of hot water on top of the sensor. Figure 5.2 shows the water pool on the surface of the specimen.

Figure 5.2. The water pool on the surface of the specimen after hot water exposure

Water condensation also occurred on the surface of the skin simulant sensor in the hot water test. In fact, the condensation was greater in hot water testing than in steam testing due to the greater mass of water impinging on the surface of the specimen as compared to steam exposure. Figure 5.3 shows the typical appearance of the condensed of water on the surface of skin simulant sensor following the hot water exposure and with the test specimen just removed.

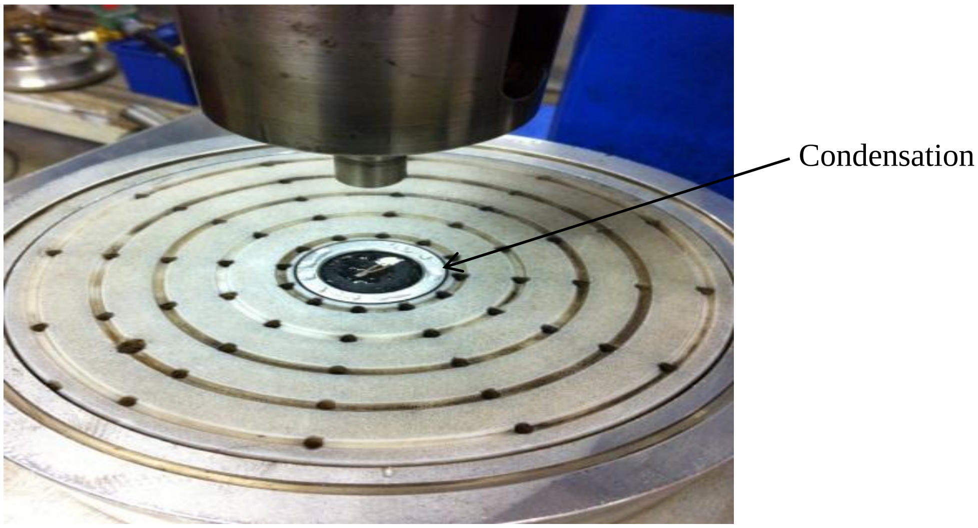

Figure 5.3. Condensation of water on the sensor following hot water exposure

For the hot water test, a shutoff valve was placed upstream of the water outlet so water left in the downstream pipe after the closure of the shutoff valve sometimes dropped onto the specimen during the post exposure data collection period resulting in a sudden temperature rise following a temperature drop. This intentional addition of liquid water artificially increased the total absorbed energy over the data recording period. This can be observed in some of the individual specimen temperature and heat flux plots attached in Appendix 2.

Test data

During both the steam and hot water tests, temperature data as a function of time were recorded using a computer. These data were then used to calculate heat flux and absorbed energy over time. Temperature, heat flux and absorbed energy data were plotted as a function of time to understand the performance of the fabric systems under high pressure steam jet and hot water jet exposures.

For each of the fabric systems for both the steam and hot water tests, absorbed energies were measured over a time period of 60 seconds. In both tests, fabric system A performed the best and fabric system E performed the worst. Results of these tests along with fabric system characteristics are summarized in Table 5.1. Detailed data for both steam and hot water tests of each fabric system are provided in Appendix 1, Tables A.4 and A.5. It should be noted, that for both steam and hot water tests none of the fabric systems reached the criteria for the onset of a second degree burn with the exception of fabric system E and two of six specimens of fabric system F during the steam test. The criterion for the onset of a third degree burn was not reached for any of the fabric systems in either of the tests.

Table 5.1. Fabric system characteristics and performance properties[1]

Fabric code	Mass[2] (CV)	Thickness[3] (CV)	Thickness under pressure[4] (CV)	Thickness change[5] (CV)	Density[6] (CV)	Density under pressure[7] (CV)	Absorbed energy[8] (steam) (CV)	Absorbed energy[8] (hot water) (CV)
A	1138(0.9)	4.2(1.4)	3.5(0.1)	16.7(5.6)	272(1.1)	327(1.1)	128(15.0)	63(9.5)
B	1047(1.2)	3.8(1.7)	3.3(0.1)	14.1(11.7)	275(1.9)	320(1.7)	128(9.5)	74(7.4)
C	987(1.3)	3.2(0.9)	2.8(0.0)	12.7(11.2)	305(1.5)	349(1.5)	148(6.1)	78(6.4)
D	745(0.3)	2.9(2.6)	2.6(0.1)	11.9(21.5)	257(2.7)	291(1.5)	142(4.0)	62(6.1)
E	744(0.9)	2.0(1.8)	1.7(0.0)	13.6(17.9)	373(2.5)	432(1.7)	182(6.9)	110(7.4)
F	748(0.4)	2.3(1.1)	1.9(0.0)	17.3(4.6)	326(1.3)	395(1.4)	155(7.1)	75(10.9)
G	563(0.6)	3.1(3.0)	2.0(0.0)	34.7(7.4)	184(2.9)	282(2.2)	138(9.4)	67(6.6)

[1] *mean results for six specimens of each fabric system (see Appendix for details).*
[2] *g/m^2, following CAN/CGSB-4.2 No.5.1 – M90.*
3 *mm, following CAN/CGSB-4.2 No. 37-2002.*
[4] *mm at 13.8 kPa*
[5] *reported as (%) change.*
[6] *kg/m^3.*
[7] *kg/m^3 at 13.8kPa*
[8] *kJ/m^2*

The temperature vs. time plots in Figure 5.4 and 5.6 are the average of six specimens of each fabric system. Plots of temperature vs. time for individual specimens are presented in Appendix 2, Figures A.1 to A.14. These figures show consistency in the shape of the curves among the six specimens of each fabric system. The heat flux and absorbed energy vs. time plots in Figure 5.5 and 5.7 are those of a typical specimen of each fabric system. Plots of heat flux and absorbed energy vs. time for individual specimens are presented in Appendix 2, Figures A.15 to A.28.

Steam test plots

Temperature vs. time

Steam exposure temperature vs. time plots (Figure 5.4) indicate that the rise in the temperature sensor is more rapid for the knit fabric systems (E to G) compared to woven fabric systems (A to D). Fabric E reached the highest temperature of all the fabric systems (~ 48 °C). According to Stoll and Chianta (1969), burn injuries to human tissues depend on the extent of the temperature rise above the critical value (44 °C) and the duration that the temperature is above that critical value. Thus, only fabric system E reached the criterion for the onset of a second degree burn while the other fabric systems did not. The decrease in temperature following exposure for woven fabric systems, especially A and B, was very gradual and steady. For knit fabric systems, the decrease in temperature is more rapid.

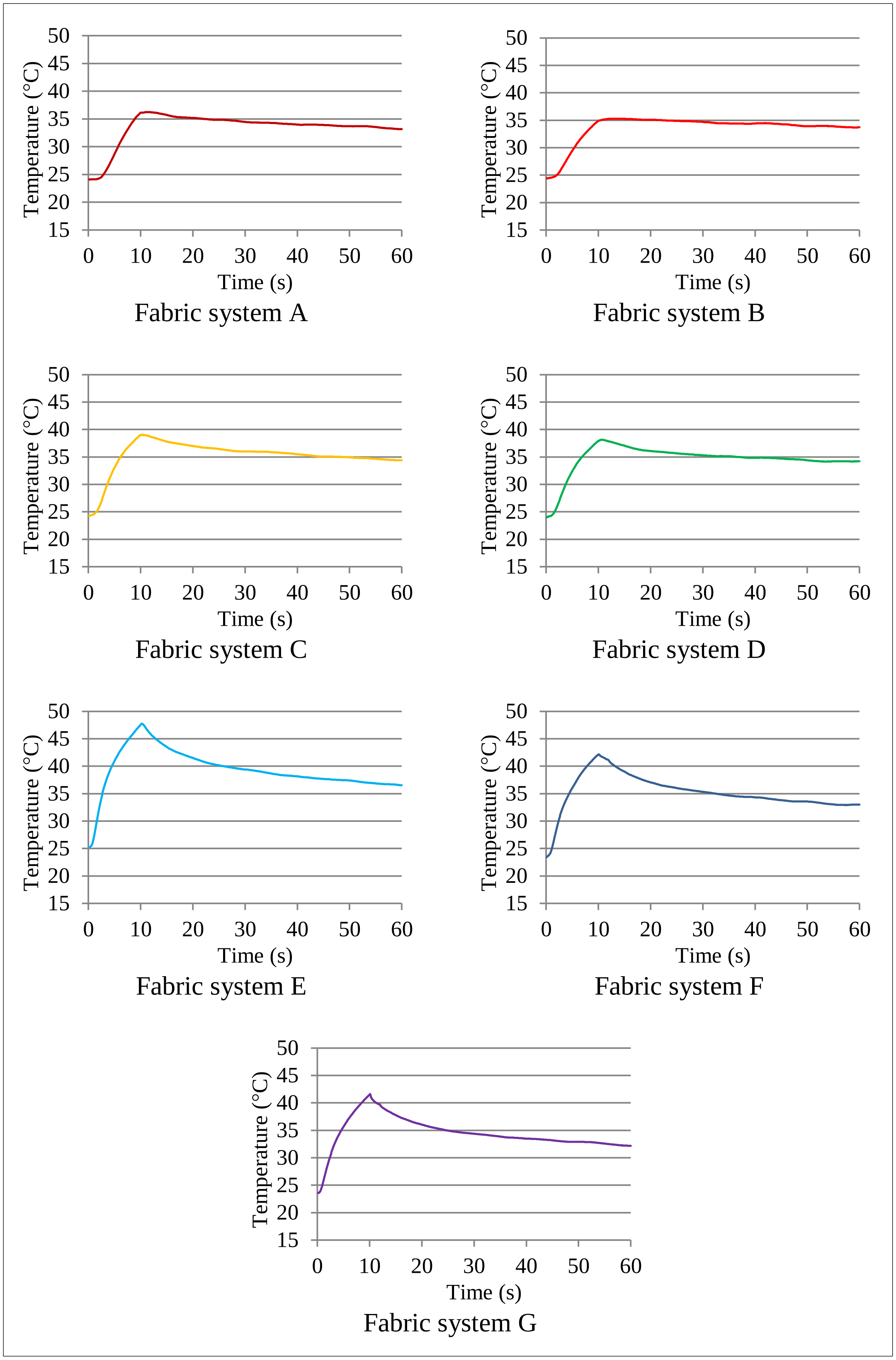

Figure 5.4. Temperature rise over time during steam tests

Heat flux and absorbed energy vs. time

Steam exposure heat flux and absorbed energy vs. time plots (Figure 5.5) show an initial rapid heat flux rise. Time to reach peak heat flux differentiates the woven fabric systems (A to D) from the knit fabric systems (E to G). Each heat flux curve rapidly rises to a peak for knit fabric systems E and F and declines slightly because once the peak heat flux is reached during steam exposure, the sensor tends to give up the heat to the surrounding atmosphere. As soon as the steam exposure stops (at ten seconds), the slope of the heat flux curve decreases more sharply in the knit fabric systems in comparison to the woven fabric systems because the knit fabric systems are thinner and retain less stored energy than the woven fabric systems. The slight decline in the heat flux curve was also detected even before ten seconds of exposure time for two of the woven fabric systems. However, the peak heat flux incident occurs within the steam exposure period (within ten seconds). In the first ten seconds after the steam exposure stopped, the slope of the heat flux curve dropped rapidly and after twenty seconds the drop in the heat flux curve (slope) is very low and the curve is fairly smooth in all fabric systems.

Absorbed energy curves Figure 5.5 also differentiate the fabric systems. Fabric system E transferred the highest energy in the form of heat. The absorbed energy curves also show that much of the energy absorbed by the sensor was transferred after the steam exposure due to the stored energy within the specimen and the aluminum cup above the specimen.

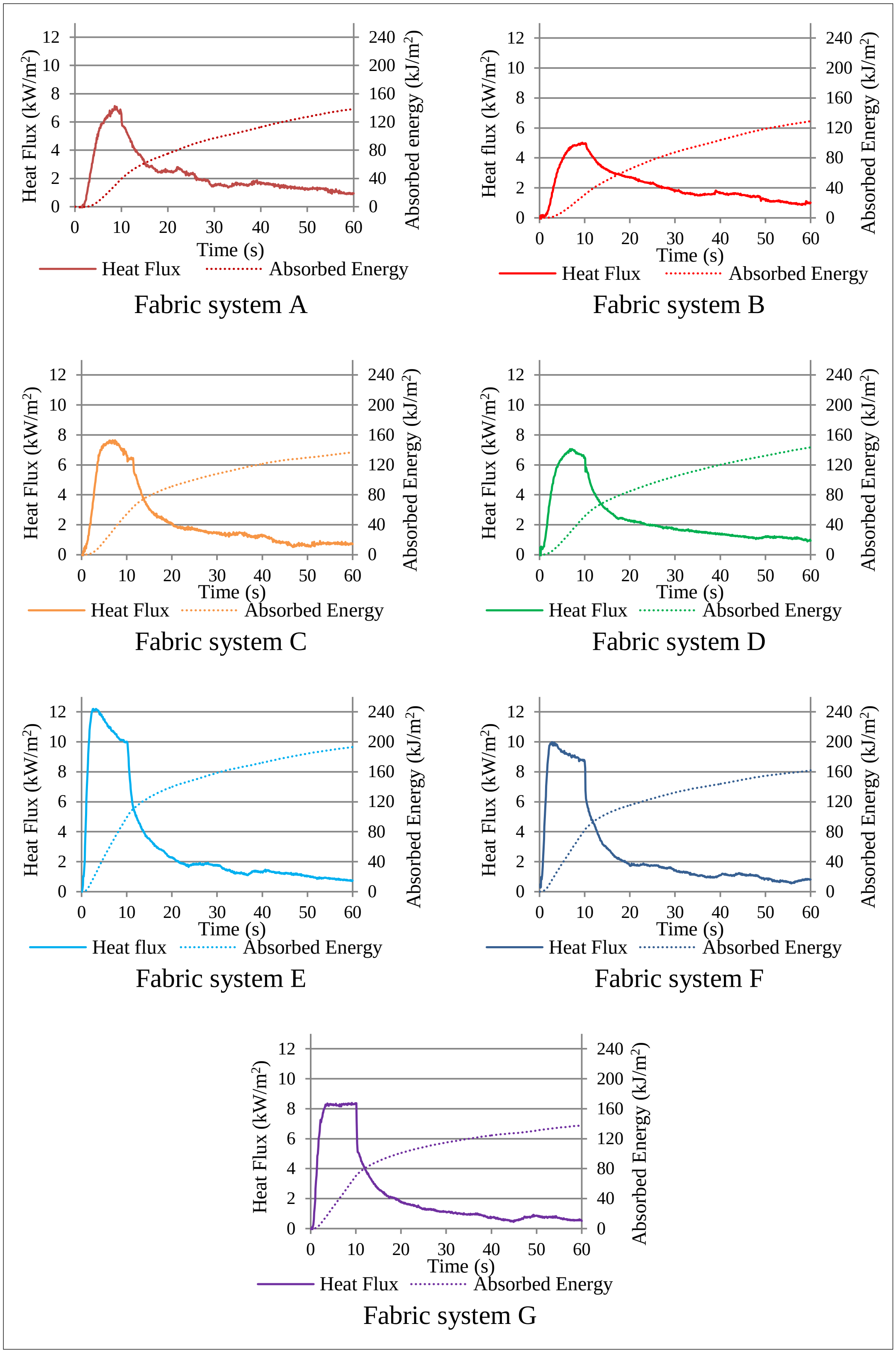

Figure 5.5. Heat flux and absorbed energy over time during steam exposure tests.

Hot water test plots

Temperature vs. time

Hot water temperature vs. time plots (Figure 5.6) indicate that the rise in temperature of the sensor is more rapid for the knit fabric systems (E to G) compared to woven fabric systems (A to D). Fabric system E reached the highest temperature. For all fabric systems, the peak temperature was reached after the period of exposure to hot water ended. For the woven fabric systems, there was no temperature rise in the sensor until after 4-5 seconds. The temperature decrease for the knit fabric systems following hot water exposure was generally greater than for woven fabric systems.

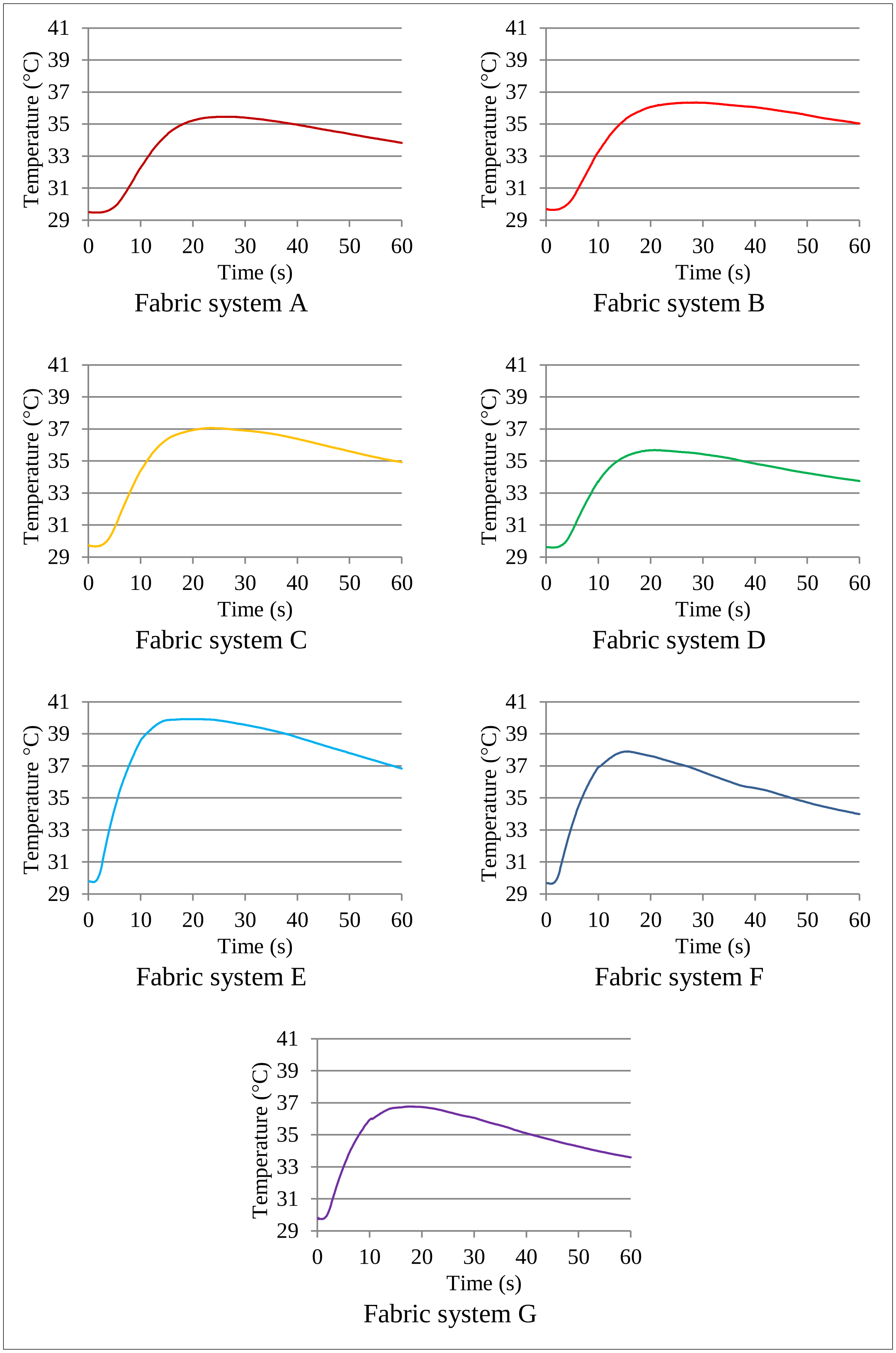

Figure 5.6. Temperature rise over time during hot water exposure tests.

Heat flux and absorbed energy vs. time

Heat flux and absorbed energy vs. time plots (Figure 5.7) for hot water tests show similar curve shapes for all of the woven fabric systems (A to D) and similar curve shapes for the knit fabric systems (E and F). Knit fabric system G is perhaps more similar to the woven fabric systems. It has similar absorbed energy to the woven fabrics and a slightly lower peak heat flux than the other knit fabrics. In the knit fabric systems, the peak heat flux was reached within ten seconds of exposure time while in woven fabric systems the peak heat flux was reached after the hot water exposure was stopped except for the fabric system D. Heat flux rapidly rises to a peak for the knit fabric systems as long as a temperature gradient exists between the water temperature and sensor temperature, but drops sharply after the exposure. For woven fabric systems (except D), the heat flux curve rises more slowly and continues to rise to a peak after the hot water valve is shut off and then drops smoothly after reaching the peak.

Absorbed energy curves also differentiate the fabric systems. Fabric system E transferred the most energy while fabric systems A and D transferred the least. Absorbed energy curves also show that most of the energy transferred to the sensor, occurred after the hot water exposure period and was from the energy stored by the fabric systems.

