Lifeline Beacon

Firefighter Safety Equipment

Product report

Qi Ai

MSc04 / ID13

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Aalborg University

TITLE PAGE

Title:
Lifeline Beacon

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ABSTRACT

This graduation project involves the development of a wearable device that meets professional standards in the firefighting domain. It aims to enhance the safety of firefighters in their mission execution through proactive protection, without compromising work efficiency.

Firefighters need to perform tasks extremely efficiently, racing against time to save citizens' lives and property. This profession has long been recognized as one of the most dangerous, often confronting highly hazardous working environments and unpredictable risks that threaten their safety. However, their personal protective equipment and some electronic devices present issues that sometimes lead to loss of functionality or even threaten their work efficiency and safety. These problems include low compliance, discomfort, and mobility impact. New products being introduced aim to eliminate these issues.

The project presents an innovative product specifically designed for firefighters, with the key principle of real-time monitoring of firefighters' vital signs and activity level to enable commanders to make dynamic strategic deployments and provide timely rescue assistance, thereby reducing the risk of casualties among firefighters and minimizing the impact on task efficiency. The information dissemination system also involves the firefighters themselves and their teammates, aiming to enhance firefighters' situational awareness and facilitate the rescue of victims. Furthermore, the product's scenario involves relevant personnel before and after a fire incident, aligning with occupational health and safety standards to continuously improve the working safety of firefighters in a proactive and sustainable manner.

TABLE OF CONTENT

FIREFIGHTER

As guardians of our community, firefighters bear the responsibility of protecting lives, property, and the environment from fires, accidents, and other disasters. Their primary tasks on the fireground involve quickly and effectively extinguishing fires and carrying out personnel rescue. They must respond swiftly to alarm, act quickly and accurately at the fire scene to minimize damage to life and property.

Despite undergoing rigorous professional training and being equipped with advanced protective gear, firefighters still face considerable risks at fire scenes. These risks include extreme heat, flames, toxic smoke, collapsing buildings, the danger of explosions, as well as physical and emotional stress and fatigue. To resist the dangers of a fire scene, firefighters must wear heavy fire-resistant garments, carry advanced respiratory equipment, and other protective gear. However, these necessary pieces of equipment also increase their physical burden and discomfort, while restricting their mobility. These factors collectively pose a severe threat to the safety of firefighters.

FIREFIGHTER CASUALTIES

60,750

Firefighter Injuries in 2021

-10 years

Life expectancy for firefighters

+14 %

Death due to cancer

In 2021, around 60,750 firefighters sustained injuries while on duty in the United States, based on the most recent data (Campbell and Hall, 2022). Moreover, firefighters' life expectancy is on average 10 years shorter than that of the general population, and they face a 14% higher risk of succumbing to cancer (Fahy and Petrillo, 2022).

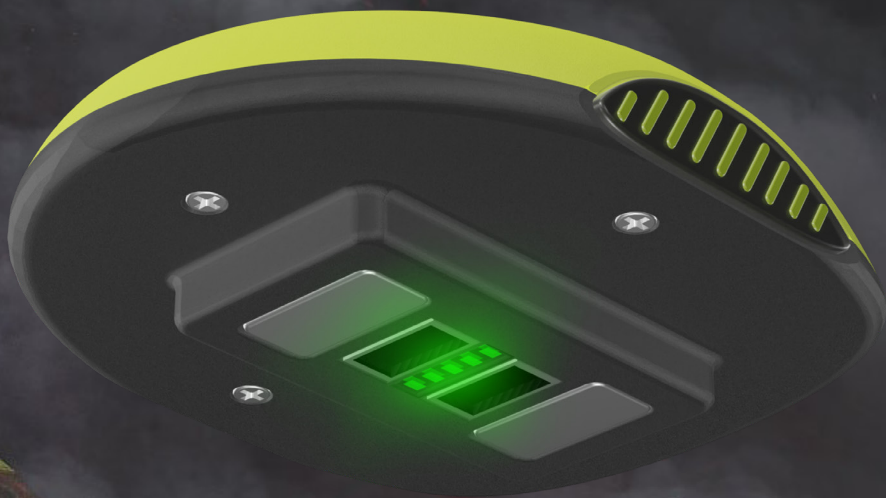

SCOTT
AIR-PAK
SCOTT

Lifeline Beacon

Firefighter Safety Equipment

Real-time monitoring of key vital signs and activity level for timely rescue.

SpO2
Heart rate
Sweat
Respiration
Temperature
Activity



No-verbal communication

Abnormal vital signs and activity levels trigger an alarm and warn nearby teammates. It can be manually shut off using action commands.

Location

GPS and barometers determine location and altitude, assisting commanders in locating firefighters.

Autonomy in decision-making

Firefighters can stay aware of their physical condition, which enhances their consciousness, as abnormal monitoring results can be conveyed through different frequencies of vibrations.

NFPA 1982 standard for PASS device

Product material can withstand Thermal Class III

Free radio channel

Data is transferred using the Zigbee protocol, without causing interference to the firefighters' radio communication systems and will not miss timely rescue due to blocked radio channels.

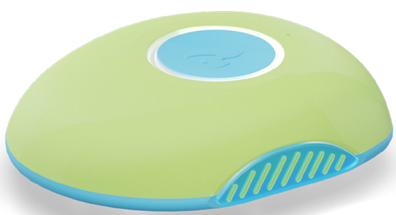
Outdoor signal transmission range can reach up to 100 meters, while indoors, it ranges from 10 to 30 meters. Installing a Repeater can extend the transmission distance.

FEATURES

Intuitive power indicator bar

The color of the light bar turns red when the battery is low

The light bar changes with the power consumption



Customizable colors to match different fireman station identities and customer preferences.

LIFELINE BEACON SOCK

Comfortable and mobility-free

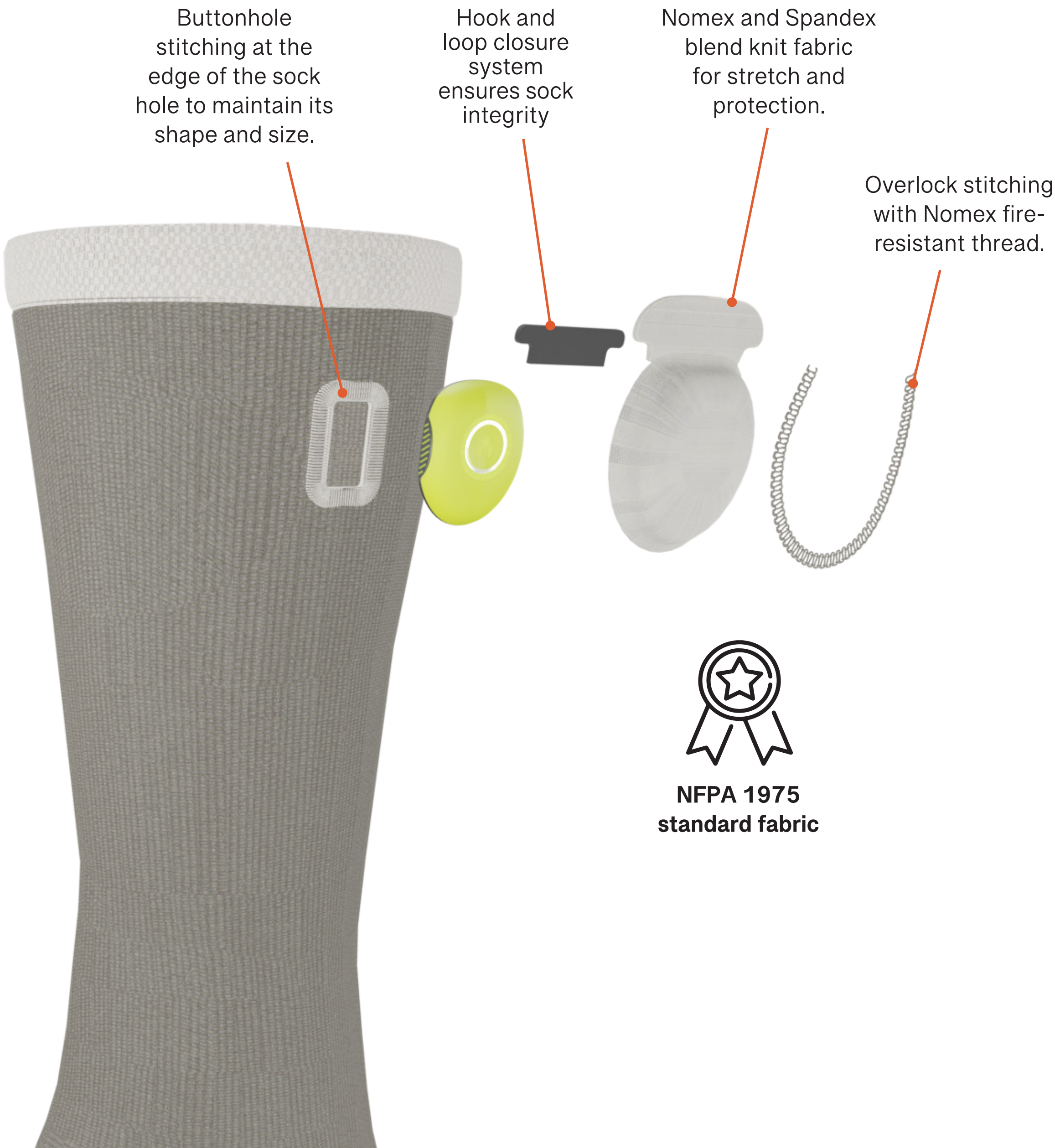
1
The product is worn through a pocket sewn close to the opening of the sock and is placed in such a way that it does not come into contact with the fire boots, minimising possible discomfort.

No additional turnout time

The product can be 'hidden' in a customised firefighter's sock, and the firefighter can always have it.

2
Only the areas that need to be in contact with the skin are prominently shaped to give maximum skin contact with the comfortable fabric.