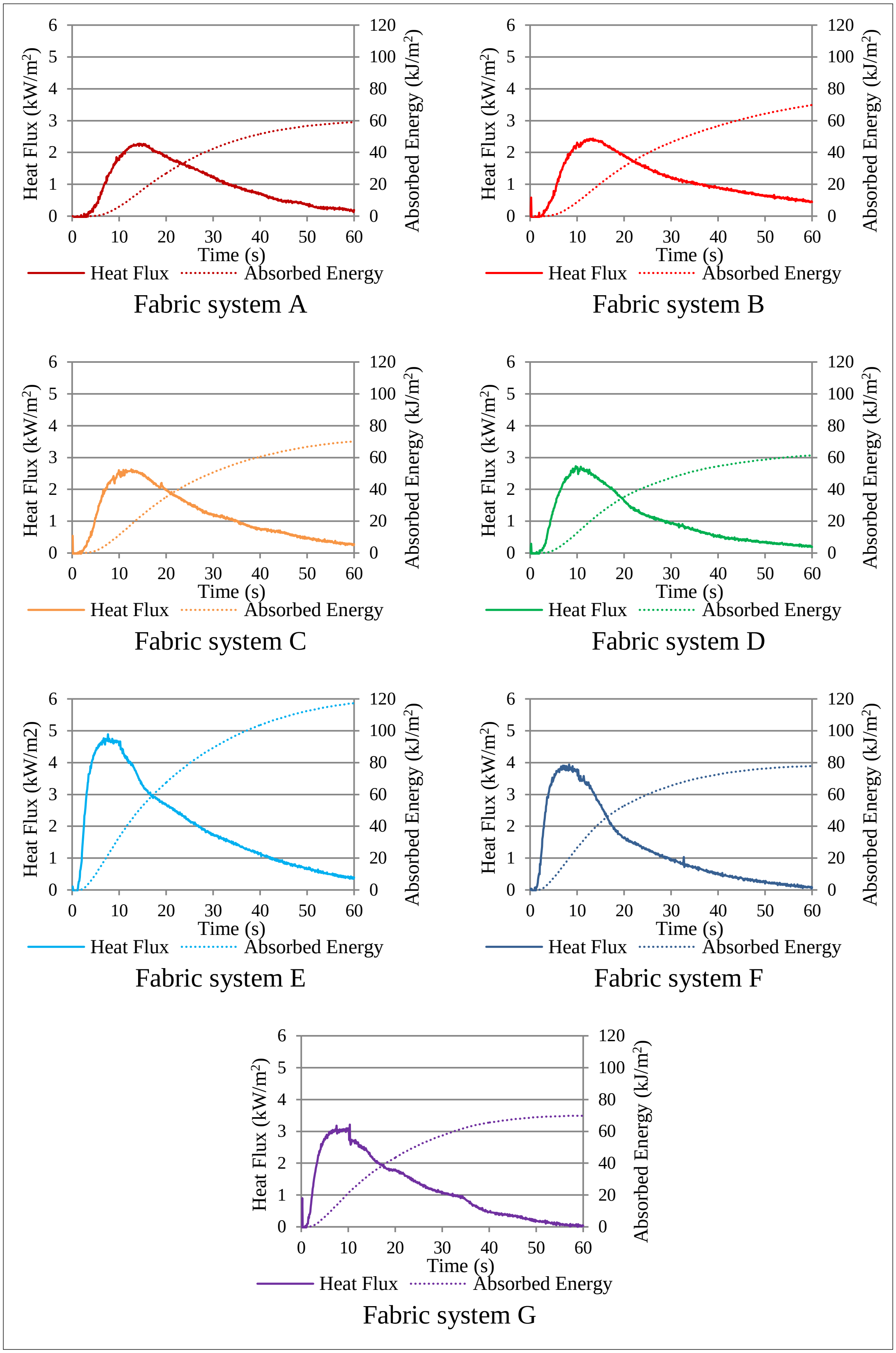

Figure 5.7. Heat flux and absorbed energy over time during hot water exposure tests.

Comparison of steam and hot water tests

During the steam and hot water tests, it was noted that the peak temperatures reached for the woven fabrics were lower than for the knit fabrics and the decrease in temperature from the peak over the recording period was less than for the knit fabrics. For example, in the steam tests, for woven fabric C, the peak was 39 °C and the decrease observed over time was 5 °C, while the peak for the knit fabric E was 42 °C and the decrease over time was 9 °C. As well, in both steam and hot water tests, the peak heat flux was higher for the knit fabric systems than for the woven fabric systems. This is because the woven fabrics were thicker than the knits and thicker fabrics, incorporating air in their structures, provide better thermal resistance to energy transfer (Lee & Barker, 1987). In the steam tests, half of the total absorbed energy was transferred during the steam exposure while in the hot water tests, most of the energy was transferred in the post exposure data collection time.

In the hot water tests, the effectiveness of the water repellent finish on the outer aramid fabric was diminished in the area directly receiving the stream of hot water during the test. This area contained a pool of water after the jet was turned off. Energy was stored by the wet outer surface and liquid water was in contact with the semi-permeable membrane directly above the skin simulant sensor. Thus some mass transfer occurred in the form of water vapour which condensed on the surface of the skin simulant sensor. Energy was transferred to the sensor during condensation of the water vapour in addition to the energy from the pool of water and the stored energy in the fabric system. In the steam test, the effectiveness of the water repellent finish was not diminished, although moisture vapour did pass through and condense on the sensor. However there was less condensation observed on the sensor in the steam tests than in the hot water tests, so the energy released by the condensation of water vapour contributed less to the total absorbed energy in steam tests.

Statistical analyses

Analyses of variance

For each of the fabric systems, absorbed energy data were collected for both steam and hot water tests. ANOVAs were conducted to determine whether significant differences existed among the fabric systems. Tests of the homogeneity of variances were conducted among fabric system groups and found that the variances were homogeneous. The one-way ANOVAs showed that the fabric system effect on absorbed energy was highly significant ($p<0.001$) in both the steam and hot water tests. One-way ANOVA results for each dependent variable are presented in Table 5.2.

Table 5.2. ANOVA: Fabric system effect on absorbed energy

		Sum of squares	d.f.	Mean square	F	p
Absorbed energy (steam test)	between groups	12689	6	2115	13.7	0.000
	within groups	5414	35	155		
	total	18103	41			
Absorbed energy (hot water test)	between groups	9697	6	1616	44.0	0.000
	within groups	1284	35	37		
	total	10981	41			

Duncan’s post-hoc tests were conducted and confirmed significant differences among fabric systems. Duncan’s post-hoc tests were able to differentiate the fabric systems into four groups for the steam test, with three of four groups overlapping, and three distinct groups for the hot water test. Therefore, the differentiation among fabrics is less clear for steam than for hot water. Details of the Duncan's post-hoc test are summarized in Tables 5.3 and 5.4.

Table 5.3. Duncan's post-hoc test: Steam protection test

Fabric code	Mean absorbed energy (kJ/m^2)
B	128
A	129
G	138
D	142
C	148
F	156
E	182

Means grouped by vertical lines are not significantly different at p<0.05 when tested by Duncan's post hoc-test.

Table 5.4. Duncan's post-hoc test: Hot water protection test

Fabric code	Mean absorbed energy (kJ/m^2)
D	62
A	63
G	67
B	74
F	75
C	78
E	110

Means grouped by vertical lines are not significantly different at p<0.05 when tested by Duncan's post-hoc test.

For the steam test, fabric systems A, B, D and G are grouped together by Duncan's post-hoc test as not being significantly different with regard to total absorbed energy over the 60 seconds of recording. Fabric systems G and D also overlap with fabric system C to form a second group of fabric systems which are not significantly different from one another. Fabric systems D, C and F form a third group and fabric system E stands alone.

Fabric systems A, B, D and G had the thickest and/or have the lowest densities among all fabric systems (see Table 5.1). The greater thickness and lowest density under pressure together played a vital role in minimizing energy transfer, so this group performed best by creating an effective barrier to the energy transfer under a high pressure jet of steam. Fabric system E stands alone in a separate group, as expected, because all specimens of this fabric system reached the criterion of the onset of a second degree burn at around eleven seconds just after the ten second steam exposure period of the test (see Table A.5 in Appendix 1). Fabric system E is the thinnest and has the highest density of all the fabric systems. Two specimens of fabric system F reached the criterion for the onset of a second degree burn, but the time was long after the steam exposure stopped (27 and 57 seconds). None of the fabric systems reached the criterion of the onset of a third degree burn during the steam exposure and data collection period of 60 seconds.

For the hot water test, there was no overlap among three distinct fabric system groups. Fabric systems D, A and G are grouped together by Duncan's post-hoc test, with no significant difference in their mean total absorbed energy. Fabric systems B, F and C form a second group which were not significantly different from one another. Fabric system E remains alone in a distinct group. Neither second nor third degree burn criteria were reached for any fabric system following hot water exposure. Details of the hot water exposure test results for individual specimens for each fabric system are provided in Appendix 1 Table A4.

Correlations between test results and fabric characteristics

The energy transfer through fabric systems under an impinging jet of steam or hot water is a function of a number of variables such as fabric system mass, thickness, compressibility and the material characteristics such as density and density under pressure. Correlations between absorbed energy for both steam and hot water tests and selected fabric characteristics were determined. Correlations were done for all the fabric systems together and for the woven and the knitted fabric systems separately. Table 5.5 shows the results of such analyses for both steam and hot water tests.

Table 5.5.Pearson correlation (r^2) between dependent variables and fabric characteristics

Fabric characteristics	r^2 absorbed energy (steam test)	r^2 absorbed energy (hot water test)
All fabric systems		
Mass	-0.368*	-0.156
Thickness	-0.743**	-0.604**
Thickness under pressure	-0.643**	-0.492**
Thickness change	-0.184	-0.237
Density	0.623**	0.717**
Density under pressure	0.695**	0.788**
Woven fabric systems only		
Mass	-0.346	0.192
Thickness	-0.480*	-0.073
Thickness under pressure	-0.500*	-0.040
Thickness change	-0.266	-0.155
Density	0.253	0.669**
Density under pressure	0.135	0.590**
Knit fabric systems only		
Mass	0.674**	0.586*
Thickness	-0.802**	-0.777**
Thickness under pressure	-0.797**	-0.916**
Thickness change	-0.775**	-0.695**
Density	0.788**	0.756**
Density under pressure	0.769**	0.761**

** *Correlation is significant at the 0.01 level*
* *Correlation is significant at the 0.05 level*

For the analyses including all fabric systems, absorbed energy for the steam test was most highly correlated with thickness followed by density under pressure and thickness under pressure and least correlated with thickness change. Absorbed energy for the hot water test was most highly correlated with density under pressure and density and least correlated with mass. Torvi & Dale (1998) in their work with aramid fabrics and protection from open flames, they concluded that the increase in thickness resulted in a lower rate of energy transfer between the heat source and the sensor. Similar results were observed in this study with the strongest negative correlation of absorbed energy with thickness. As thickness increased, the rate of heat transfer decreased, hence the thicker the fabric, the greater the time to reach the predicted onset of a second degree burn.

For woven fabric systems only, correlations were generally quite low because of similar fabric structure and properties. The absorbed energy for the steam test was most highly correlated with thickness under pressure and thickness and least correlated with density under pressure. The absorbed energy for hot water test was most highly correlated with density and density under pressure and least correlated with thickness for woven fabric systems.

For knit fabric systems only, the absorbed energy for steam test was most highly correlated with thickness and thickness under pressure and least correlated with mass, but all correlations were > 0.5. The absorbed energy for hot water test was most highly correlated with thickness under pressure and the least correlated with mass for knitted fabric systems, but all correlations were > 0.5.

For all fabric systems, woven fabric systems only and knit fabric systems only, absorbed energy in the steam test is most highly correlated with thickness and thickness under pressure due to the phenomenon of compression/deformation of fabric structure under the high pressure steam jet. Thickness and thickness under pressure are correlated more than other characteristics because under a high pressure jet, thickness and thickness under pressure are affected directly and hence hiding effects of density and density under pressure. Correlation is due to the fabric structure compression/deformation under high pressure steam jet.

In the hot water tests for all fabric systems and for woven fabric systems, density and density under pressure are highly correlated with absorbed energy due to the change in density during the test. For knit fabric systems, thickness under pressure is highly correlated with absorbed energy because one of the knit fabric systems (G) is more compressible than the rest of the fabric systems.

Regression analyses

In order to predict absorbed energy for both steam and hot water tests for the fabric systems tested, regression analyses were performed. Based on regression analyses, regression models for absorbed energy in both steam and hot water tests were created. Regression analysis was performed using the independent variables mass, thickness, thickness under pressure, thickness change, density and density under pressure. Regression analysis was performed for all fabric structures combined, as well as for woven and knit structures separately, for both dependent variables. The regression models for absorbed energy are provided in Equations 5.1 to 5.3 for the steam test and 5.4 to 5.6 for the hot water test.

Regression model, absorbed energy for all fabrics (steam test)

$Q = 138.241 - 14.615t + 0.154\rho p$ ……..…Eq. 5.1

Regression model, absorbed energy for woven fabrics (steam test)

$Q = 196.022 - 19.551tp$ ……..…Eq. 5.2

Regression model, absorbed energy for knit fabrics (steam test)

$Q = 251.885 - 38.091t$ ……..…Eq. 5.3

Regression model, absorbed energy for all fabrics (hot water test)

$Q = -10.631 + 0.252\rho p$ ……..…Eq. 5.4

Regression model, absorbed energy for woven fabrics (hot water test)

$Q = -15.609 + 0.306\rho$ ……..…Eq. 5.5

Regression model, absorbed energy for knit fabrics (hot water test)

$Q = 380.137 - 158.367tp$ ……..…Eq. 5.6

Where,

Q= total absorbed energy (kJ/m^2)

t = thickness (mm)

tp = thickness under pressure (mm)

ρ = density

ρp = density under pressure (kg/m^3)

An attempt has been made in this research to combine the effects of the various fabric system characteristics into one mathematical model, using regression analyses, because when fabric characteristics are considered together, rather than individually, they can better help to explain the results of an experiment. Based on the regression models, absorbed energy for future steam and hot water tests can be predicted. Statistical analyses indicated significant differences among fabric systems in the dependent variables using the models. However, these analyses which focus on the total absorbed energy over the 60 second test period do not take into account the shape of the heat flux and temperature curves which are used in burn injury predictions.

Fabric characteristics vs. steam and hot water absorbed energy

To demonstrate the relationship between the selected fabric characteristics and heat transfer, the mean values of the absorbed energies were plotted for the independent variables in the regression models. The absorbed energy regression model for steam for all fabric systems found thickness and density under pressure to be the most important of the fabric characteristics, so these characteristics were plotted (Figure 5.8) to show the relationships. The thickness vs. absorbed energy plot shows the trend line (solid line) for the absorbed energy with a linear indirect (negative) relationship; as the thickness increases, the absorbed energy decreases (better protection from steam hazard). The density under pressure vs. absorbed energy plot also shows the trend line (solid line) for absorbed energy with a linear direct (positive) relationship; if the density under pressure increases, the absorbed energy in the steam test also increases (less protection from steam hazard).

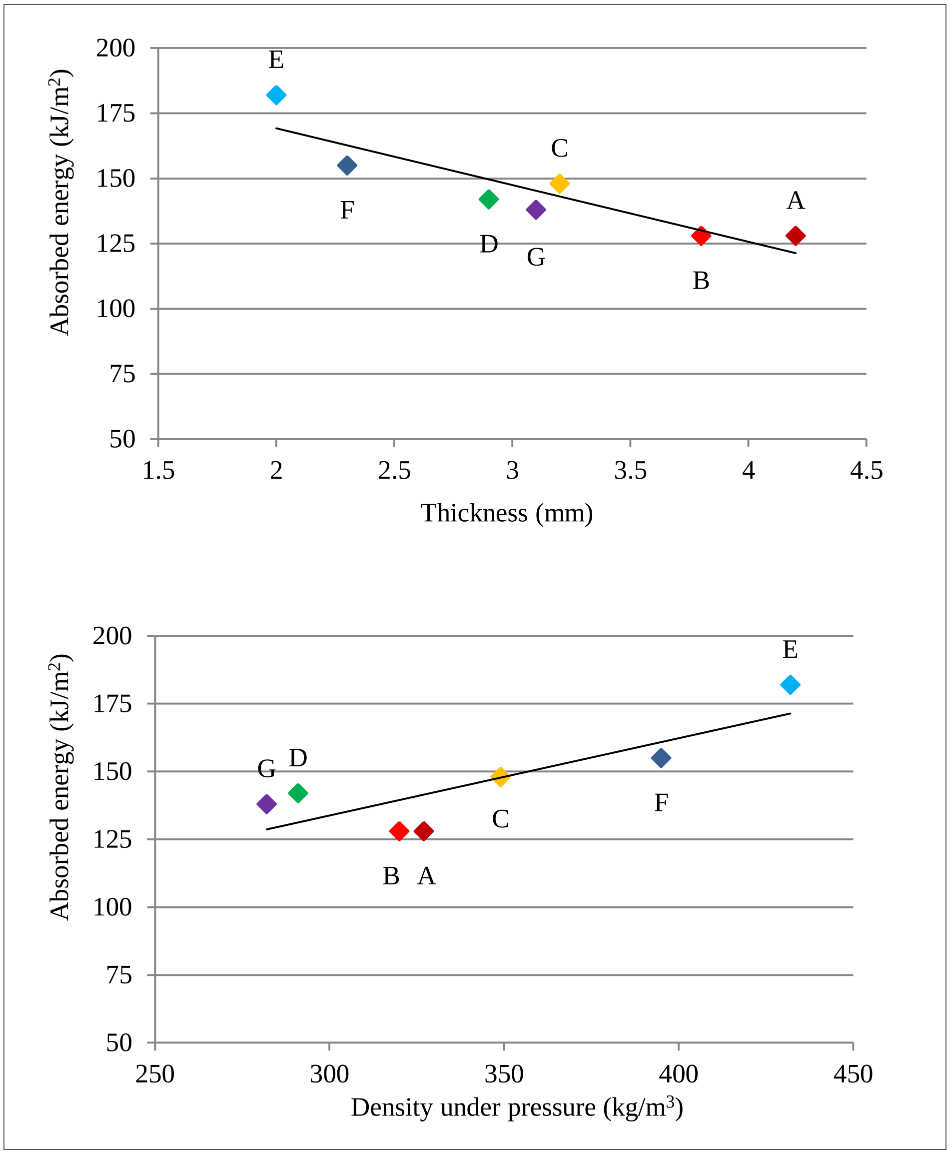

Figure 5.8. Effect of thickness and density under pressure on absorbed energy: steam test; all fabrics

The absorbed energy regression model for hot water for all fabric systems indicated that the density under pressure was the most important fabric characteristic so this characteristic was plotted (Figure 5.9) to show the relationship. The plot shows the trend line (solid line) for the absorbed energy with a linear direct (positive) relationship; as the density under pressure increases, the absorbed energy also increases (less protection from hot water hazard).

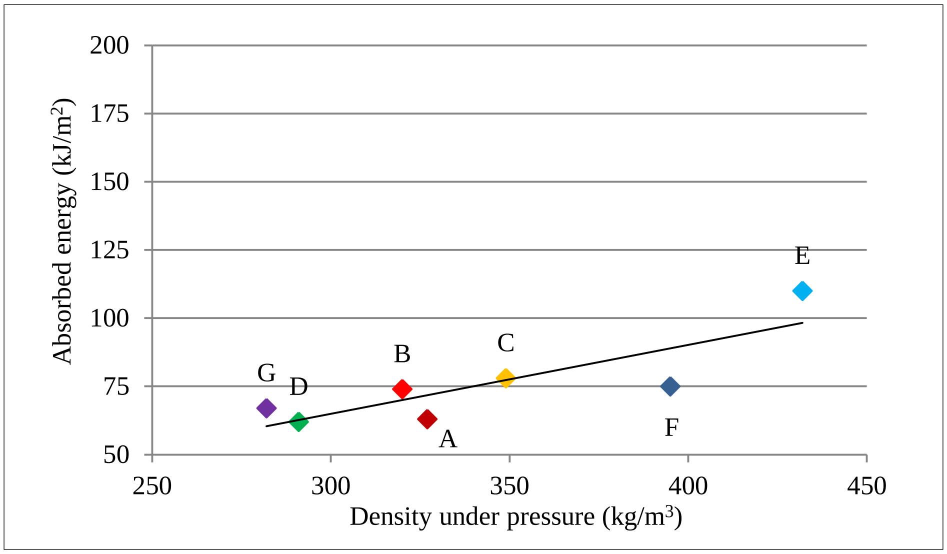

Figure 5.9. Effect of density under pressure on absorbed energy: hot water test; all fabrics

All of the fabric systems were multi-layer and consisted of the same outer fabric with a PU membrane. Therefore, any difference in absorbed energy was the result of the insulation layers in the fabric systems. Fabric E, which is a thinner fabric system, showed the least resistance to energy transfer for both steam and hot water absorbed energies and also it has the highest density and density under pressure. Fabrics A and B performed the best in the steam tests as they are the thickest fabrics among all of the fabric systems. Fabrics D, A and G performed the best in the hot water tests, because they are either thicker or lower density than other system which did not perform as well. Fabric system G performed the best among the knit fabrics in both the steam and hot water tests as it was the thickest and the least dense among the knit fabric systems.

Discussion of objectives and hypothesis

Objective 1

The first objective of this research was to determine the fabric characteristics and properties that contribute most to reduce heat transfer and improve steam protection based on correlations of data from Phase I. This objective was accomplished through statistical analyses of data from Phase I. It was determined that density under pressure and density, followed by the thickness under pressure, contribute highly to the absorbed energy. Therefore, these correlations suggested that as the density and density under pressure increase, the absorbed energy will also increase, while as the thickness increases, the absorbed energy will decrease. Thus density was considered to be an important factor when designing new fabric systems.