3
The rounded appearance avoids any discomfort caused by sharp edges.



NFPA 1975 standard fabric

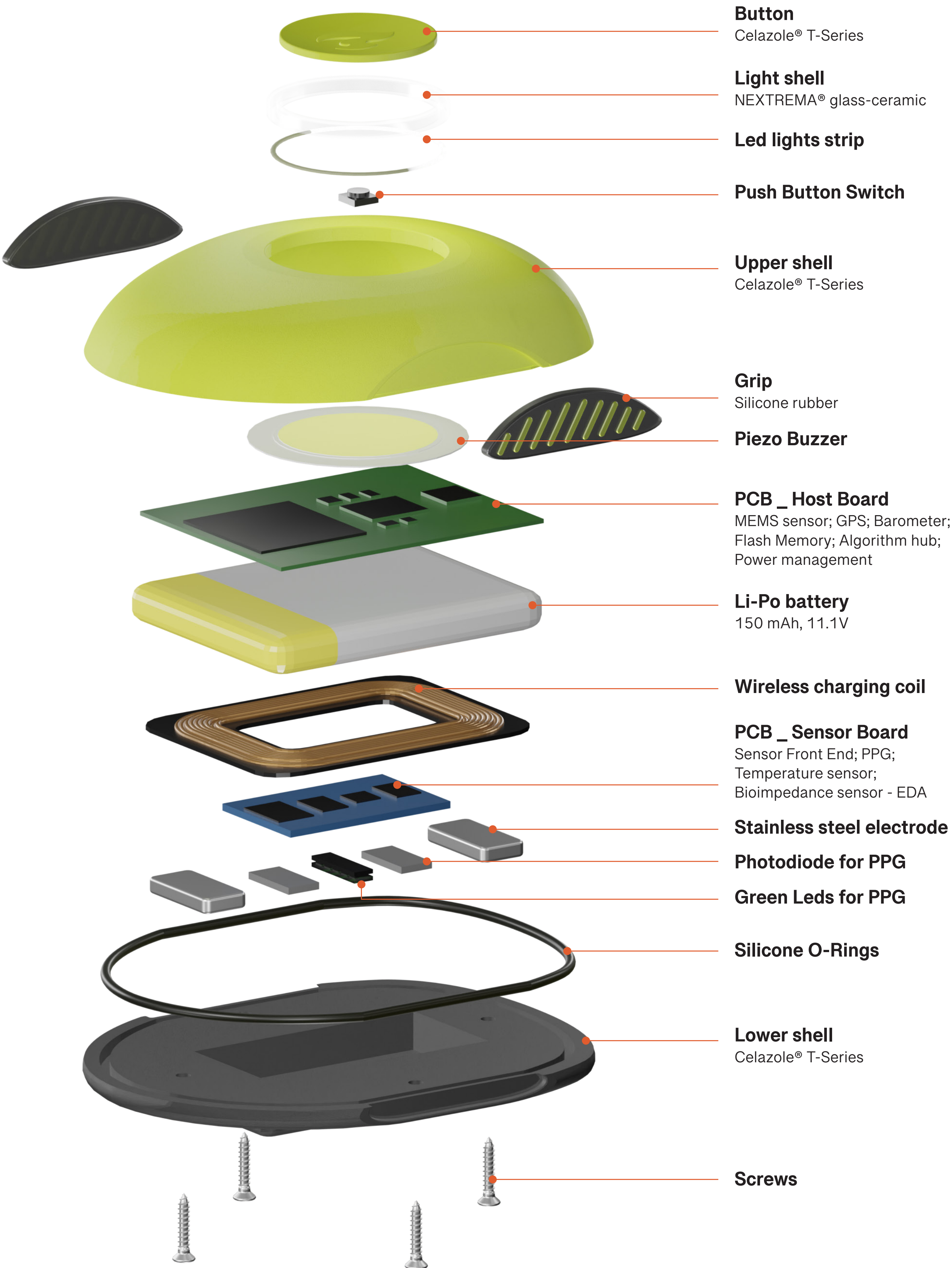
LIFELINE BEACON CHARGER

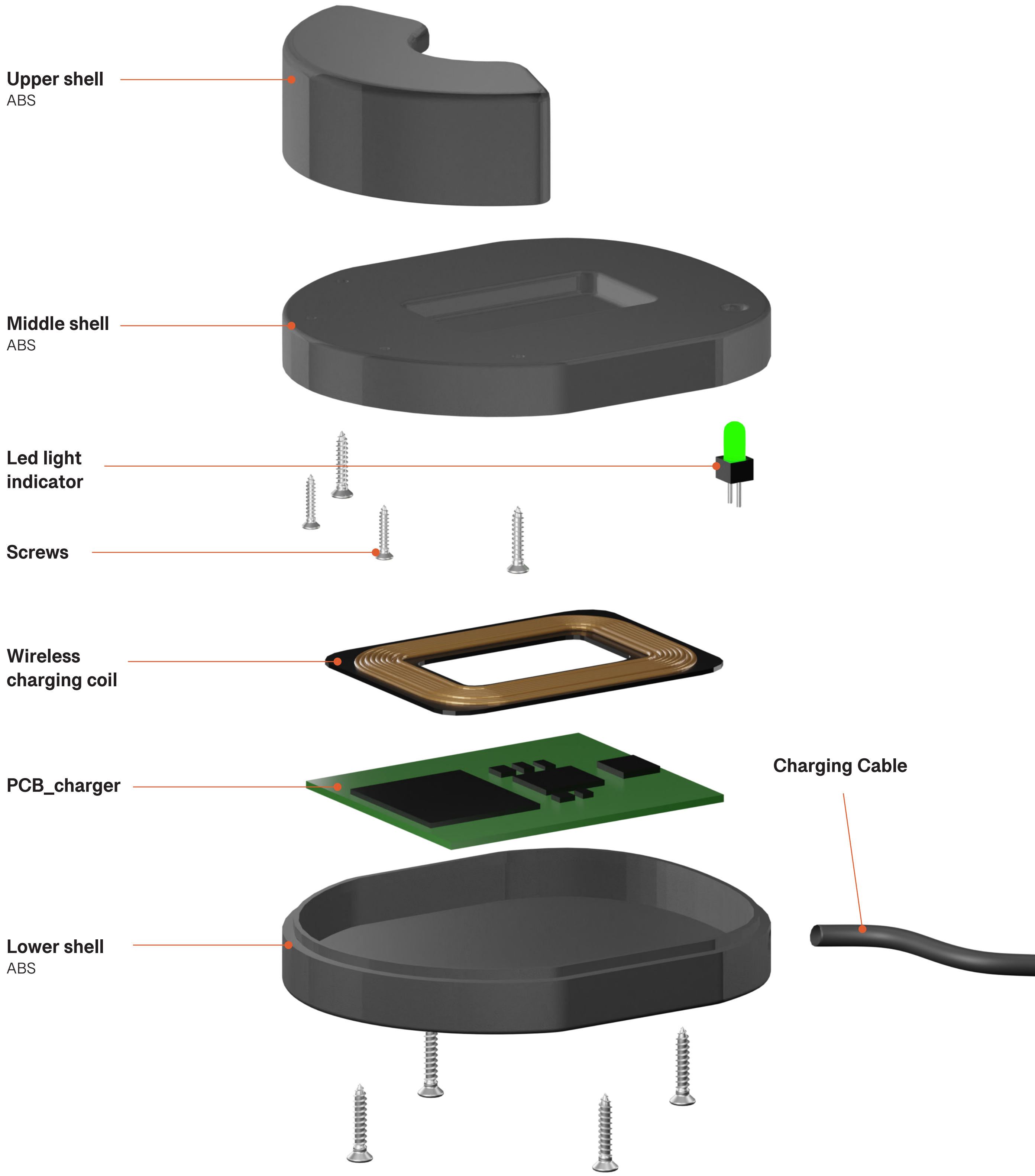
The charging base has a sleek appearance, aligned with the product's style and shape. Its color is consistent with other chargers in the fire department. A slot design provides product support and secures it in place, even on vertical or slanted surfaces.

The charging base can operate independently or be placed side by side. In addition, an LED indicator on the upper right corner serves as a sign of successful power supply.


MSA
TITAN
WeTech

COMPONENTS


Button
Celazole® T-Series
Light shell
NEXTREMA® glass-ceramic
Led lights strip
Push Button Switch
Upper shell
Celazole® T-Series
Grip
Silicone rubber
Piezo Buzzer
PCB _ Host Board
MEMS sensor; GPS; Barometer;
Flash Memory; Algorithm hub;
Power management
Li-Po battery
150 mAh, 11.1V
Wireless charging coil
PCB _ Sensor Board
Sensor Front End; PPG;
Temperature sensor;
Bioimpedance sensor - EDA
Stainless steel electrode
Photodiode for PPG
Green Leds for PPG
Silicone O-Rings
Lower shell
Celazole® T-Series
Screws


Upper shell
ABS
Middle shell
ABS
Led light
indicator
Screws
Wireless
charging coil
PCB_charger
Charging Cable
Lower shell
ABS

BUSINESS STRATEGY

1st round of development $400,000

Design and business proposal

1. R&D

The project's progression owes much to the close collaboration with NOBR, the fire department headquarters in Northern Jutland. As the project is still in the concept validation stage, creating and testing functional prototypes in a real environment is essential, followed by constant optimization. The plan is to continue collaborating with NOBR, aiding in iterative testing of the MVP, thereby promoting the project's development and execution.

NORDJYLLANDS BEREDSKAB

2. CERTIFICATION

Professional tests are conducted to ensure compliance with relevant standards and thus guarantee product quality. This requires referring to the NFPA 1982 standard to understand the fire resistance and alarm-related requirements of PASS devices.

NFPA

3. COLLABORATION

An investment amount of $83,400 comes from Dräger, a global leader in medical and safety technology and highly respected in the firefighting equipment domain. Collaborating with and obtaining investment from Dräger acts as the primary sales platform for the B2B sales model. This helps establish a brand image and introduce the product to their existing customer base. Moreover, integrating this product with their mature, fire scenario-compatible wireless data transmission physical gateway brings them additional economic benefits and shortens the launch time to the market.

Dräger

1 Year

4. PRODUCTION AND LAUNCH

Cooperation with material and service suppliers enables mass production and market launch of the product. The marketing strategy involves simultaneously opening B2B and B2C sales channels, which helps expand distribution channels and market coverage. Customers can obtain the product through the Dräger platform or directly purchase from the company's official website.

Celazole DUPONT — Material suppliers

ANALOG DEVICES — Electronics suppliers

Azure — Cloud service

5. BREAK-EVEN

After a certain number of products are sold, the company and investor reaches the break-even point.

6. SCALING UP

The company invests in developing the next-generation product to expand the market to other target groups, including sports and healthcare, as they have needs for vital signs monitoring. The product is designed to support future expansion and can be customized with monitoring features and compatible wearables according to the specific needs of different customer groups.

2nd round of development $400,000

B2B

$ 240

B2C

$ 315

Membership fee

$ 20/month

PRICING

Firefighter Beacon is sold as a set, including one main product, two pairs of socks, and a charging base. Customers can also purchase individual accessories based on their needs. The retail price for a set is $315, consistent with key competing products like Personal Alert Safety Systems (PASS) on the market, ensuring customer price acceptance and market competitiveness for this type of safety equipment. The company sells to B2B partners at a price of $240, enabling them to benefit.

Since the company's business model is to establish long-term relationships with customers, a monthly membership fee of $20 is charged to each customer in exchange for app, cloud, and after-sales repair services. To estimate revenue, it's assumed that each customer will purchase a one-year membership.

INVESTMENT

$400,000

$83,400

COST

$111

$85

(>10000 pcs,)

BREAKEVEN

807 pcs.

878 pcs.

The company invests $400,000 for product development. Investors contribute $83,400 to assist the company in purchasing machinery for manufacturing and software development.

The manufacturing cost decreases when the manufacturing volume exceeds 10,000 units. The cost calculation is based on the sale of the product as a set.

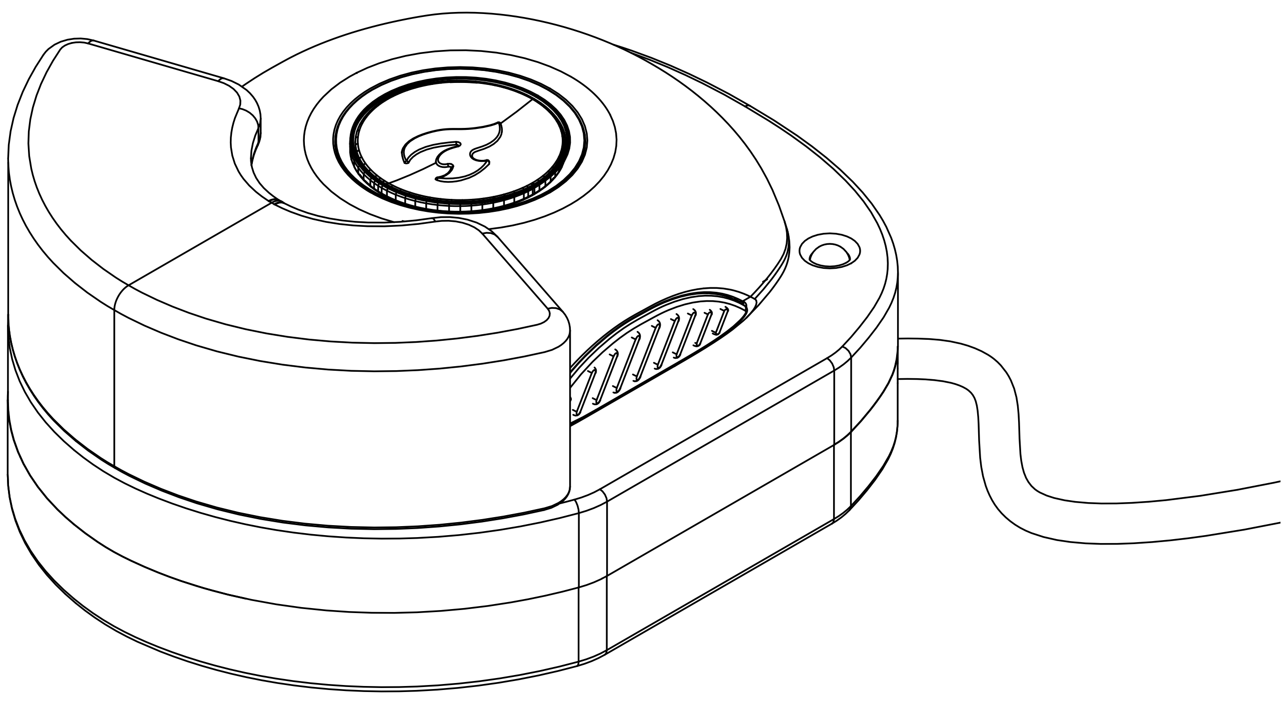
The company's revenue comes from B2C product sales, sales sharing from the B2B model, and membership fees. Without considering B2B earnings, the company can reach a break-even point by selling 807 sets of products. Investors primarily earn a share of profits through product sales, and can reach their break-even point by selling 878 sets of products.