Objectives 2 and 3

The second and third objectives of this research were to design a series of fabric systems that would provide a high level of steam and hot water protection and that could be worn for short-term but high risk exposure situations and to develop the prototype fabric systems. These prototype systems included an existing exterior layer and insulation layers developed by the researcher. These objectives were successfully met and the outcome of this study shows that six of the seven fabric systems incorporating the developed insulation layers did not reach the criteria for the onset of a second or third degree burn within the data collection period of 60 seconds. It should be noted that the prototype fabric insulations were not made from flame resistant materials and for most end uses where steam or hot water protection is needed, there are likely to be requirements for flame resistant materials.

The total mass of the fabric systems developed was higher than the masses generally used for shirts and pants for protective clothing. Generally shirting fabrics have masses ranging from 150 to 300 g/m^2 while bottom fabrics range from 300 to 850 g/m^2. The developed fabric systems had masses ranging from 750 to 1140 g/m^2. These fabrics could be produced with lower masses by incorporating finer yarns. For example, fabric systems B and D are similar in structure, but D is approximately 300 g/m^2 lighter than fabric system B because it is woven from finer yarns. These fabrics had similar results in both the steam and hot water tests.

Objective 4

The fourth objective of this research was to test the newly developed fabric systems for energy absorption and time to reach the onset of a second or third degree burn when exposed to pressurized steam and hot water. This objective was also successfully met for the seven fabrics tested. The null hypothesis that there are no significant correlations between fabric characteristics and properties and (a) steam protection parameter or (b) hot water protection parameters, stands rejected as the absorbed energy through different fabric systems varied significantly. Fabric E showed the least protection under both steam and hot water exposure followed by fabrics F and C. Fabrics A and B have the highest protection under steam exposure followed by Fabrics G and D.

Fabrics D and A have the highest protection under hot water exposure followed by fabrics G, B and F.

During both the steam and hot water testing, it was observed that the fabric system F (100% cotton) was not absorbing the condensate water. Water was found in the form of tiny droplets on the inner surface of the fabric facing the sensor. Hairiness on the surface of this fabric acted to repel the water and also reduced the contact area of the water with the fabric surface and with the sensor. For this reason, fabric system F performed better in both the steam and hot water tests compared to fabric system E which had similar fabric characteristics and knit structure.

Rossi et al (2004) concluded that in steam tests, transfer of energy was dependent on the water vapour permeability of materials and on the thickness of the thermal insulation layer of the specimen. In this study, all the fabrics had the same semi-permeable membrane and moisture vapour permeability was not measured. However, the fabrics were of different thicknesses and only the construction of the insulation materials varied. Fabric system A, with the thickest insulation layer, performed the best in both steam and hot water tests, while fabric system E, with the thinnest insulation layer, performed the worst. Lee and Barker (1987) reported that thermal protection increases with a decrease in fabric bulk density. An increase in bulk density increases the fraction of fibres in fabrics of similar mass, reducing the air volume and leading to more conductive heat transfer. A similar result was shown in this study where fabric system E had the highest density and it transferred the highest energy among all the fabric systems in both steam and hot water tests. Fabric system G had the lowest density even after compression. It transferred the second lowest energy in the steam test and third lowest in the hot water test. It was not the best fabric because it was still thinner than some other fabrics.

6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

In this chapter, a summary of the research is presented followed by the conclusions. Recommendations for the test apparatus are made as are recommendations for the textile industry. Finally, further research suggestions are presented.

Summary

In the energy sectors of Alberta, especially in oil and gas industries, the use of pressurized steam and hot water has led to instances where workers have been seriously injured (Fennel, 2009). These workers were not protected by the existing FR protective clothing used in these industries because steam and hot water can easily penetrate FR clothing currently in use. Also this FR protective clothing was not tested for exposure to steam and hot water because, until now, there has been no standard test method and test apparatus that can expose them to pressurized steam or hot water.

Since 2006, research at the University of Alberta has focused on the development of a test method and device to evaluate garments for protection against steam and hot water exposure. In this regard this research focused on the development of fabric systems to meet or exceed the specifications for protection against steam and hot water exposure that were established in the earlier steam and hot water protection research (Ackerman et al., 2012; Jalbani et al., 2012). Tests were conducted to understand the selected fabric systems and their performance upon exposure to pressurized steam. Based on the results, fabric systems were developed to provide better steam and hot water protective properties and improved protection from high pressure steam exposure. These fabrics were then evaluated for steam and hot water protection. In the steam test, steam pressure and temperature were 210 kPa and 150 °C. The jet was positioned 60 mm from the face of the fabric. In the hot water test, water pressure and temperature were 0.6 kPa and 85 °C. The nozzle was positioned 50 mm from the surface of the fabric and the flow rate of water was six litres per minute. Each specimen was exposed for ten seconds and temperature data as a function of time were collected for sixty seconds which include ten second exposure time and fifty second post exposure time to incorporate any effect of stored energy. Temperature data were then used to calculate the burn injuries, heat flux and absorbed energy. The test results were used to assess the protection that the developed fabrics would provide if used in protective clothing.

Conclusions

All fabric systems developed for steam and hot water protection were successful in preventing partial or full-thickness burns from heat transfer onto skin during or after exposure to steam and hot water with the exception of one fabric system in the steam test. It is concluded that thickness, density and density under pressure are the most important fabric characteristics in providing protection against pressurized steam and hot water hazards. An insulation layer incorporating air makes the fabric less dense and hence provides better protection. It was evident from Phase I research that at least a liquid water barrier is required in the fabric systems designed for steam and hot water protection. Without the semi-permeable or impermeable barrier steam and hot water can easily penetrate these fabric systems. An insulation layer behind the semi-permeable membrane or impermeable barrier is also necessary and the properties of the insulation layer are very important in determining the protection offered by the fabric system. As well there is a need for an outer fabric layer to protect the semi-permeable barrier.

Recommendations for test apparatus

It was observed that there is a need for calibration of the test instrument following installation of a new sensor because the position of the sensor relative to the specimen is very important. The sensor needs to be levelled with the PTFE support so that the specimen always touches the sensor and lies completely flat on the PTFE support. Figure 6.1 shows the correct placement of the skin simulant sensor. For calibration purposes, a calibration fabric should be found. This fabric needs a liquid water barrier with moderate fabric thickness to allow heat transfer to the sensor in a calibration test run. The calibration will ensure that the instrument will give reproducible results even after installation of a new skin simulant sensor.

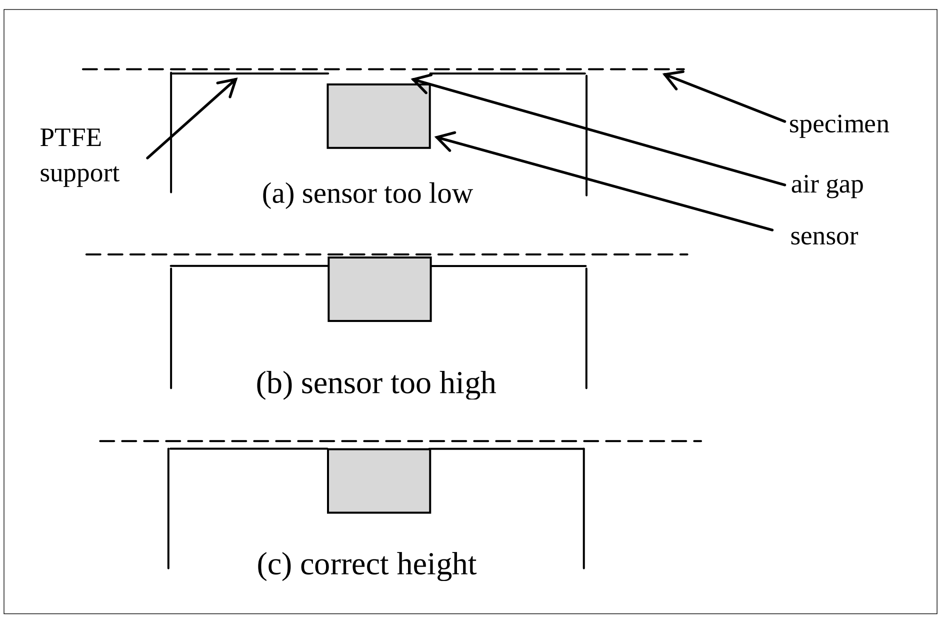

Figure 6.1. Placement of skin simulant sensor

During the first few runs (trial) of the hot water tests it was observed that the absorbed energy results were influenced by the initial sensor temperature for both blank tests and tests with specimens on top of the skin simulant sensor. The water used in the tests is at 85 °C and a temperature difference of 5 °C in the sensor at the start of the test replication can change the results by ~ 12%. Therefore, the initial sensor temperature was controlled to 30 °C for each test replication used for this research and it is recommended that the initial sensor temperature must be selected, controlled and monitored carefully. The 30 °C temperature that was used seems a reasonable starting temperature as this is close to skin temperature and was possible to achieve through cooling (Umeno et al., 2001). Water pooling on the surface of the specimen above the sensor also suggests that specimens should be inclined enough to allow the water to drain off the surface of the specimen during the exposure and post exposure data collection periods.

In steam testing, the aluminum cup used to trap the steam and hold the specimen restraint in place, absorbs energy during the steam exposure period and transfers the energy to the sensor during the post exposure data collection period. Ideally no cup should be used or the contribution of energy from the cup should be estimated and removed from the test result. As more and more specimens are tested, the aluminum cup retains energy from the steam. This energy is transferred during the post exposure time in the subsequent tests so cooling of aluminum cup is recommended between specimen replications of the tests. Water pooling was also observed on the surface of the specimen in steam testing.

However, the pooling was not consistently above the sensor so specimen inclination is recommended to avoid water pooling above the sensor producing inconsistent absorbed energy results within a group of specimens.

Recommendations to textile industry

It is evident in this research that the thickness and density of a fabric system (especially the insulation layer) influences the energy transfer. However, there will always be a trade-off between thickness and the mass of the fabric system. As the fabric becomes thicker and more protective its mass will increase and at some point it will be too thick to function as clothing fabric. The insulation fabrics developed in this research can be used either as a separate layer in a garment or laminated to make a composite fabric. Many fabrics already developed for steam protection and tested in Phase I were tri-laminates. The advantage of using the insulation as a separate layer in a garment could be the incorporation of air between the fabric layers which can reduce heat transfer. However, if used as a separate layer in the garment, then protection of the semi-permeable membrane from abrasion while the garment is in use should be taken into account.

In this research, pile woven structures, weft rib knits and a warp terry knit were considered for insulation layers in fabric systems. The pile woven fabrics were found to be less compressible than the knits of the same thickness. However, production costs for producing the woven pile is higher than that of the knits. Knits with similar structure (ribbed, pile and lightly brushed) incorporating air in the fabric structure would be good candidates for further development of the insulation layers, as long as these knit structures are not too easily compressed or distorted.

Further research

In this research, only non-FR materials were available for the insulation layer. Therefore, further work with inherently FR fibres and treated FR cotton is needed. As well, the apparatus was only able to provide a hot water jet with pressure of 0.6 kPa, while the workplace hazard is likely to have a pressure in the range of 700 to 2000 kPa (D. J. Fennell, Senior Safety Advisor, Imperial Oil Resources, personal communication, August 20, 2012). Therefore, a pressurized hot water tester is needed to better simulate hot water exposure conditions encountered in industry. It was observed during both the steam and hot water tests that condensation occurred on the sensor surface and the quantity of this diffused water vapour will have affected the test results. Further research should investigate how the condensation energy from the water vapour affects the results and how the water vapour diffusion resistance of the fabric system could be altered to control this phenomenon.

In this research, fabric characteristics were the only independent variables and performance properties were not assessed in relation to heat transfer under the test conditions. The effect of other performance properties such as air permeability and water vapour diffusion should be investigated and incorporated in numerical modeling for energy transfer in both steam and hot water exposure.

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Appendix 1: Tables of test results

Table A.1. Woven fabric system characteristics

Fabric code	Spec. No.	Mass[1]	Thickness[2]	Thickness under pressure[3]	Thickness change[4]	Density[5]	Density under pressure[6]
A	1	1148	4.17	3.51	15.9	276	328
	2	1128	4.09	3.43	16.1	276	329
	3	1128	4.19	3.51	16.4	269	322
	4	1142	4.19	3.48	17.0	273	328
	5	1151	4.27	3.48	18.5	270	331
	6	1130	4.19	3.51	16.4	270	322
	Mean	**1138**	**4.2**	**3.5**	**16.7**	**272**	**327**
	CV %	**0.92**	**1.37**	**0.85**	**5.61**	**1.14**	**1.13**
B	1	1038	3.84	3.25	15.2	271	319
	2	1032	3.76	3.30	12.2	275	313
	3	1062	3.89	3.25	16.3	273	327
	4	1047	3.89	3.33	14.4	269	315
	5	1061	3.73	3.28	12.2	284	324
	6	1042	3.78	3.25	14.1	275	320
	Mean	**1047**	**3.8**	**3.3**	**14.1**	**275**	**320**
	CV %	**1.17**	**1.71**	**0.98**	**11.70**	**1.91**	**1.68**
C	1	968	3.20	2.82	11.9	302	343
	2	991	3.28	2.79	14.7	302	355
	3	989	3.25	2.79	14.1	304	354
	4	1006	3.20	2.84	11.1	314	354
	5	981	3.23	2.84	11.8	304	345
	6	987	3.25	2.84	12.5	303	347
	Mean	**987**	**3.2**	**2.8**	**12.7**	**305**	**349**
	CV %	**1.26**	**0.95**	**0.88**	**11.12**	**1.49**	**1.45**
D	1	745	2.79	2.54	9.1	267	293
	2	747	2.97	2.57	13.7	251	291
	3	742	3.00	2.51	16.1	248	295
	4	747	2.90	2.59	10.5	258	288
	5	744	2.92	2.62	10.4	255	284
	6	744	2.84	2.51	11.6	262	296
	Mean	**745**	**2.9**	**2.6**	**11.9**	**257**	**291**
	CV %	**0.25**	**2.63**	**1.62**	**21.52**	**2.69**	**1.53**

[1] *g/m^2, following CAN/CGSB-4.2 No.5.1 – M90*
[2] *mm, following CAN/CGSB-4.2 No. 37-2002*
[3] *mm at 13.8 kPa*
[4] *reported as (%) change*
[5] *kg/m^3*
[6] *kg/m^3 at 13.8 kPa pressure*

Table A.2. Knit fabric system characteristics

Fabric code	Spec. No.	Mass[1]	Thickness[2]	Thickness under pressure[3]	Thickness change[4]	Density[5]	Density under pressure[6]
E	1	736	2.03	1.68	17.5	362	439
	2	738	1.98	1.75	11.5	372	421
	3	753	1.96	1.73	11.7	385	436
	4	743	2.01	1.70	15.2	370	437
	5	743	2.03	1.75	13.8	366	424
	6	752	1.96	1.73	11.7	384	435
	Mean	**744**	**2.0**	**1.7**	**13.6**	**373**	**432**
	CV %	**0.91**	**1.76**	**1.72**	**17.86**	**2.51**	**1.74**
F	1	748	2.31	1.91	17.6	324	393
	2	745	2.34	1.93	17.4	319	386
	3	747	2.29	1.88	17.8	327	397
	4	750	2.29	1.88	17.8	328	399
	5	753	2.29	1.88	17.8	329	401
	6	748	2.26	1.91	15.7	331	392
	Mean	**748**	**2.3**	**1.9**	**17.3**	**326**	**395**
	CV %	**0.37**	**1.14**	**1.09**	**4.63**	**1.34**	**1.37**
G	1	568	3.05	1.98	35.0	186	287
	2	563	3.18	1.96	38.4	177	288
	3	563	2.95	2.01	31.9	191	281
	4	565	3.05	1.96	35.8	185	289
	5	557	2.97	2.03	31.6	187	274
	6	563	3.15	2.03	35.5	179	277
	Mean	**563**	**3.1**	**2.0**	**34.7**	**184**	**282**
	CV %	**0.62**	**3.00**	**1.76**	**7.40**	**2.91**	**2.18**

[1] *g/m^2, following CAN/CGSB-4.2 No.5.1 – M90*
[2] *mm, following CAN/CGSB-4.2 No. 37-2002*
[3] *mm at 13.8 kPa*
[4] *reported as (%) change*
[5] *kg/m^3*
[6] *kg/m^3 at 13.8 kPa pressure*

Table A.3. Skin properties used in the analysis of thermal injury (ASTM, 2000)

	Thickness[1]	Thermal conductivity[2]	Volumetric heat capacity[3]	Blood perfusion rate[4]
Epidermis	$8.0 \cdot 10^{-5}$	0.255	$4.32 \cdot 10^{6}$	0
Dermis	$2.0 \cdot 10^{-3}$	0.523	$3.87 \cdot 10^{6}$	$1.25 \cdot 10^{-3}$
Subcutaneous	$1.0 \cdot 10^{-2}$	0.167	$2.76 \cdot 10^{6}$	$1.25 \cdot 10^{-3}$
Blood	-	-	$3.99 \cdot 10^{6}$	-

[1] *m*
[2] $W\ m^{-1}\ K^{-1}$
[3] $J\ m^{-3}\ K^{-1}$
[4] $m^3\ s^{-1}$ *per* m^3 *tissue*

Table A.4. Skin burn injury prediction and absorbed energy for woven fabric systems: detailed data

Fabric code	Spec. No.	Time to second degree burn for steam[1]	Time to third degree burn for steam[2]	Absorbed energy for steam[3]	Time to second degree burn for hot water[4]	Time to third degree burn for hot water[5]	Absorbed energy for hot water[6]
A	1	-	-	94.9	-	-	56.9
	2	-	-	138.5	-	-	59.7
	3	-	-	116.6	-	-	67.3
	4	-	-	136.8	-	-	57.7
	5	-	-	147.5	-	-	72.0
	6	-	-	136.5	-	-	61.6
	Mean			**128**			**63**
	CV %			**15.03**			**9.50**
B	1	-	-	105.1	-	-	84.6
	2	-	-	132.8	-	-	73.7
	3	-	-	130.4	-	-	70.9
	4	-	-	140.8	-	-	70.8
	5	-	-	129.0	-	-	69.8
	6	-	-	132.5	-	-	75.2
	Mean			**128**			**74**
	CV %			**9.47**			**7.41**
C	1	-	-	136.9	-	-	73.8
	2	-	-	139.2	-	-	78.9
	3	-	-	157.5	-	-	78.8
	4	-	-	156.0	-	-	82.6
	5	-	-	144.9	-	-	70.2
	6	-	-	154.3	-	-	82.8
	Mean			**148**			**78**
	CV %			**6.07**			**6.40**
D	1	-	-	133.9	-	-	67.8
	2	-	-	143.9	-	-	61.3
	3	-	-	146.1	-	-	60.0
	4	-	-	135.5	-	-	65.3
	5	-	-	147.4	-	-	57.2
	6	-	-	143.3	-	-	63.2
	Mean			**142**			**62**
	CV %			**3.97**			**6.08**

[1, 2, 4, 5] *seconds*

[3, 6] *kJ/m^2*

- means no burn criteria reached within 60 seconds of data collection period.

Table A.5. Skin burn injury prediction and absorbed energy for knit fabric systems: detailed data

Fabric code	Spec. No.	Time to second degree burn for steam[1]	Time to third degree burn for steam[2]	Absorbed energy for steam[3]	Time to second degree burn for hot water[4]	Time to third degree burn for hot water[5]	Absorbed energy for hot water[6]
E	1	13.01	-	160.0	-	-	117.5
	2	11.57	-	186.6	-	-	117.4
	3	11.79	-	187.5	-	-	95.2
	4	9.79	-	191.9	-	-	110.6
	5	9.71	-	193.0	-	-	109.9
	6	10.04	-	175.2	-	-	109.6
	Mean	**11.05**		**182**			**110**
	CV %	**1.30**		**6.93**			**7.39**
F	1	-	-	155.2	-	-	77.8
	2	57.26	-	167.4	-	-	61.0
	3	-	-	135.0	-	-	86.0
	4	-	-	157.7	-	-	76.2
	5	26.60	-	161.9	-	-	72.1
	6	-	-	155.6	-	-	75.2
	Mean	**41.9**		**155**			**75**
	CV %	**21.68**		**7.09**			**10.94**
G	1	-	-	138.0	-	-	72.6
	2	-	-	147.3	-	-	62.6
	3	-	-	156.6	-	-	62.0
	4	-	-	128.8	-	-	64.1
	5	-	-	137.6	-	-	69.8
	6	-	-	120.0	-	-	69.0
	Mean			**138**			**67**
	CV %			**9.40**			**6.55**

[1, 2, 4, 5] *seconds*
[3, 6] *kJ/m^2*
- means no burn criteria reached within 60 seconds of data collection period.