Lifeline
Beacon

Lifeline Beacon

Firefighter Safety Equipment

Technical drawings



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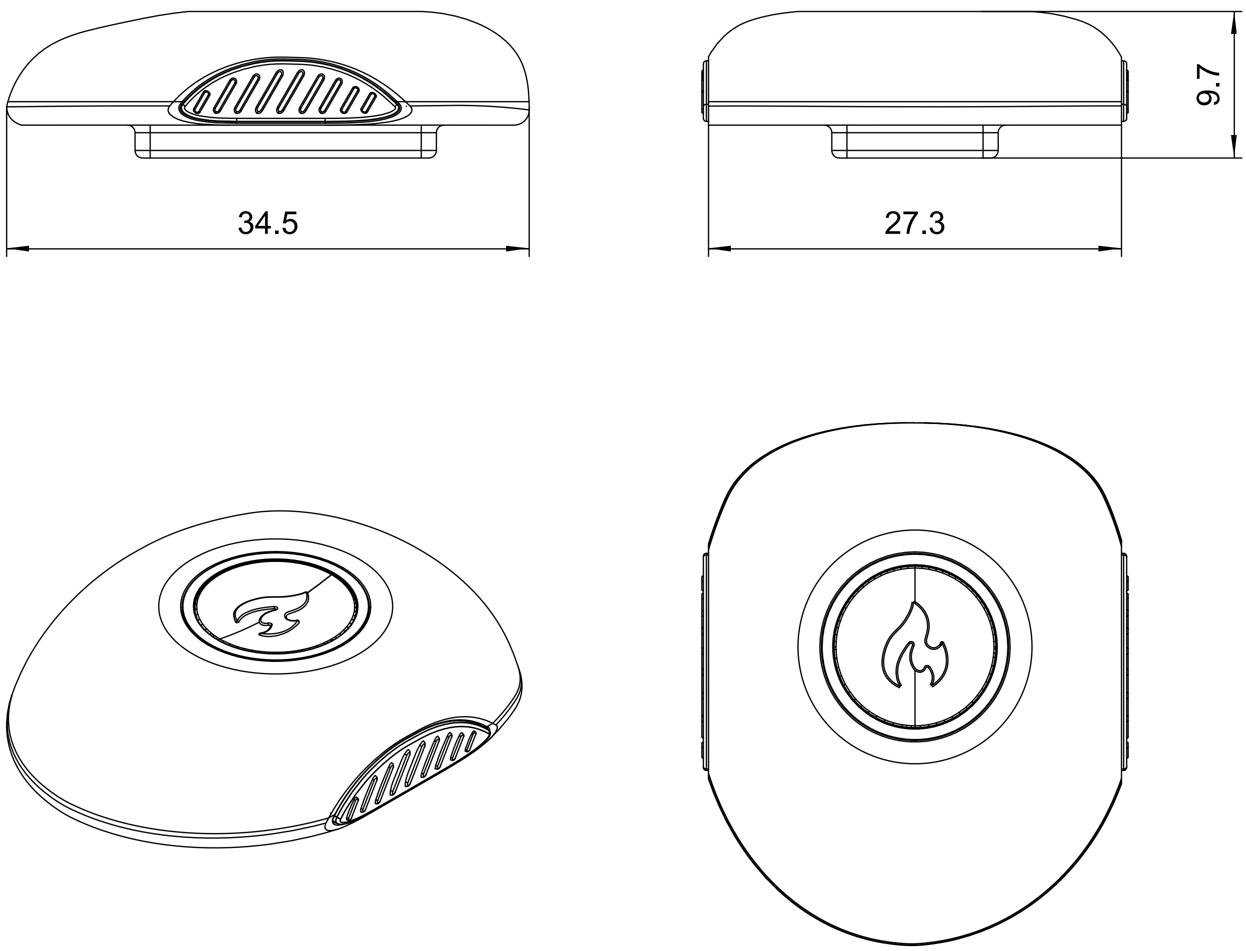
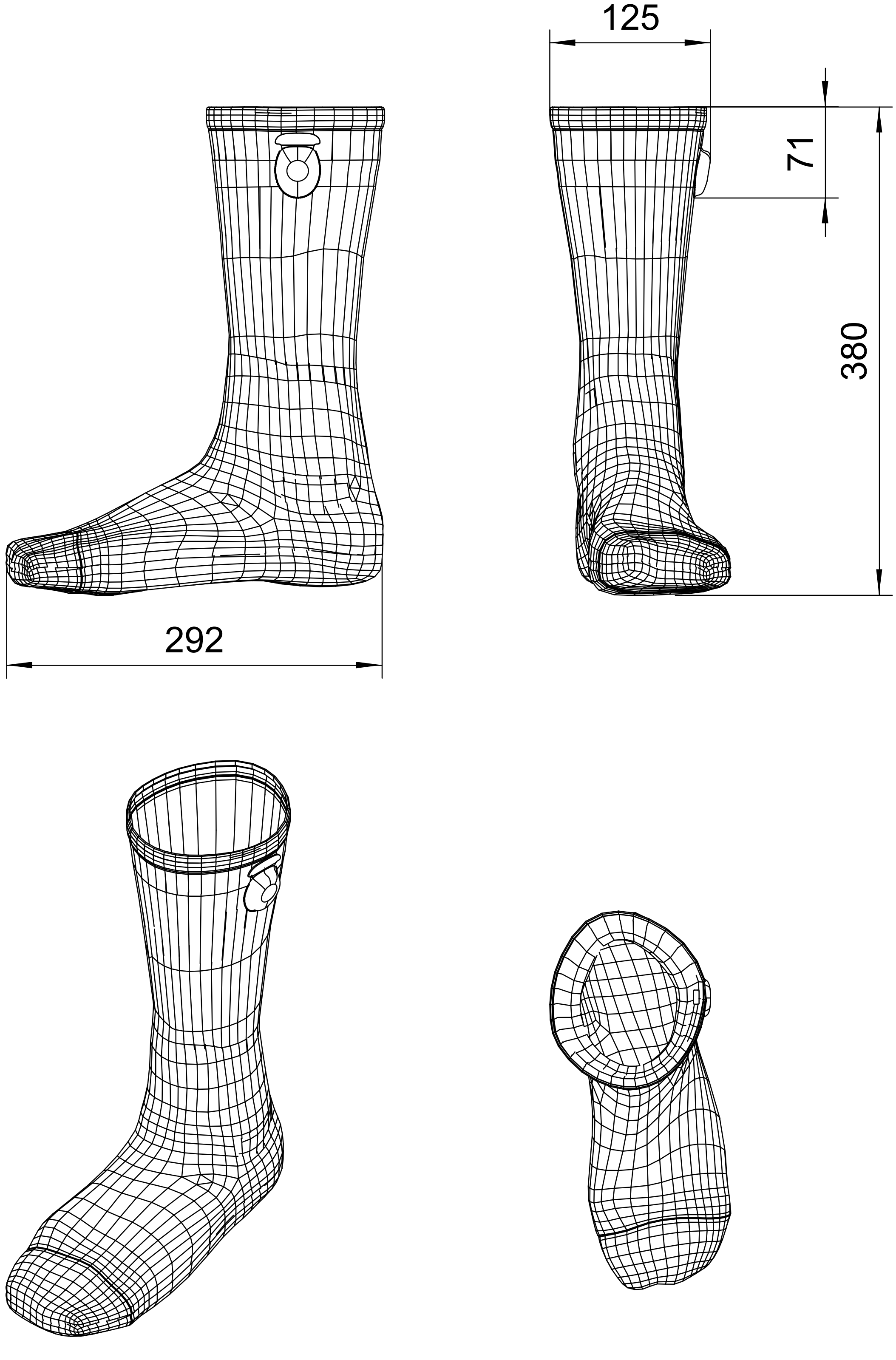


	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish		Revision
		PM-T1	TITLE: Main product	
	Name	Dato		
DRAWN	QI	May19, 2023		
Material			DWG NO. 001	A4
			Weight:	Scale 2:1



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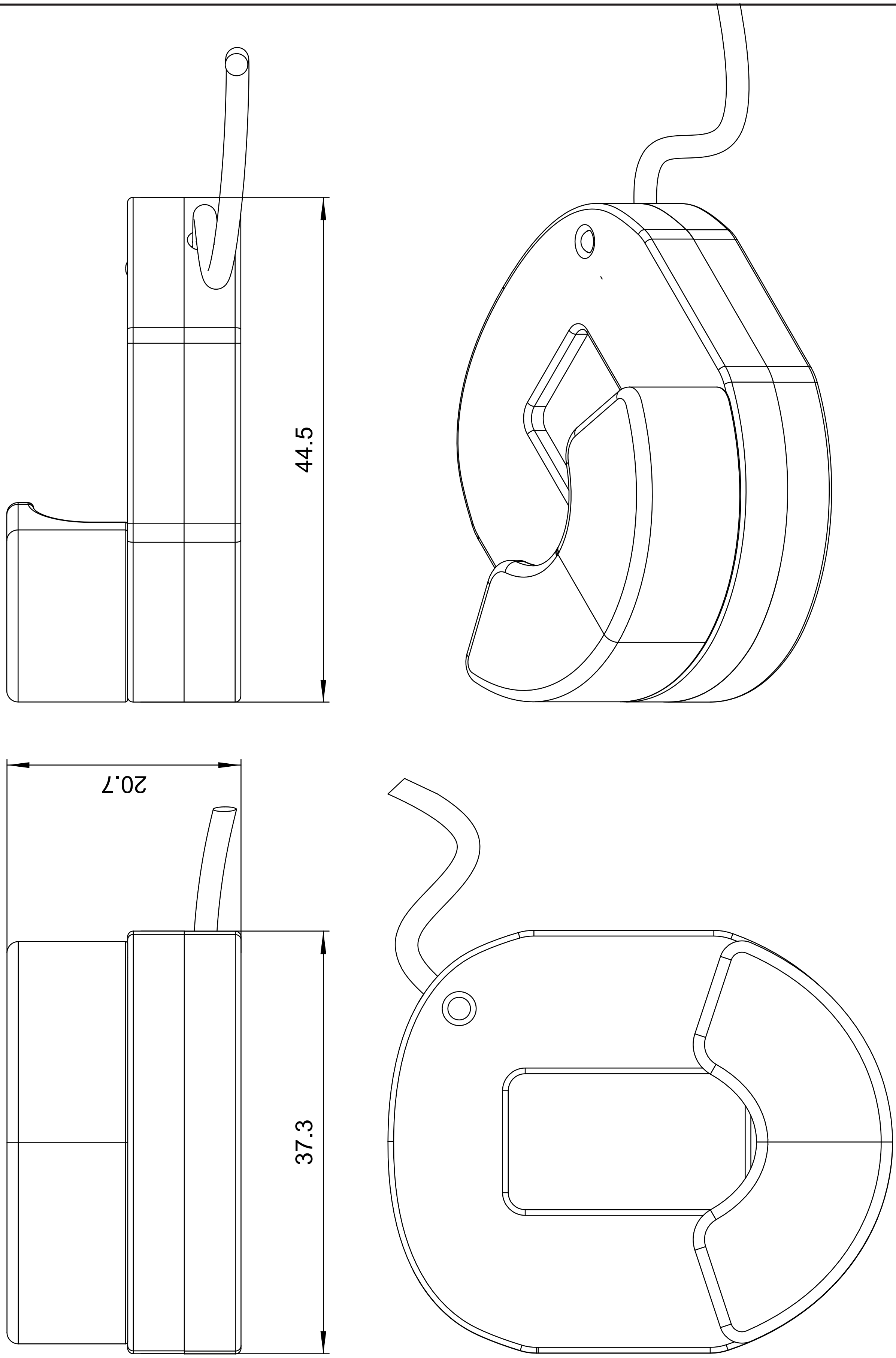
			TITLE:	
	Name	Dato	Sock	
DRAWN	QI	May19, 2023		
Material			DWG NO. 002	A4
			Weight:	Scale 1:5