Appendix 2: Charts of test results

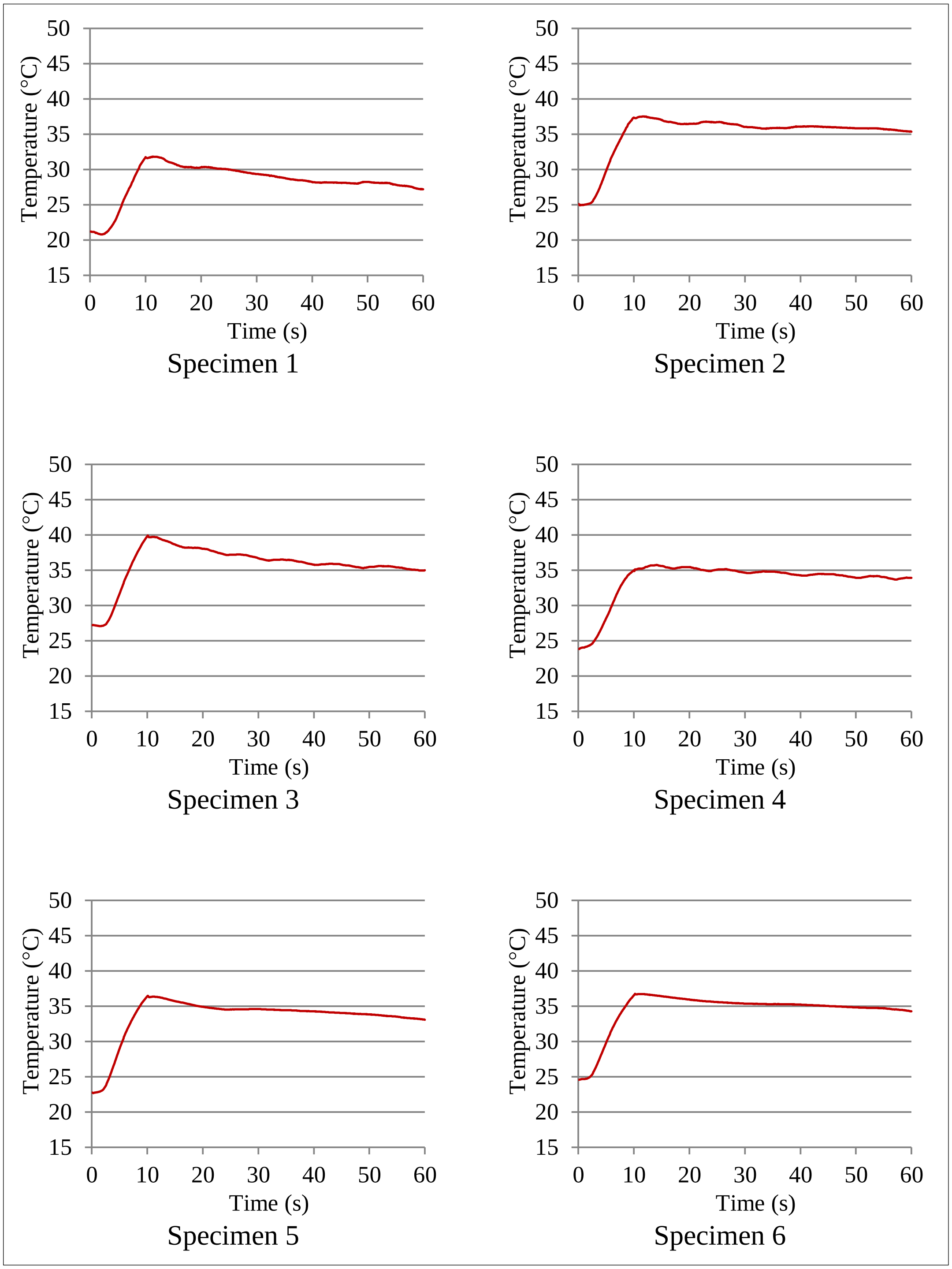

Figure A.1. Fabric system A: Temperature rise over time during steam exposure tests.

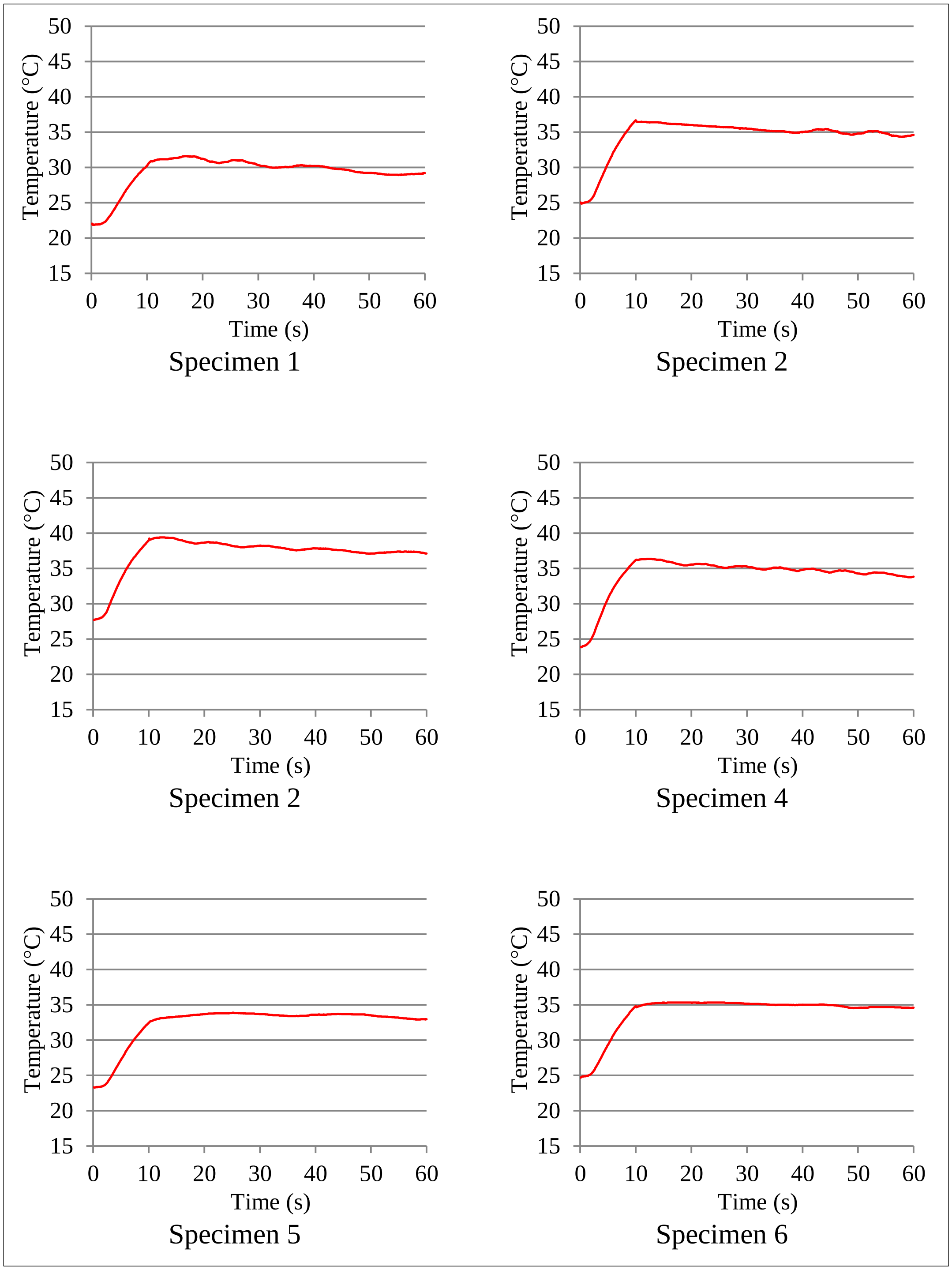

Figure A.2. Fabric system B: Temperature rise over time during steam exposure tests.

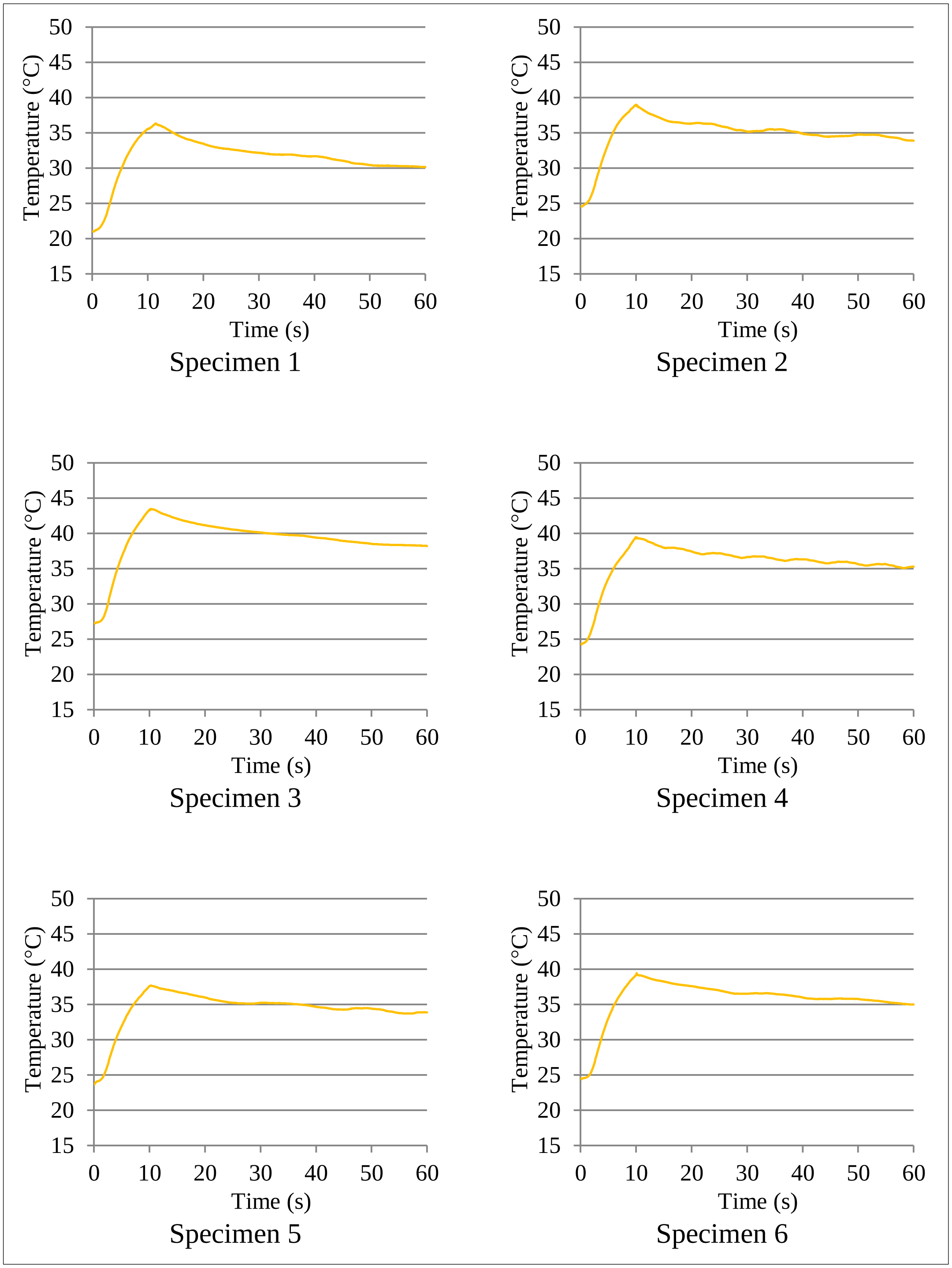

Figure A.3. Fabric system C: Temperature rise over time during steam exposure tests.

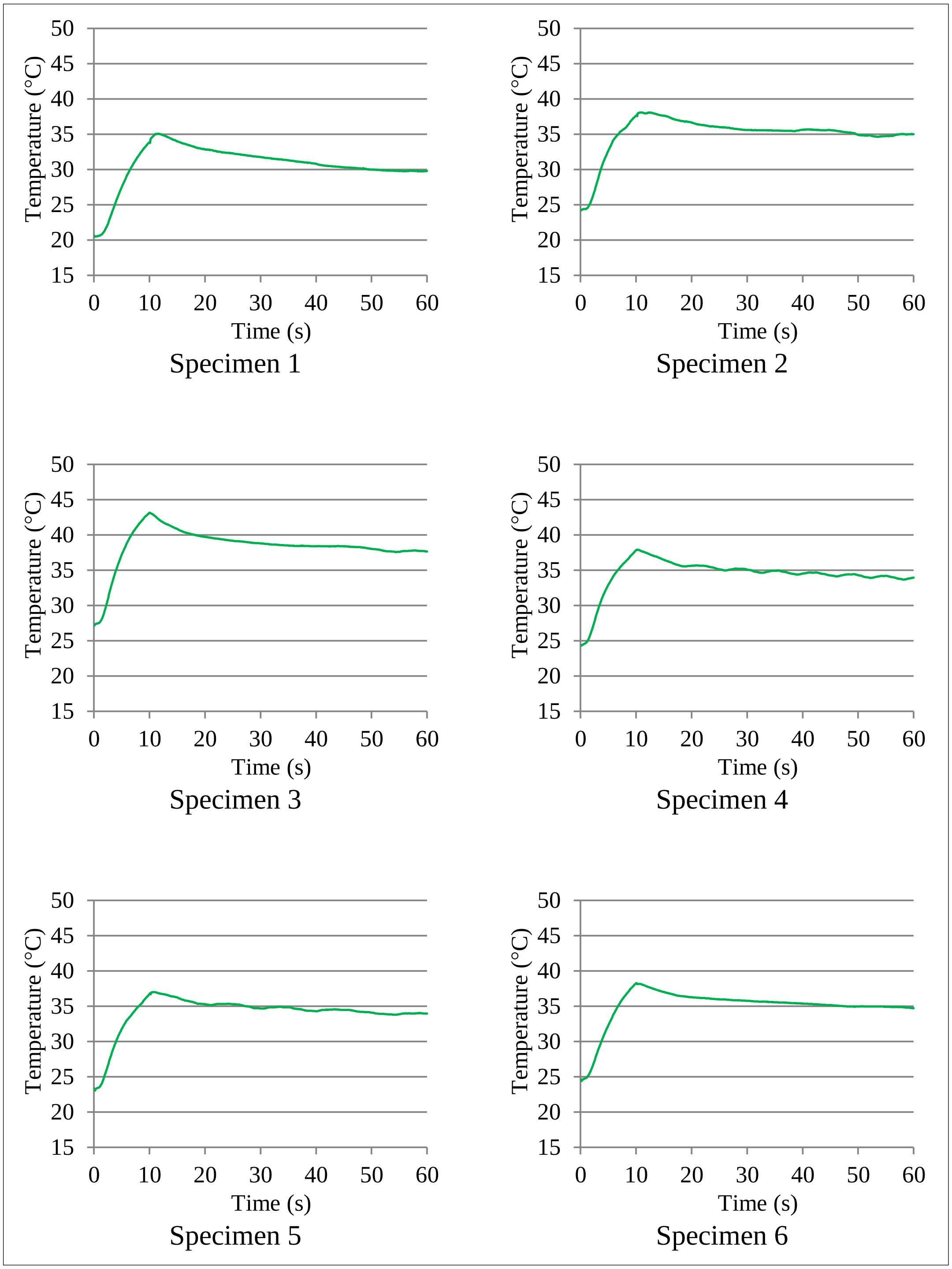

Figure A.4. Fabric system D: Temperature rise over time during steam exposure tests.

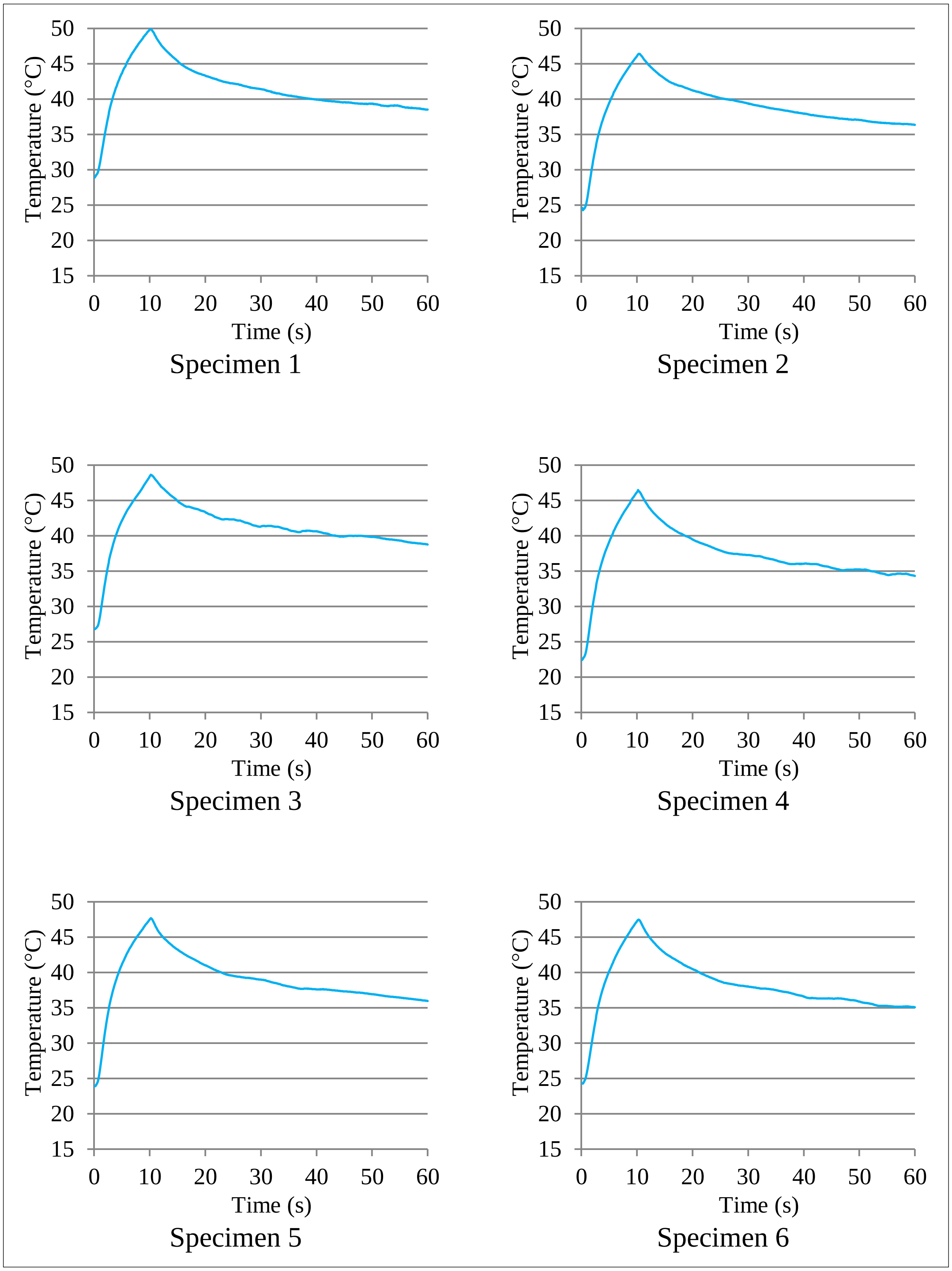

Figure A.5. Fabric system E: Temperature rise over time during steam exposure tests.

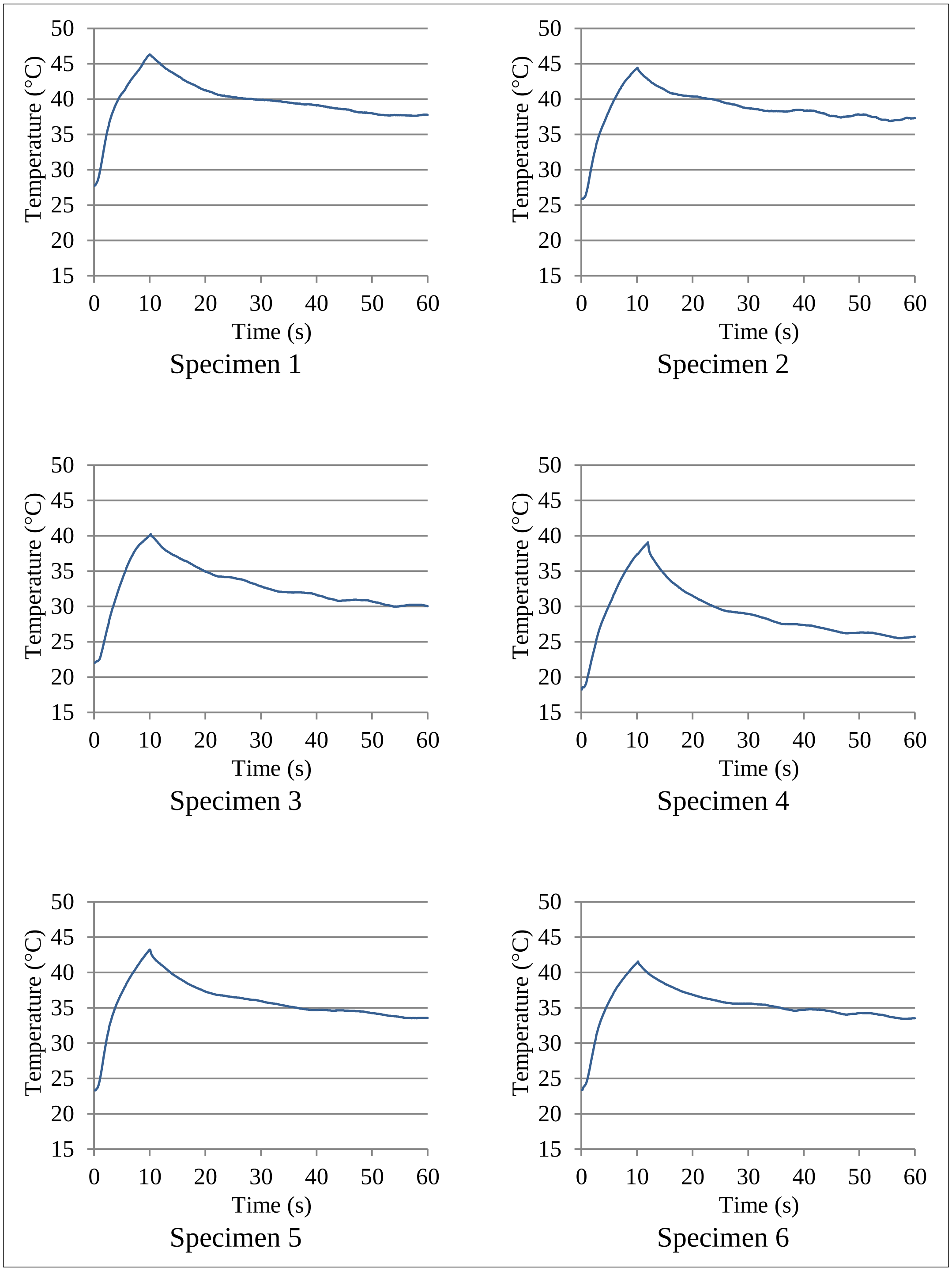

Figure A.6. Fabric system F: Temperature rise over time during steam exposure tests.