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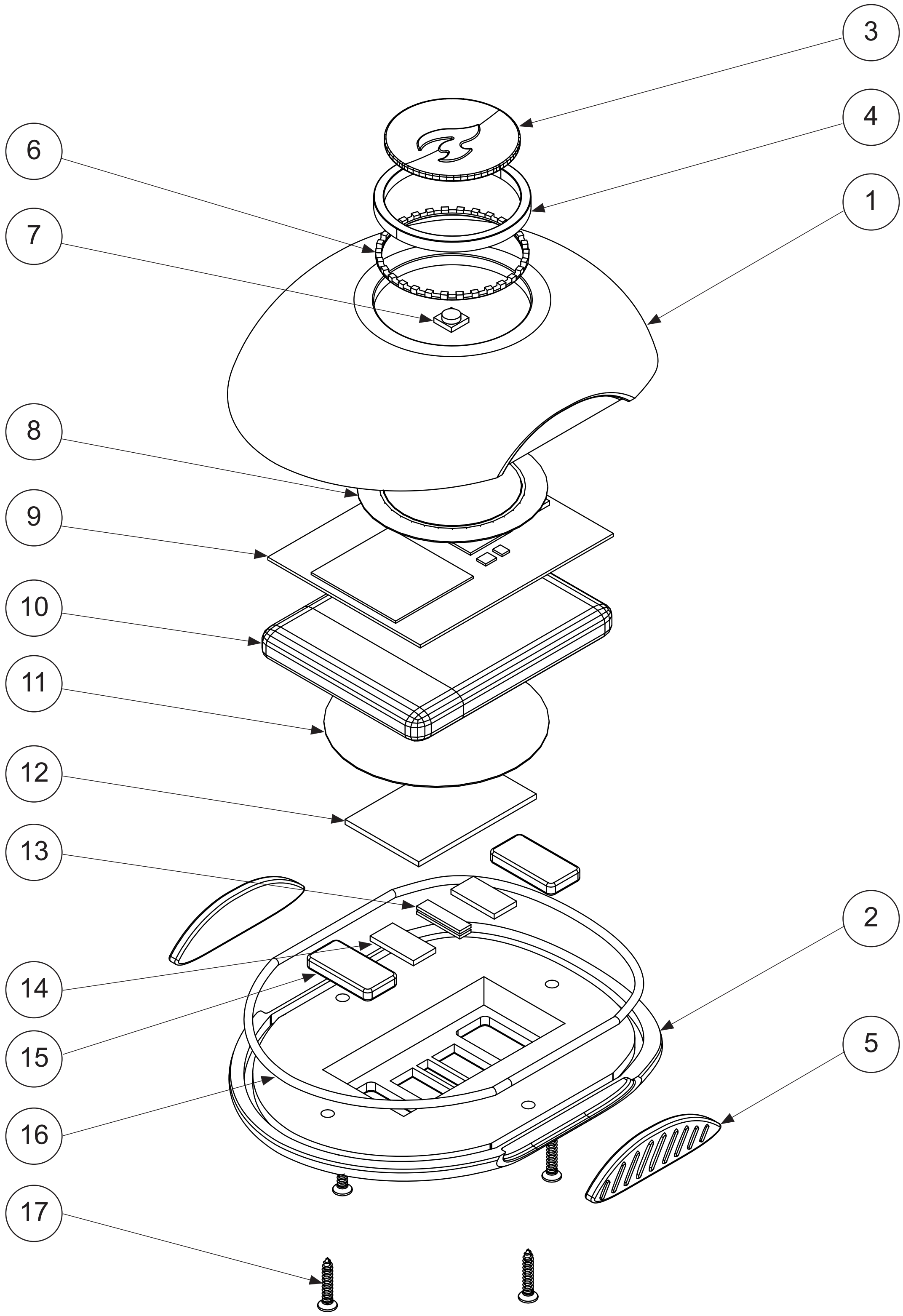
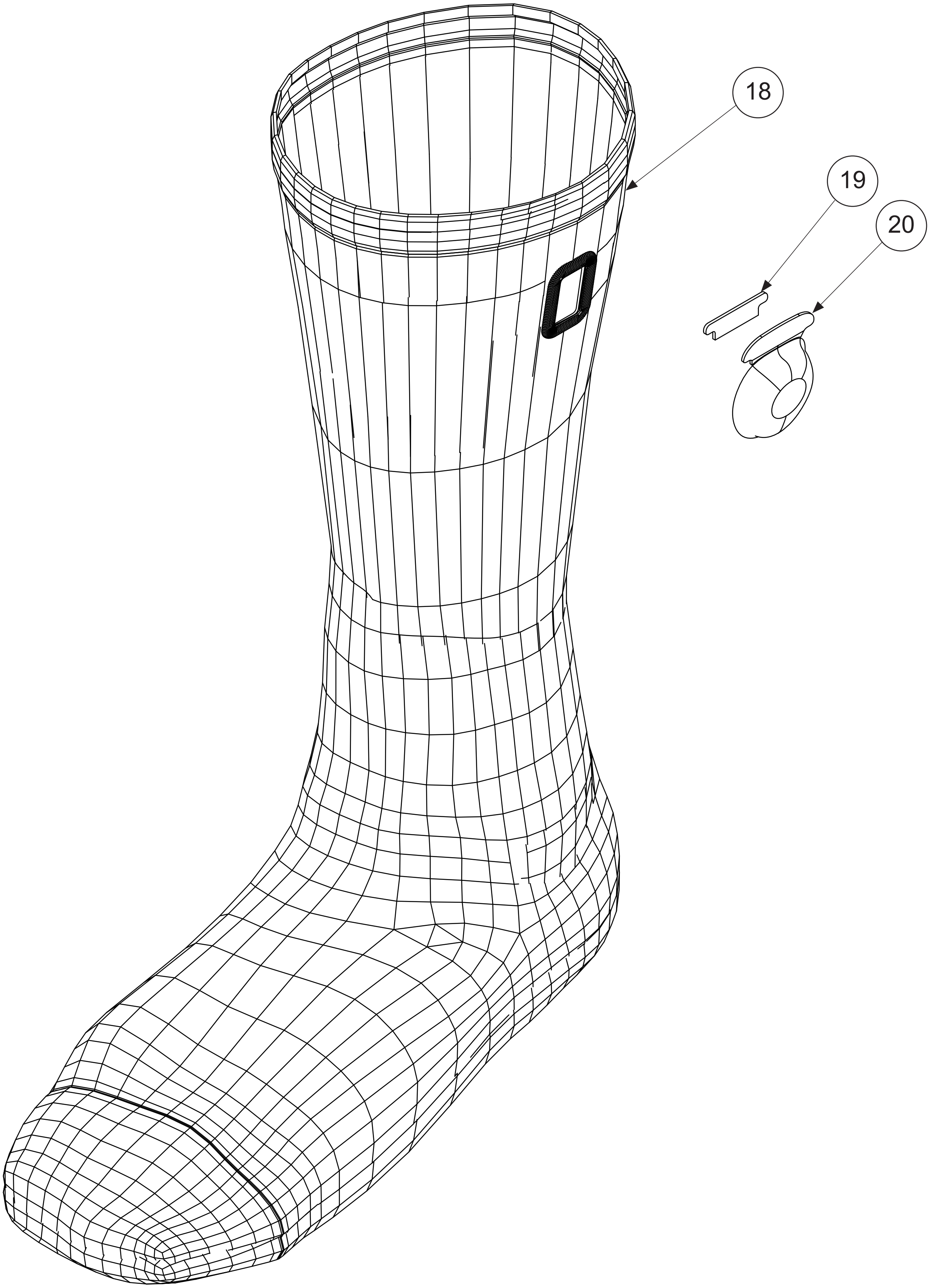
		PM-T1	TITLE: Charger	
	Name	Dato		
DRAWN	QI	May19, 2023		
Material			DWG NO. 003	A4
			Weight:	Scale 1:1