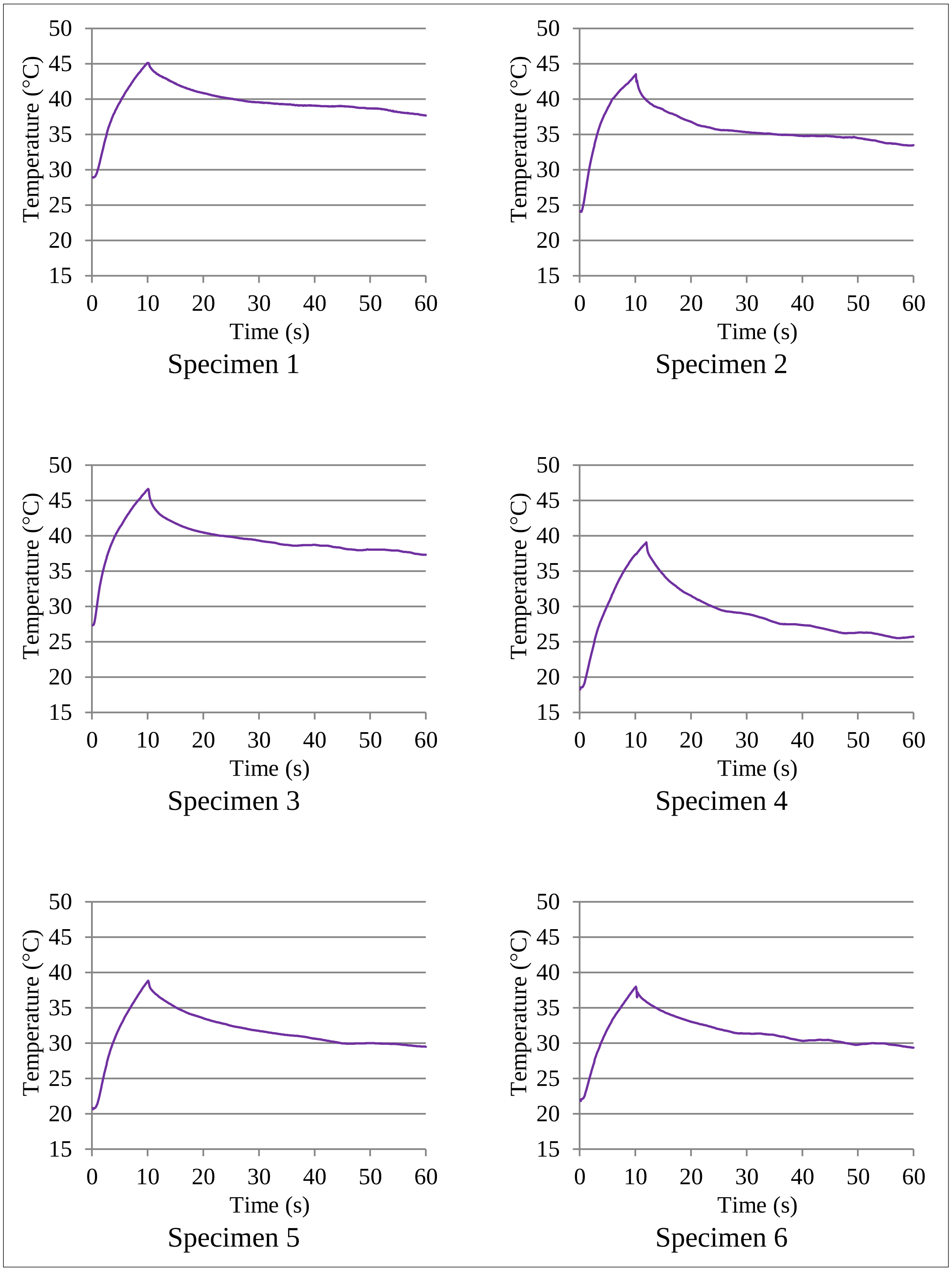

Figure A.7. Fabric system G: Temperature rise over time during steam exposure tests.

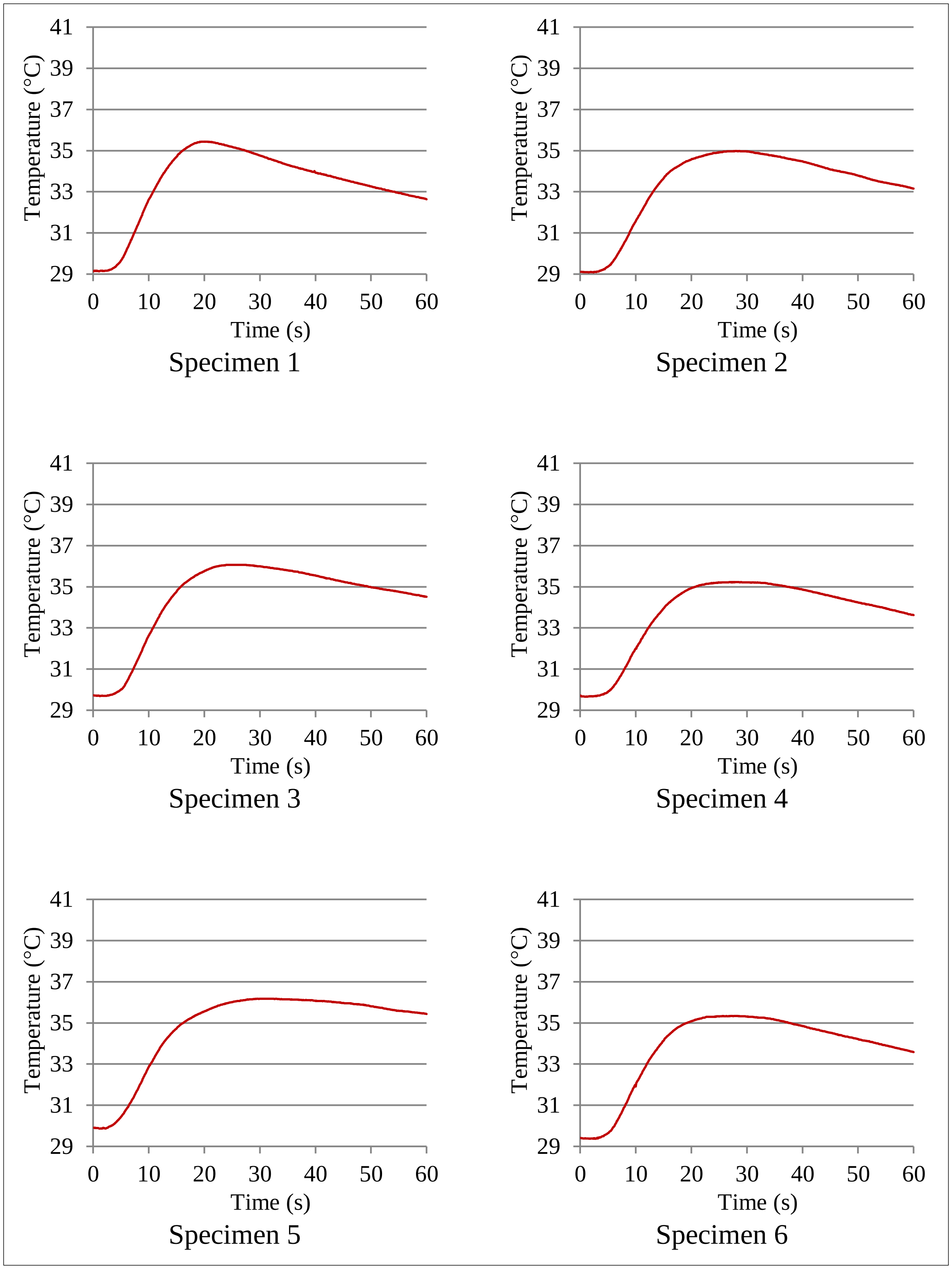

Figure A.8. Fabric system A: Temperature rise over time during hot water exposure tests.

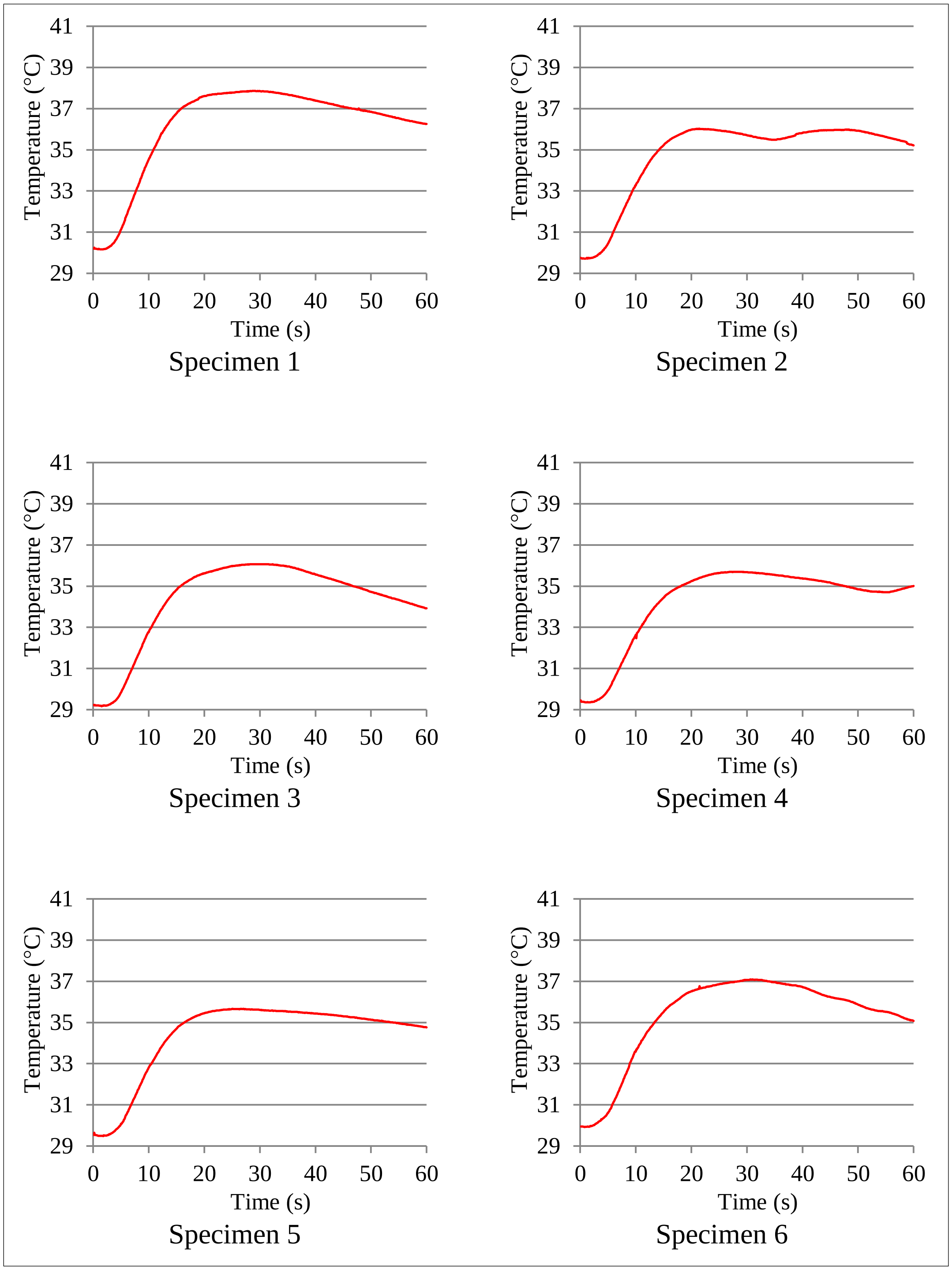

Figure A.9. Fabric system B: Temperature rise over time during hot water exposure tests.

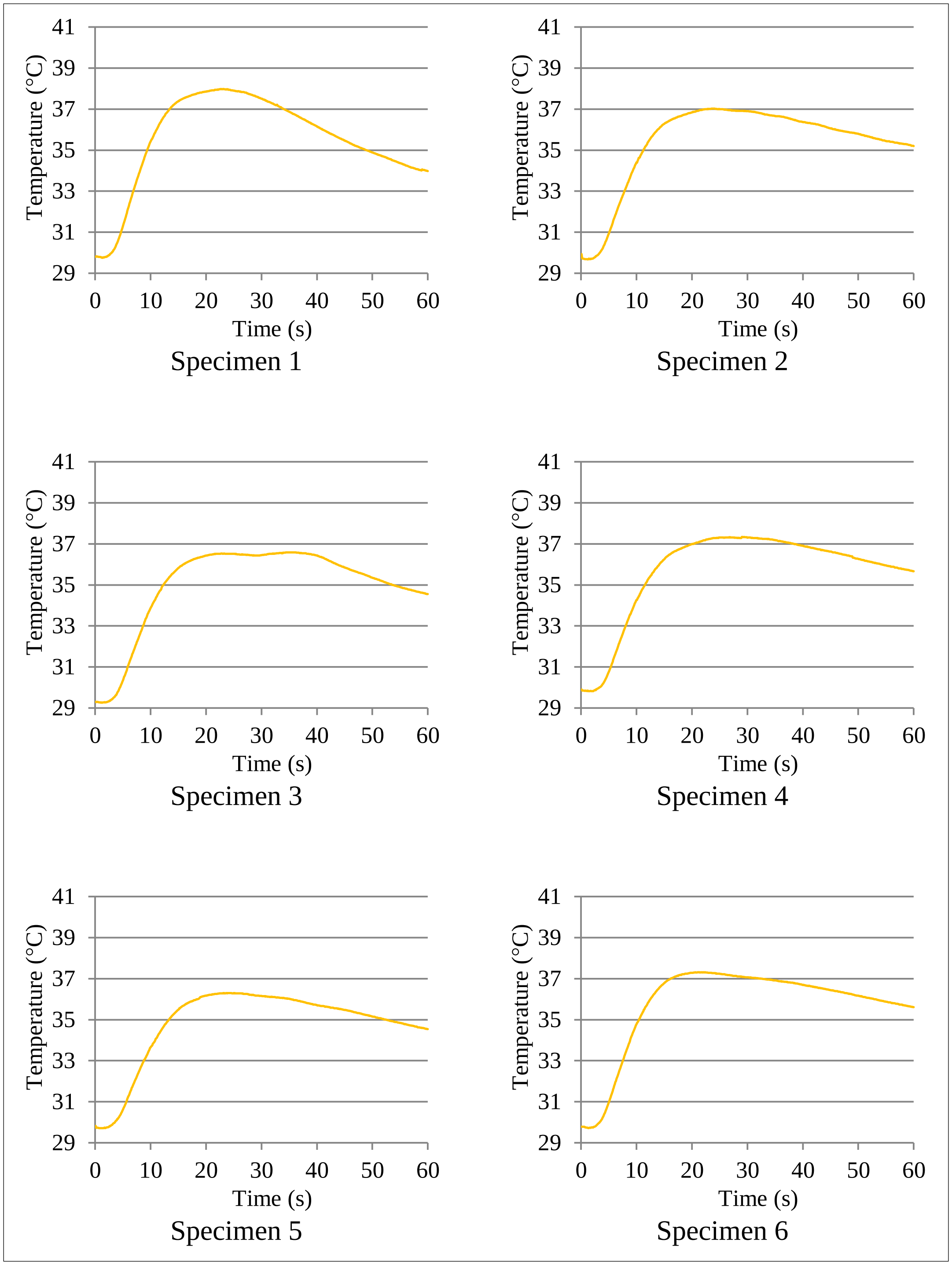

Figure A.10. Fabric system C: Temperature rise over time during hot water exposure tests.

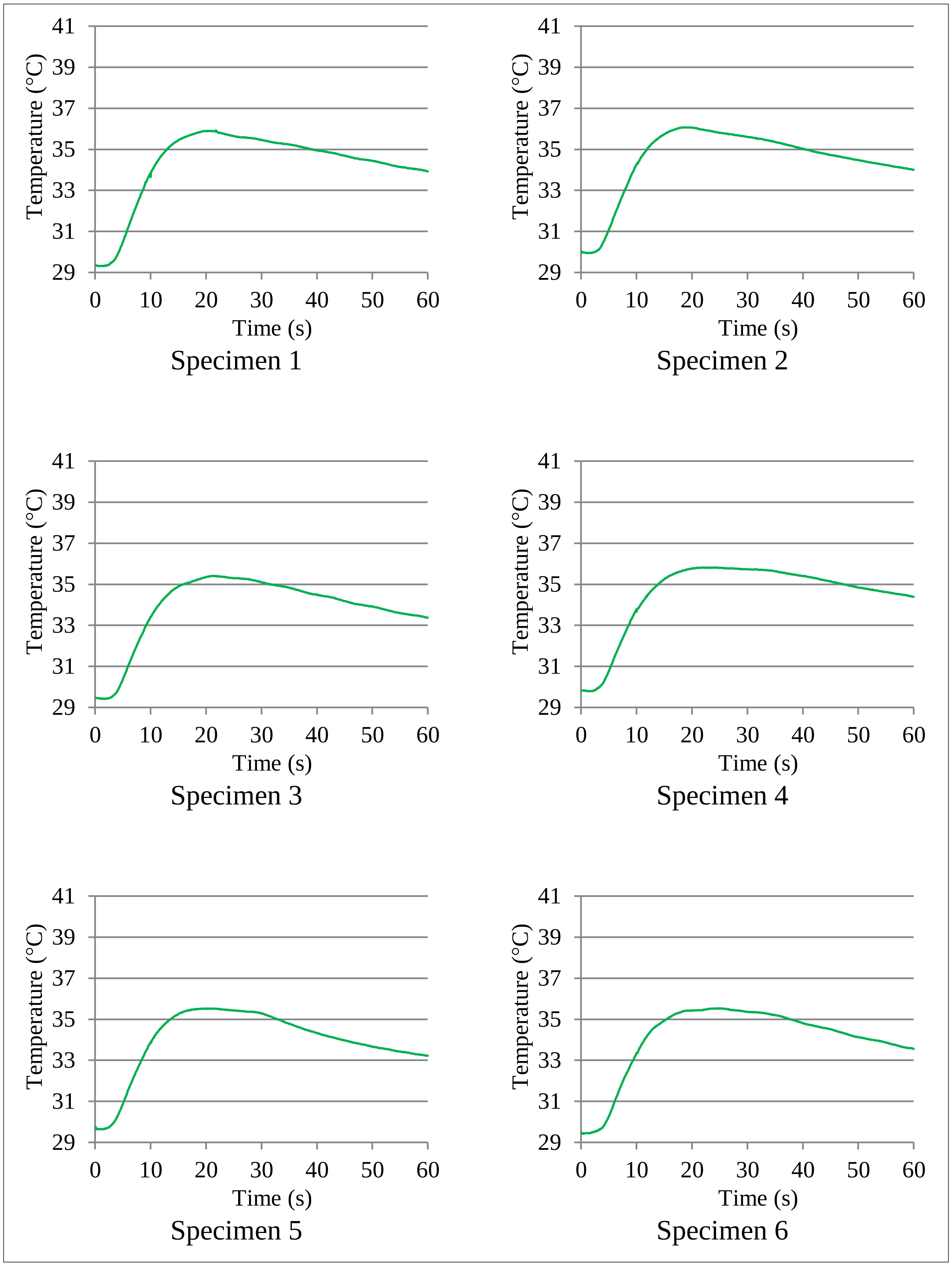

Figure A.11. Fabric system D: Temperature rise over time during hot water exposure tests.

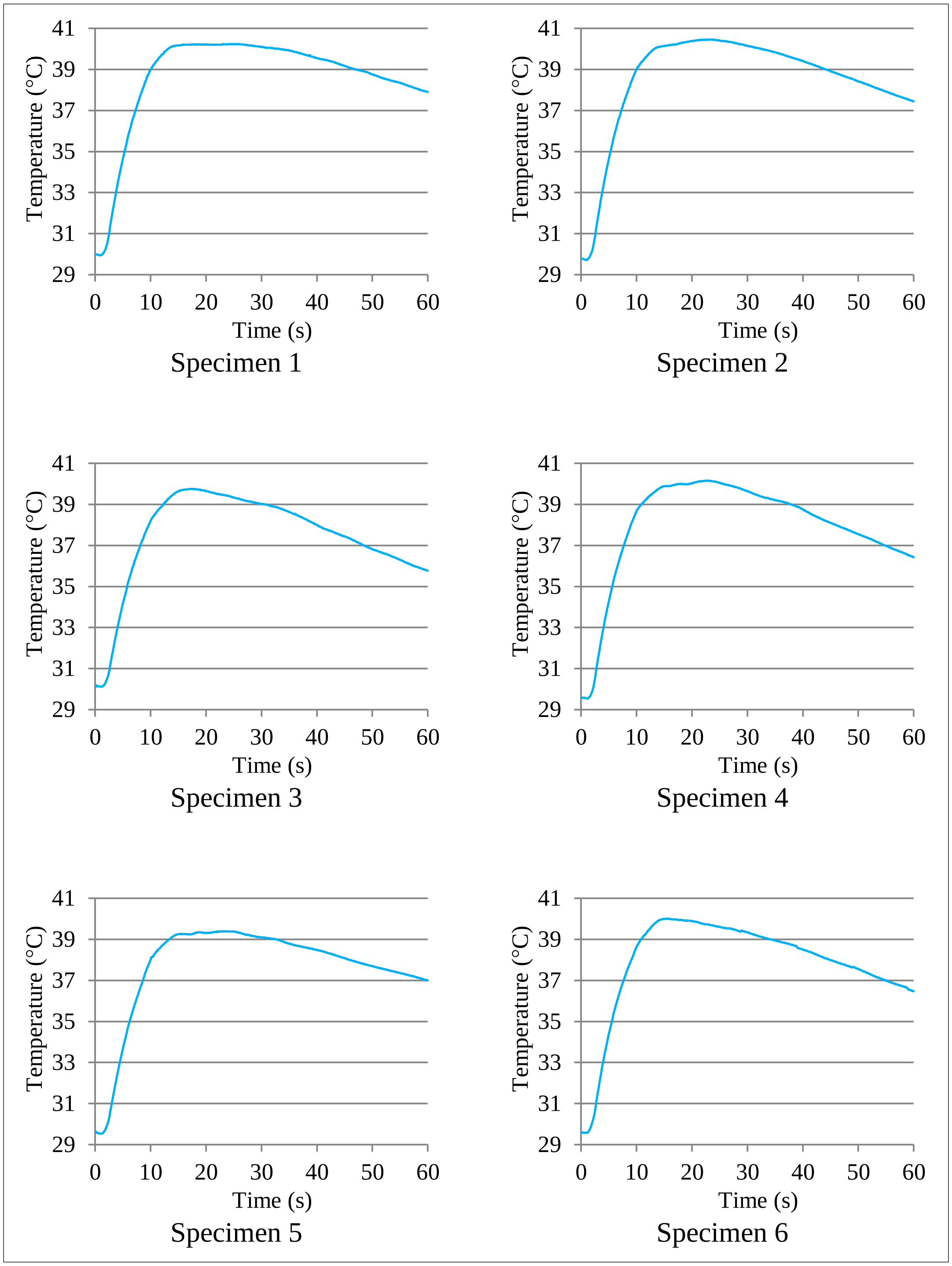

Figure A.12. Fabric system E: Temperature rise over time during hot water exposure tests.

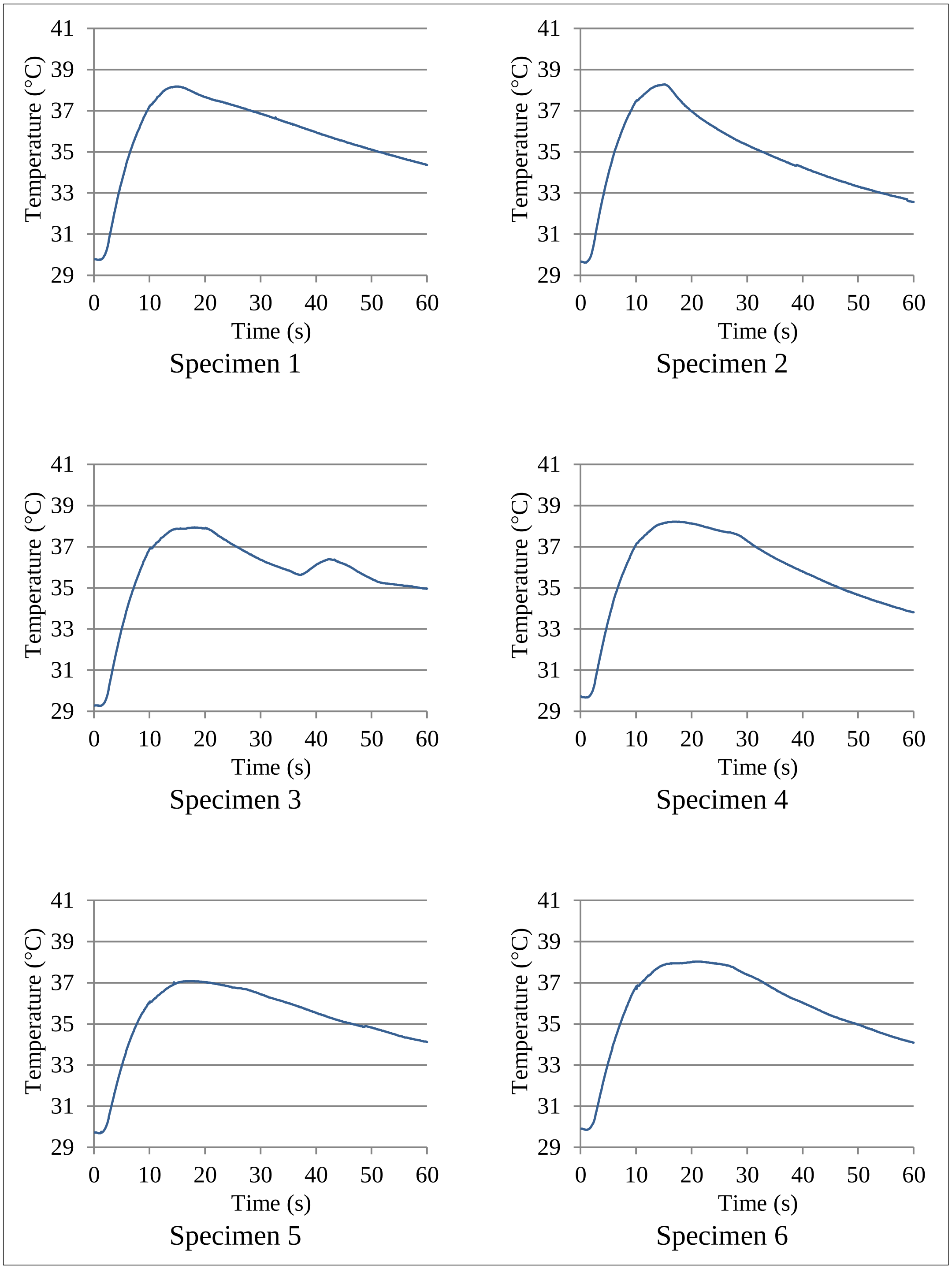

Figure A.13. Fabric system F: Temperature rise over time during hot water exposure tests.

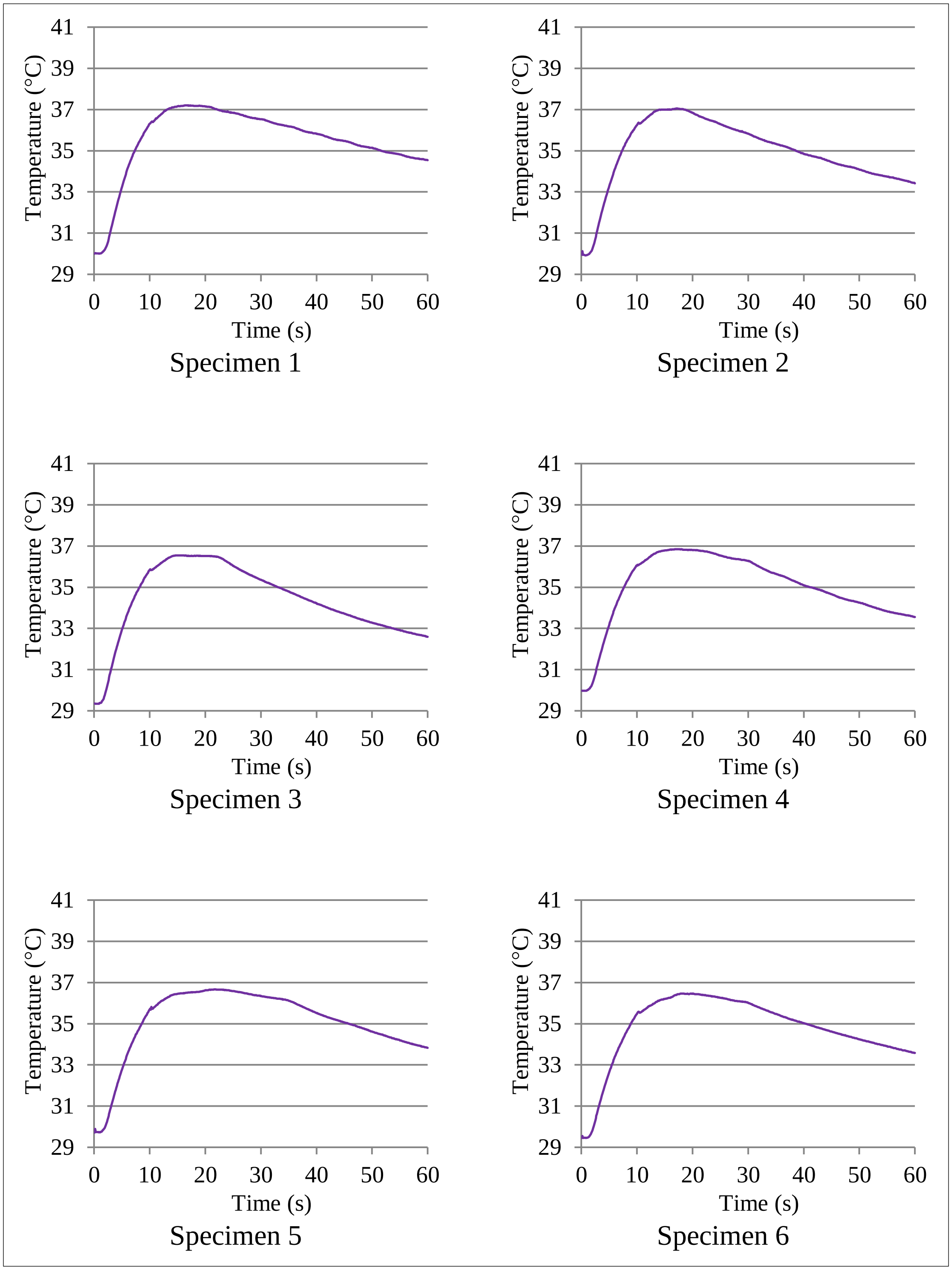

Figure A.14. Fabric system G: Temperature rise over time during hot water exposure tests.

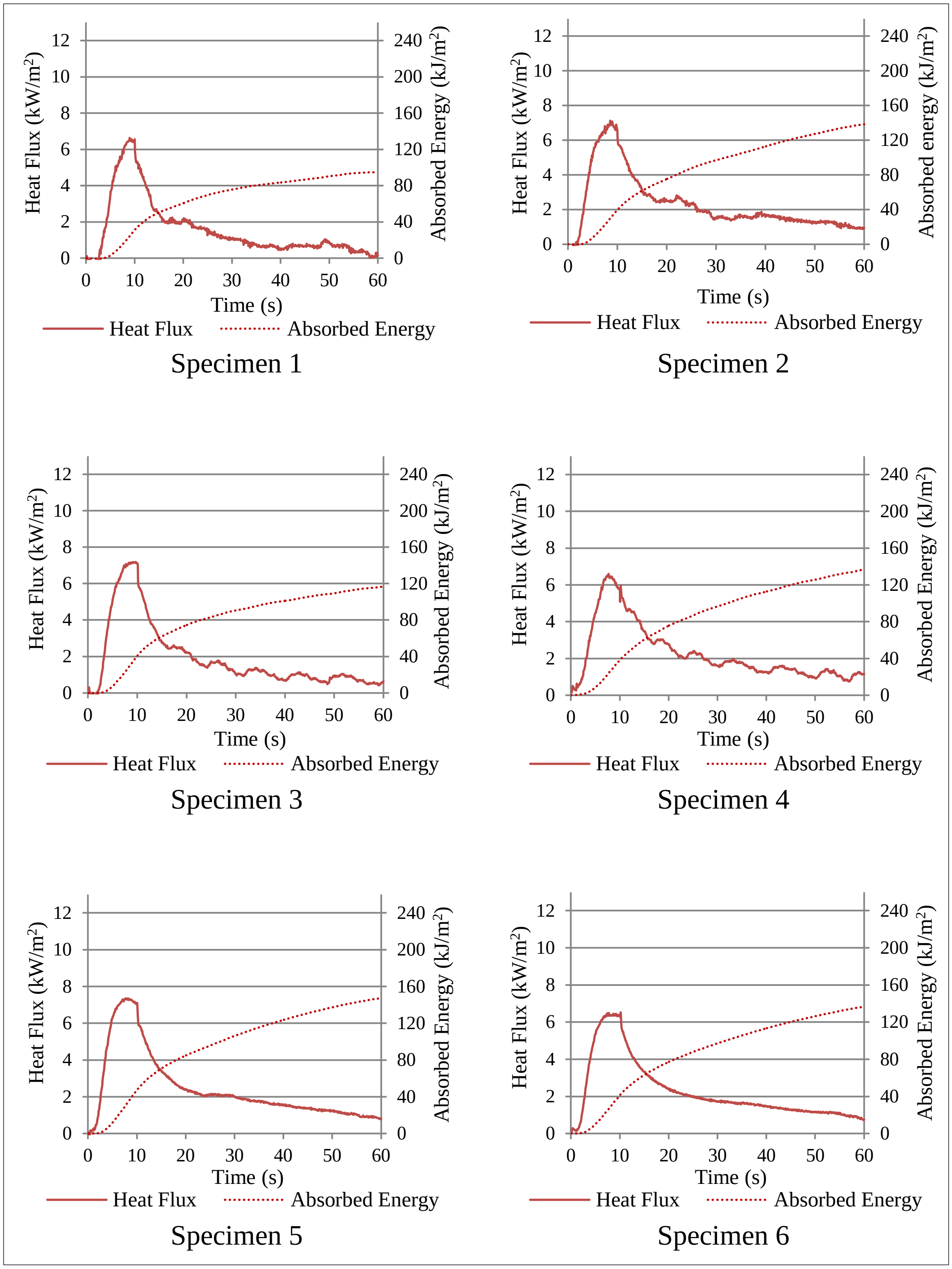

Figure A.15. Fabric system A: Heat flux and absorbed energy over time during steam exposure tests.

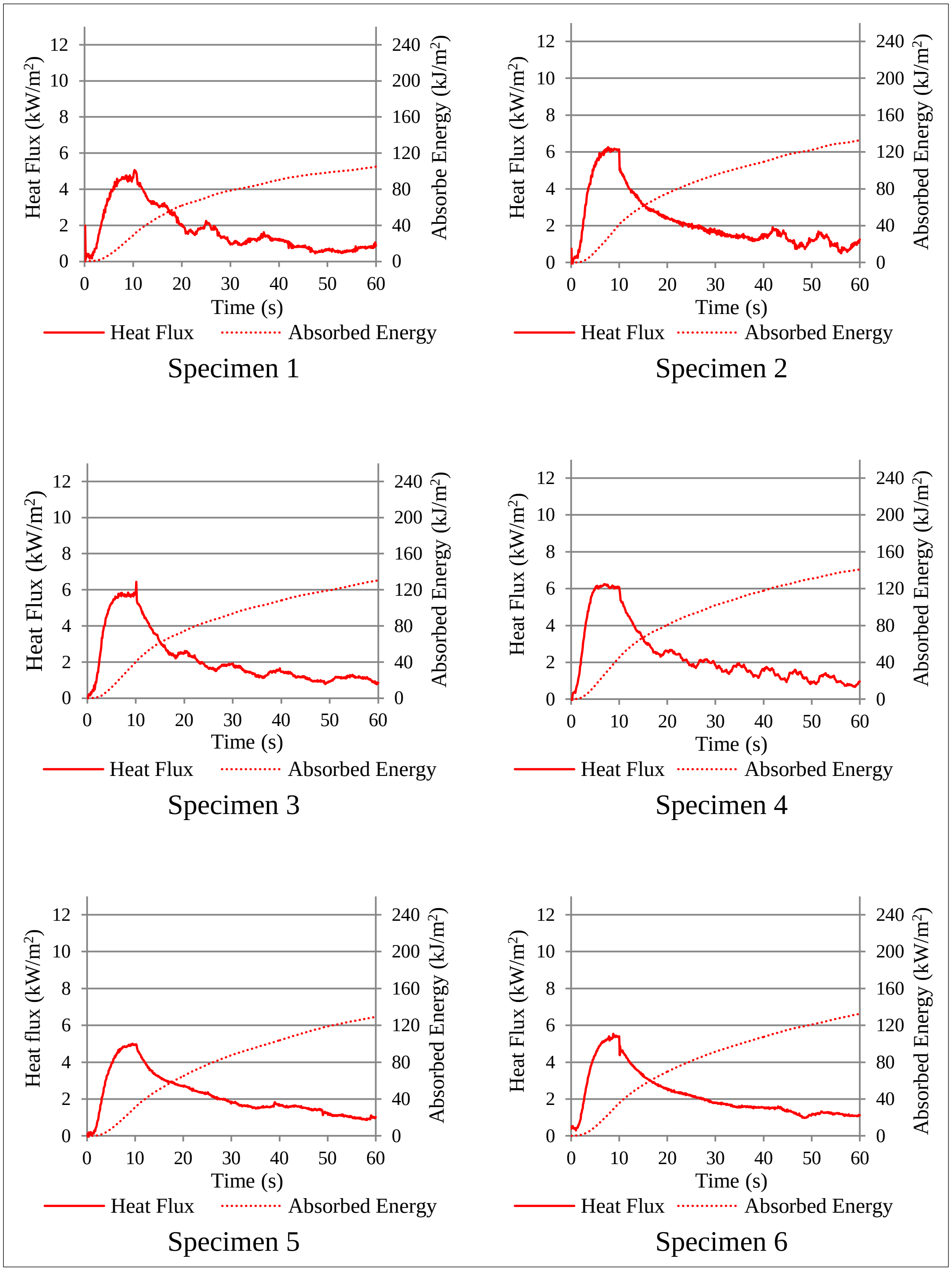

Figure A.16. Fabric system B: Heat flux and absorbed energy over time during steam exposure tests.

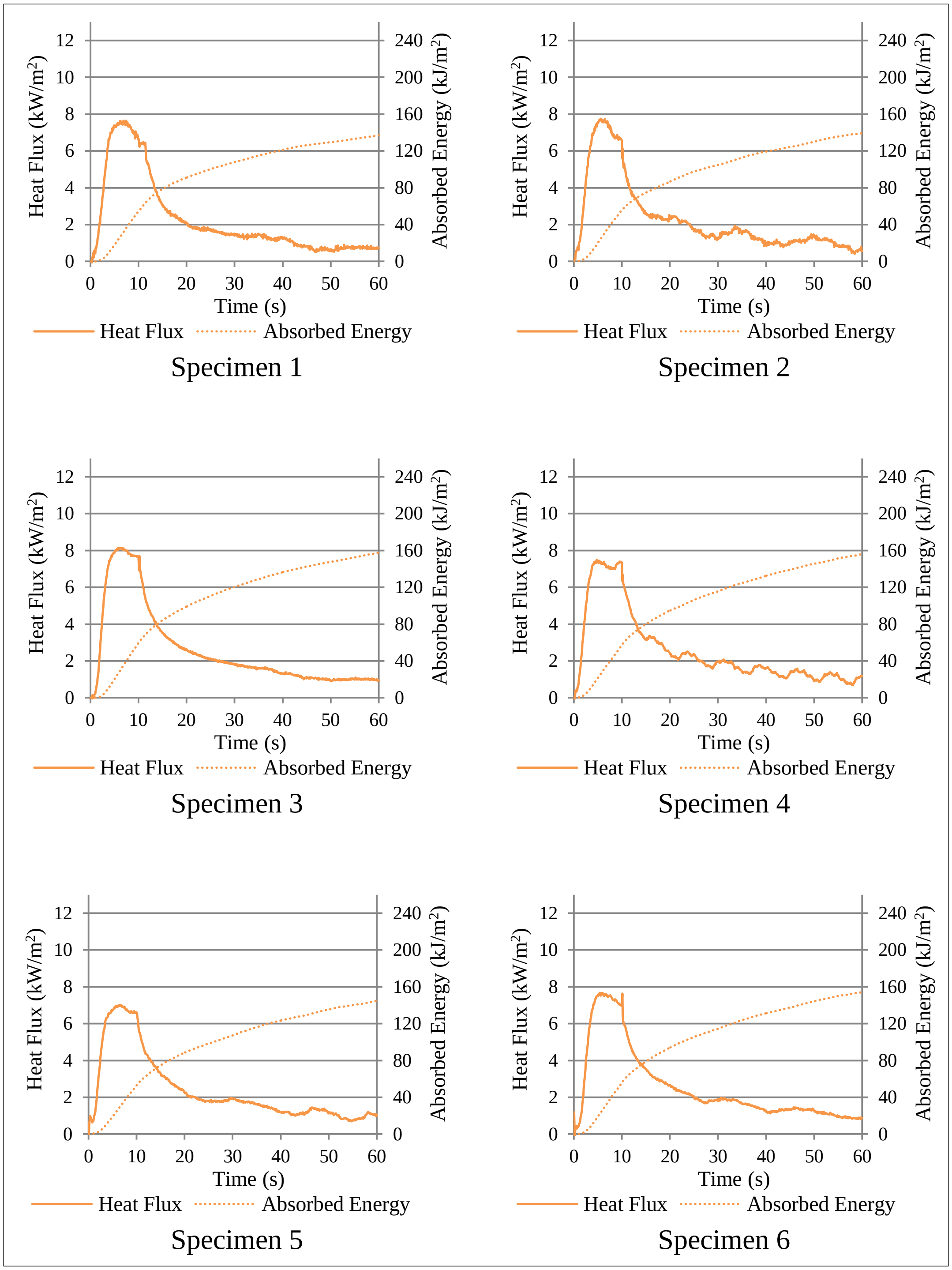

Figure A.17. Fabric system C: Heat flux and absorbed energy over time during steam exposure tests.

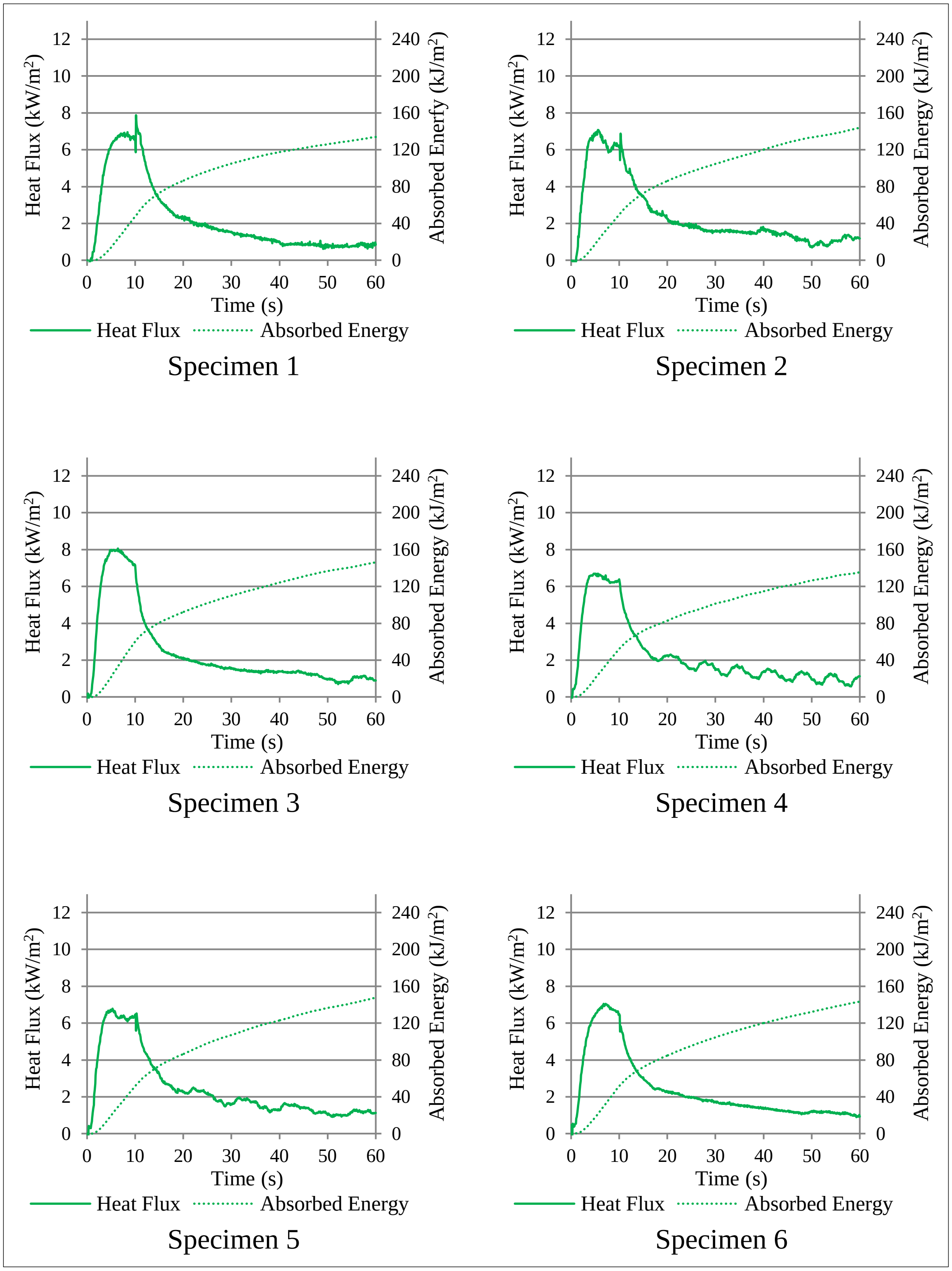

Figure A.18. Fabric system D: Heat flux and absorbed energy over time during steam exposure tests.

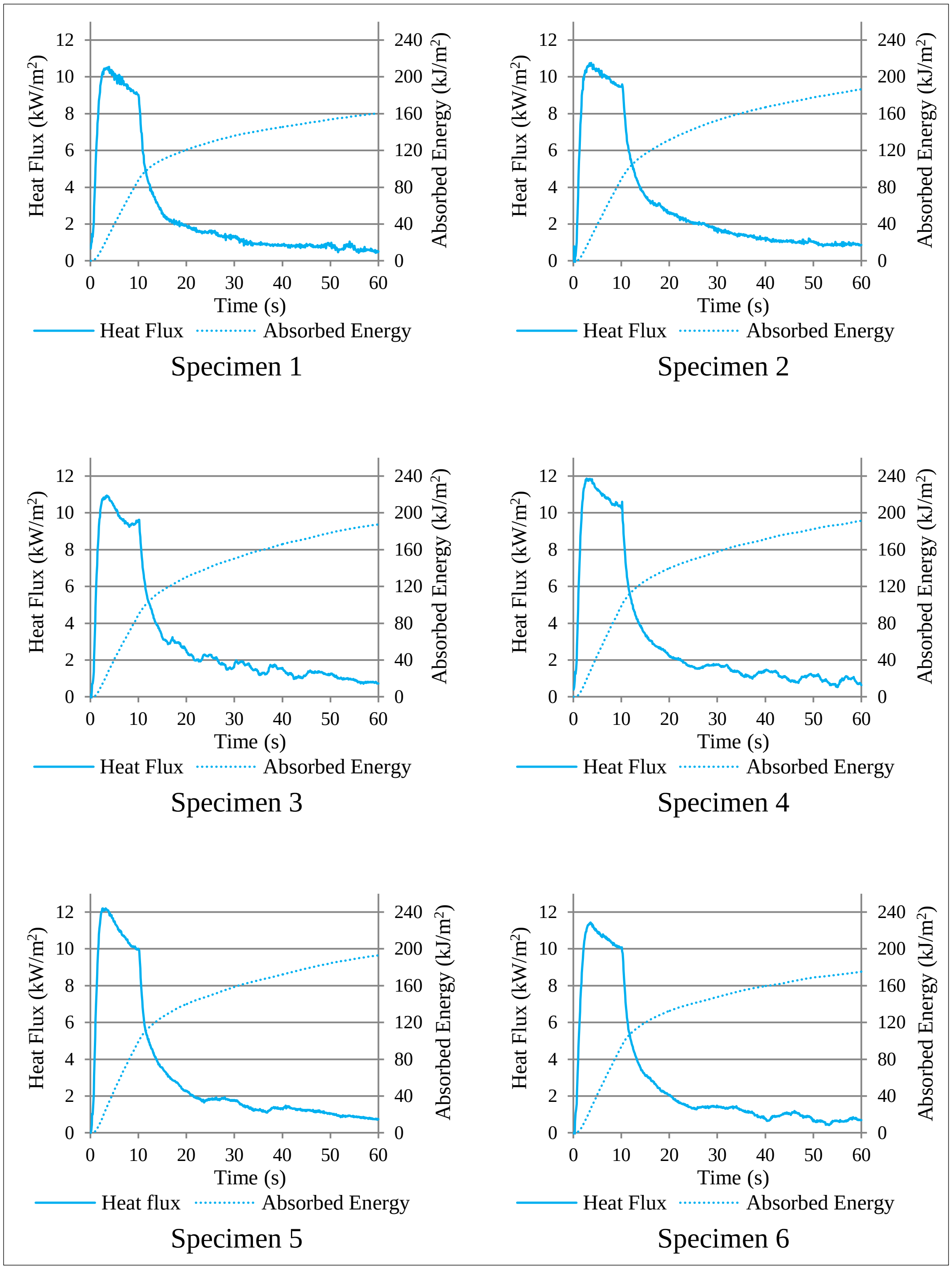

Figure A.19. Fabric system E: Heat flux and absorbed energy over time during steam exposure tests.

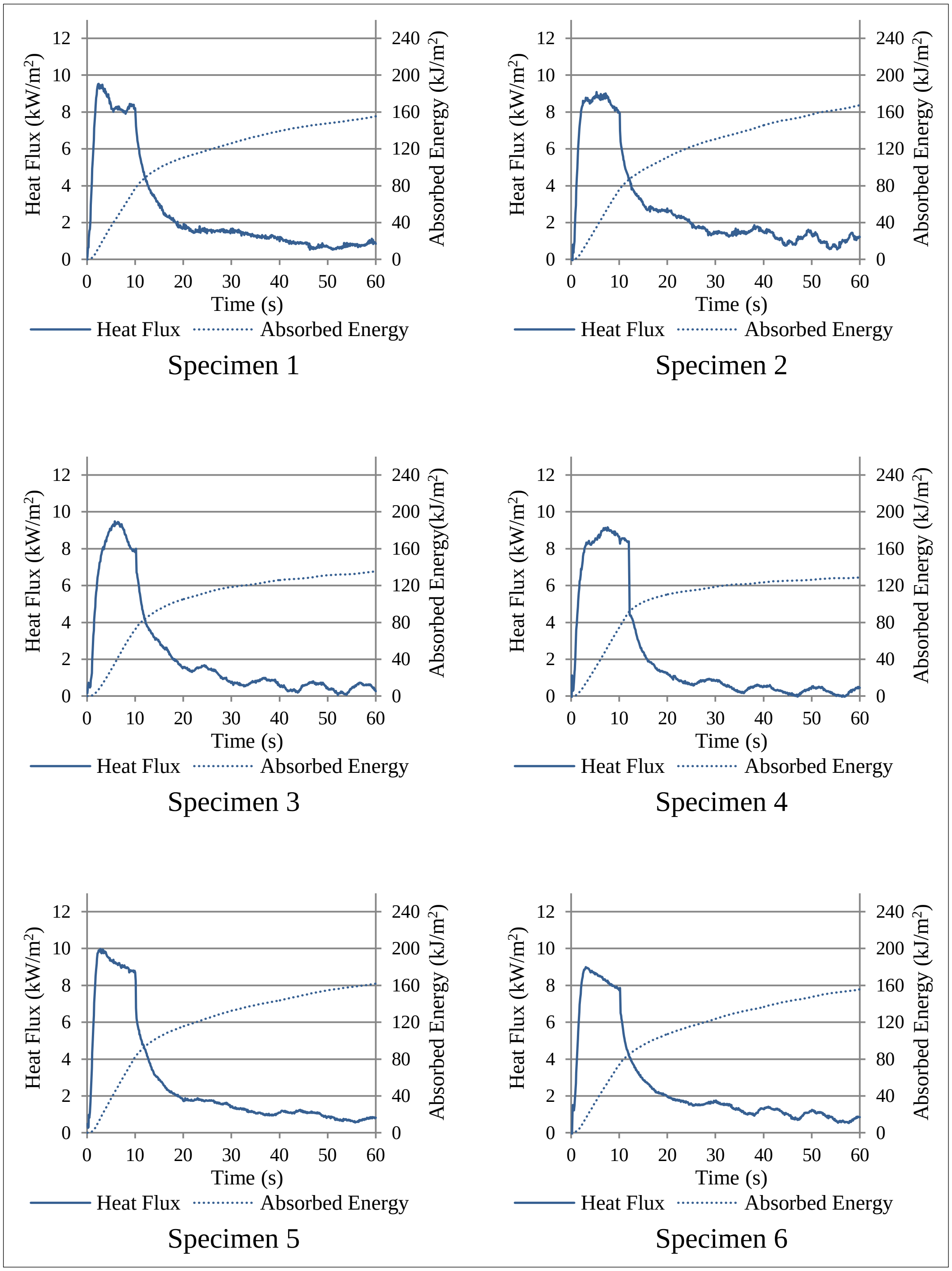

Figure A.20. Fabric system F: Heat flux and absorbed energy over time during steam exposure tests.

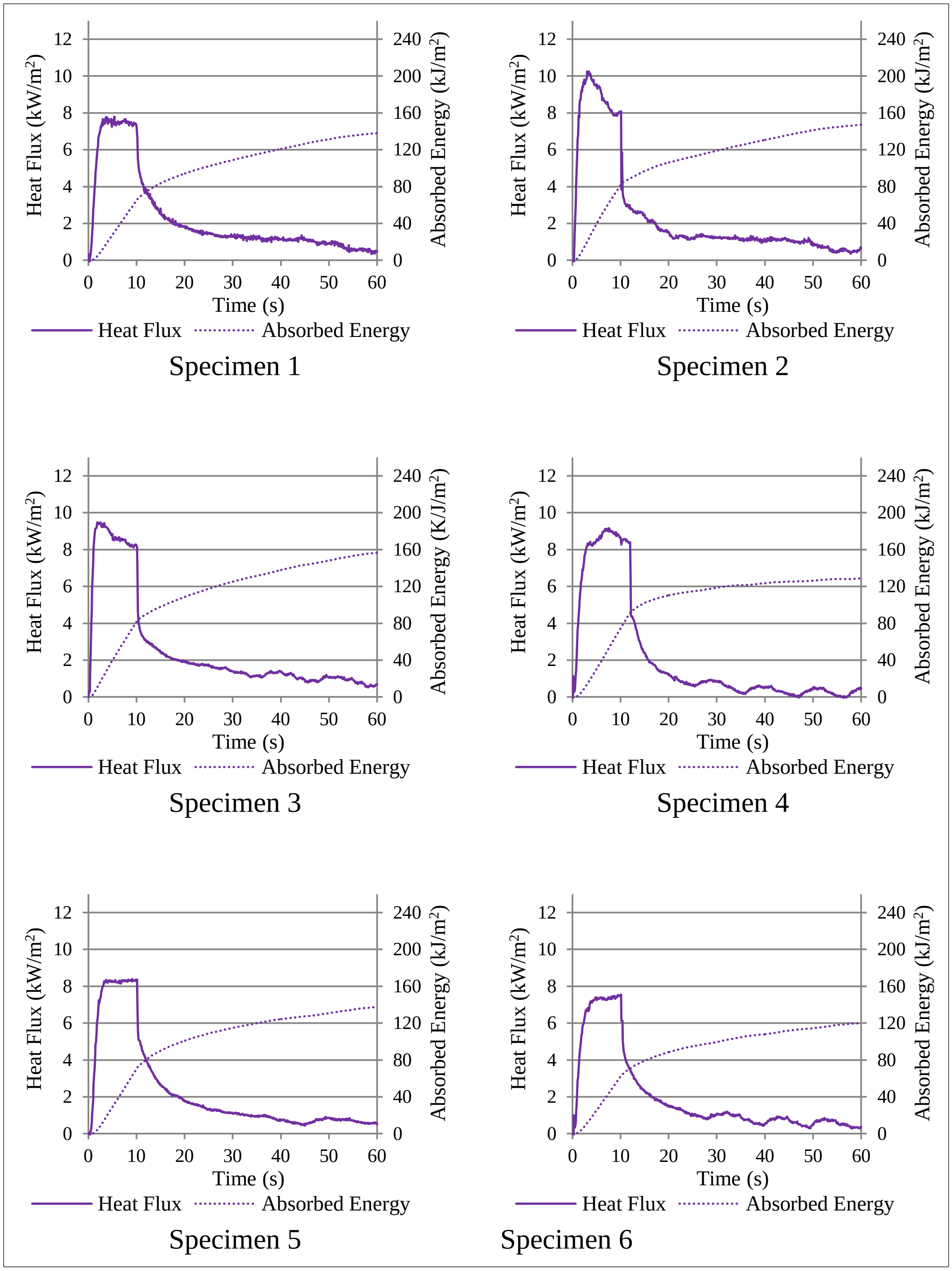

Figure A.21. Fabric system G: Heat flux and absorbed energy over time during steam exposure tests.

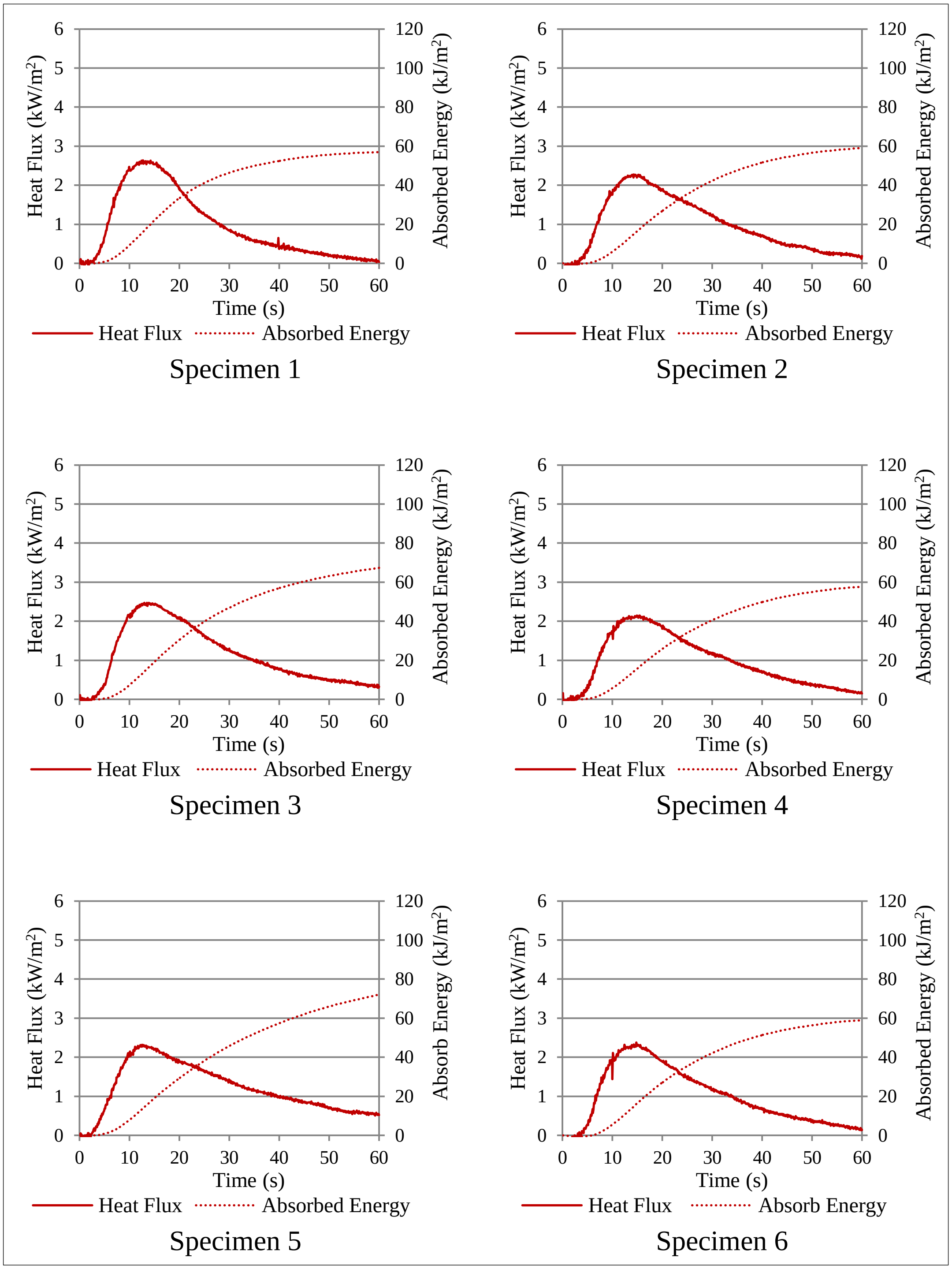

Figure A.22. Fabric system A: Heat flux and absorbed energy over time during hot water exposure tests.

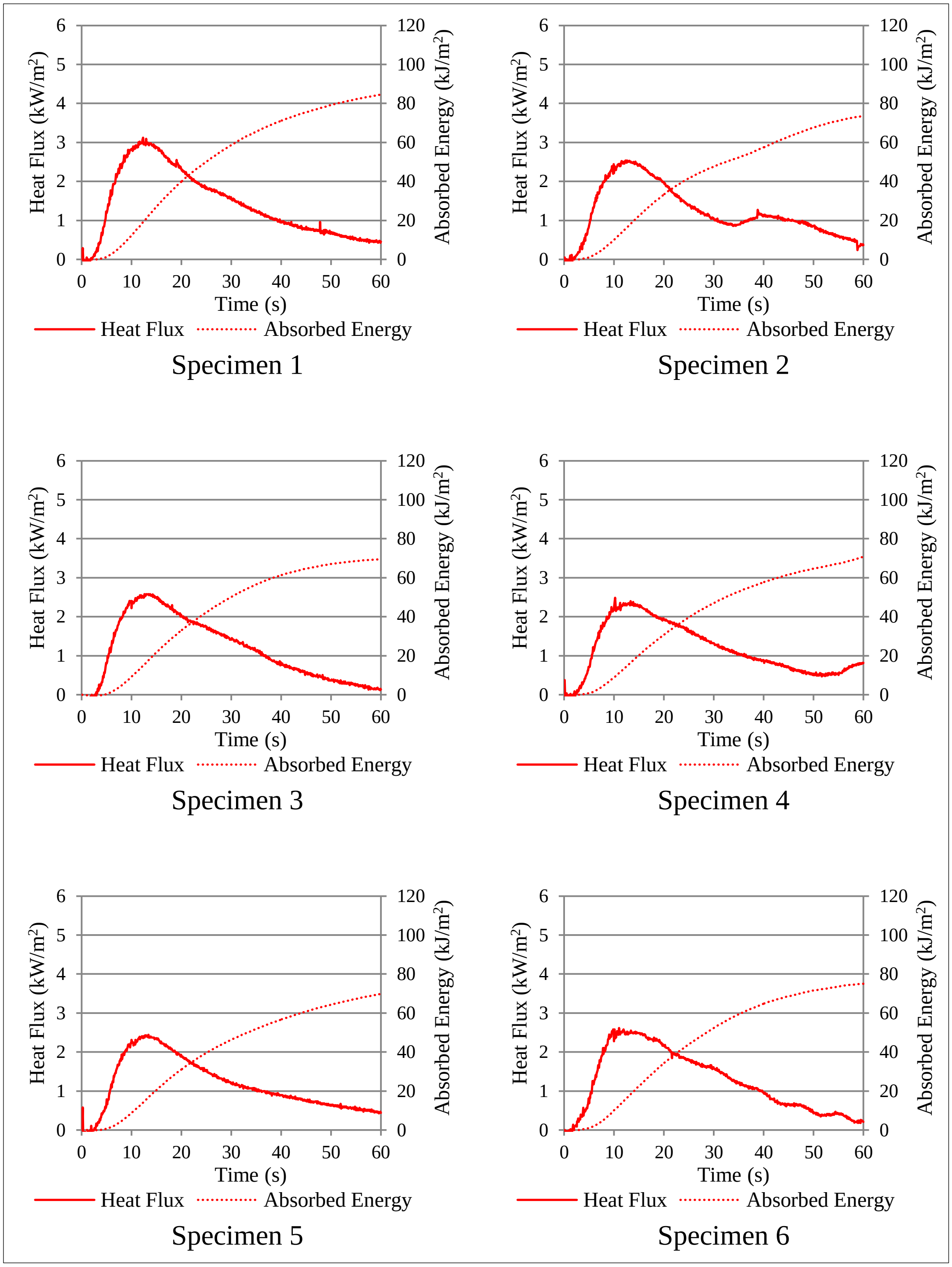

Figure A.23. Fabric system B: Heat flux and absorbed energy over time during hot water exposure tests.

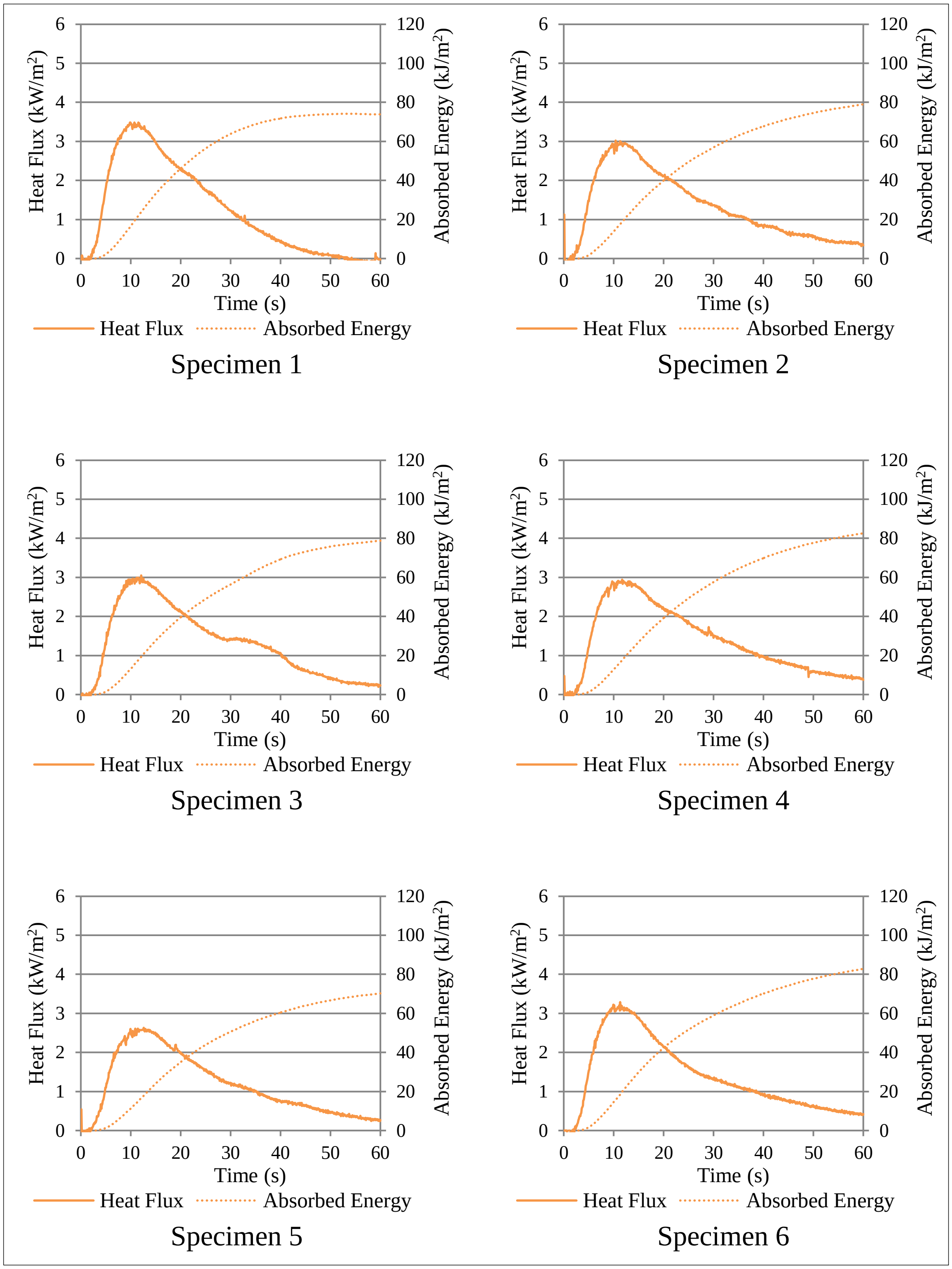

Figure A.24. Fabric system C: Heat flux and absorbed energy over time during hot water exposure tests.

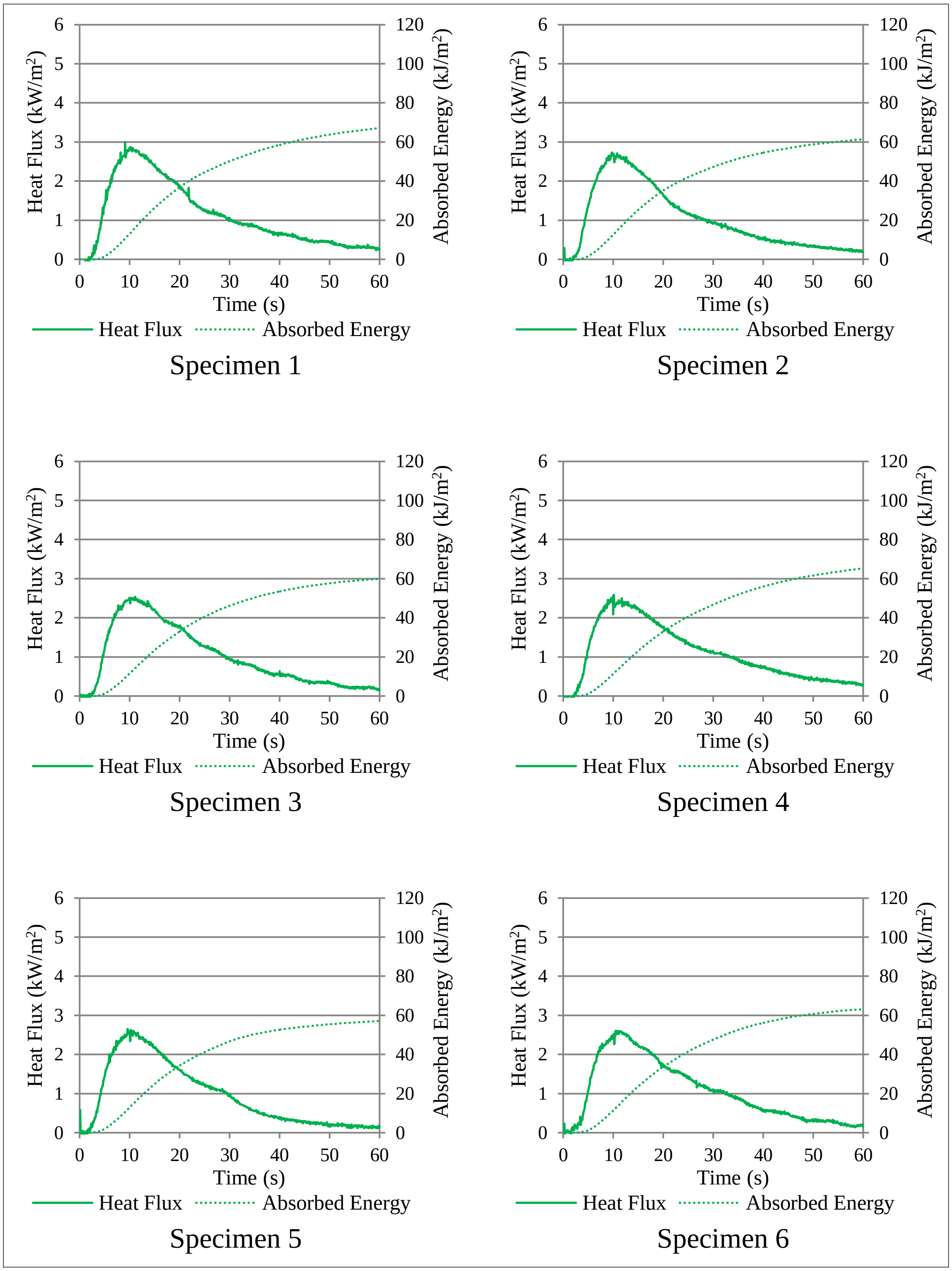

Figure A.25. Fabric system D: Heat flux and absorbed energy over time during hot water exposure tests.

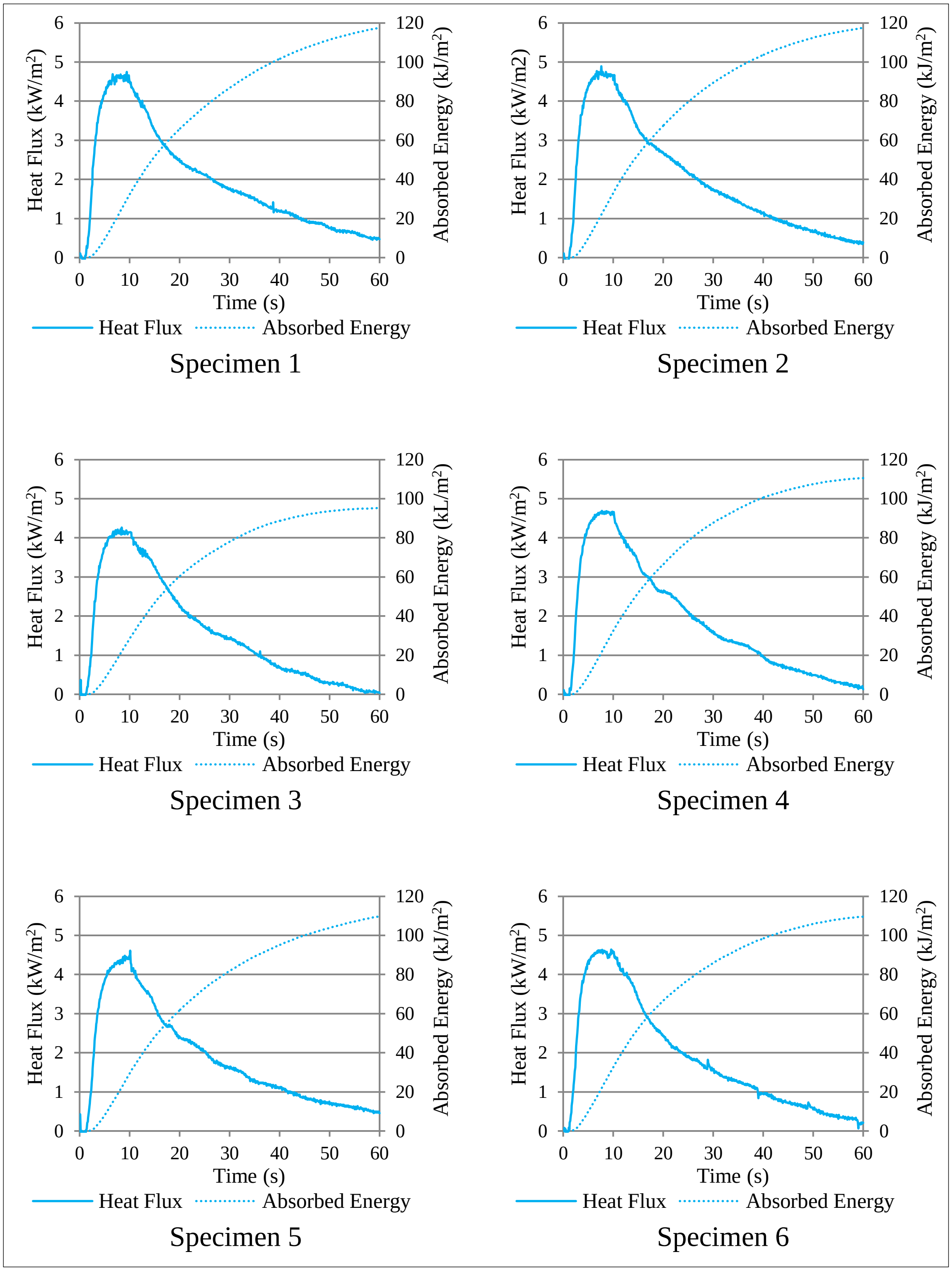

Figure A.26. Fabric system E: Heat flux and absorbed energy over time during hot water exposure tests.

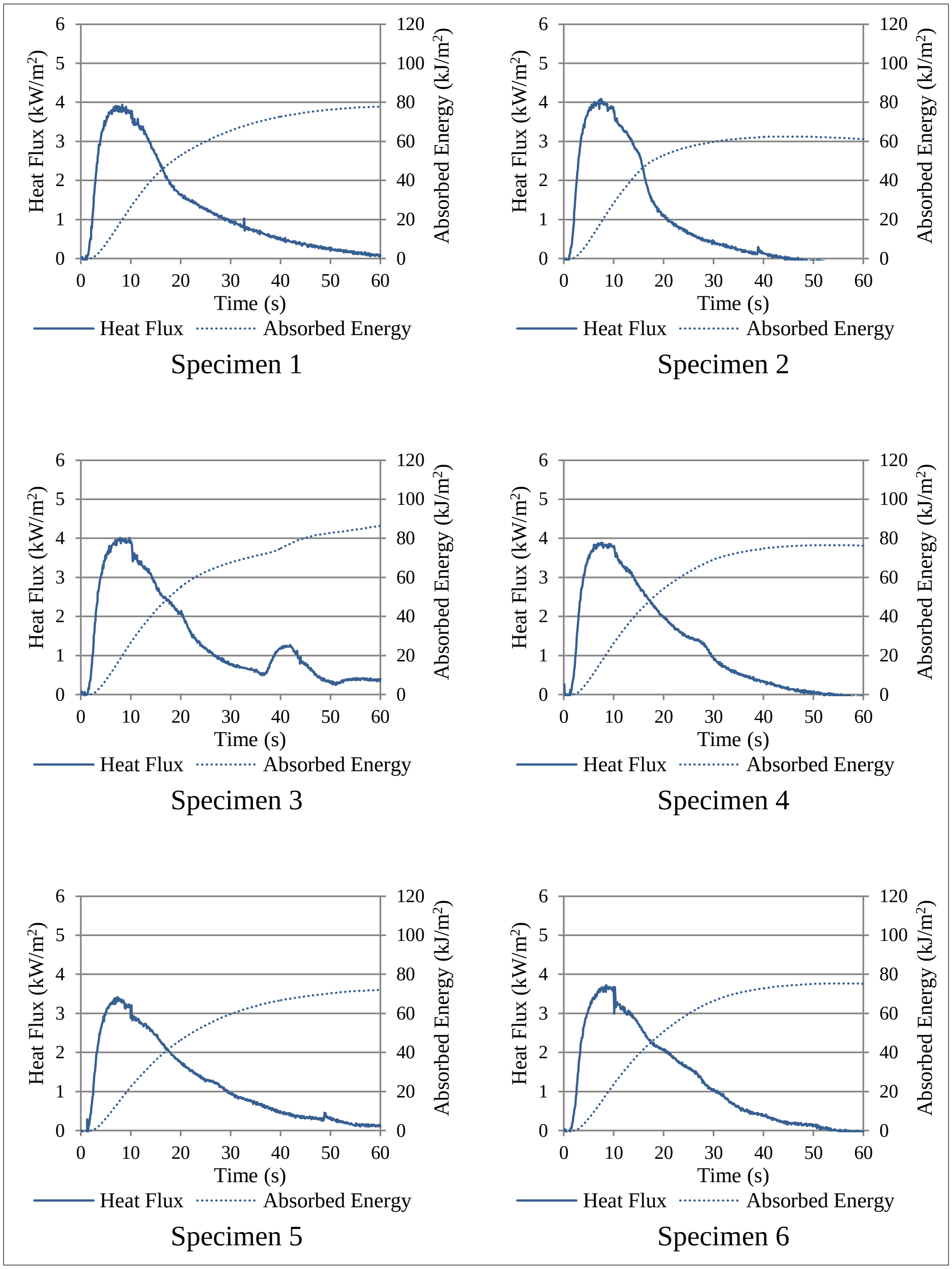

Figure A.27. Fabric system F: Heat flux and absorbed energy over time during hot water exposure tests.

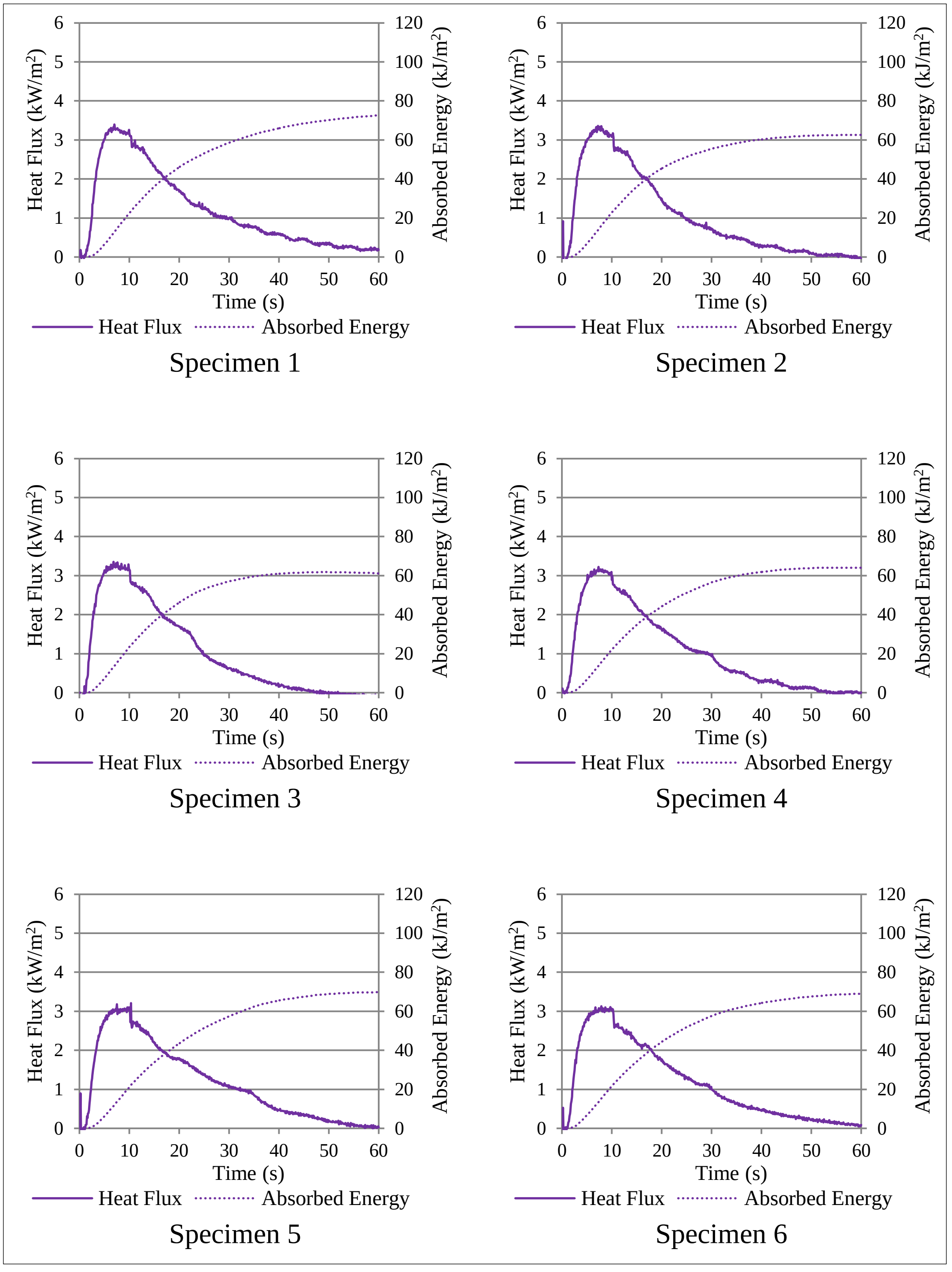

Figure A.28. Fabric system G: Heat flux and absorbed energy over time during hot water exposure tests.