	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish			Revision
			TITLE: BOM - Main product		
	Name	Dato			
DRAWN	QI	May19, 2023			
Material			DWG NO. 004		A4
			Weight:		Scale 2:1



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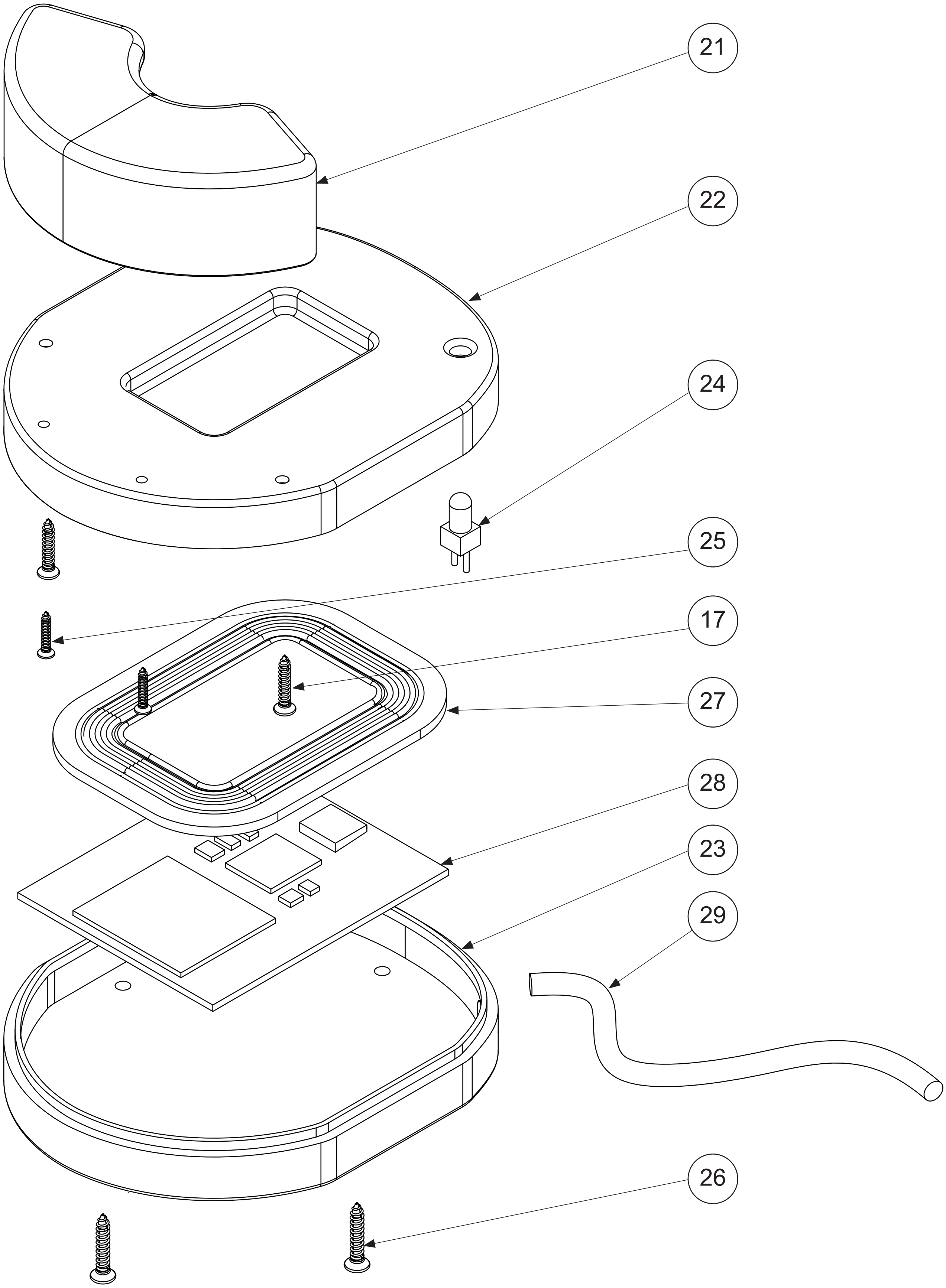
			TITLE: BOM - Sock		
	Name	Dato			
DRAWN	QI	May19, 2023			
Material			DWG NO. 005		A4
			Weight:		Scale 1:1



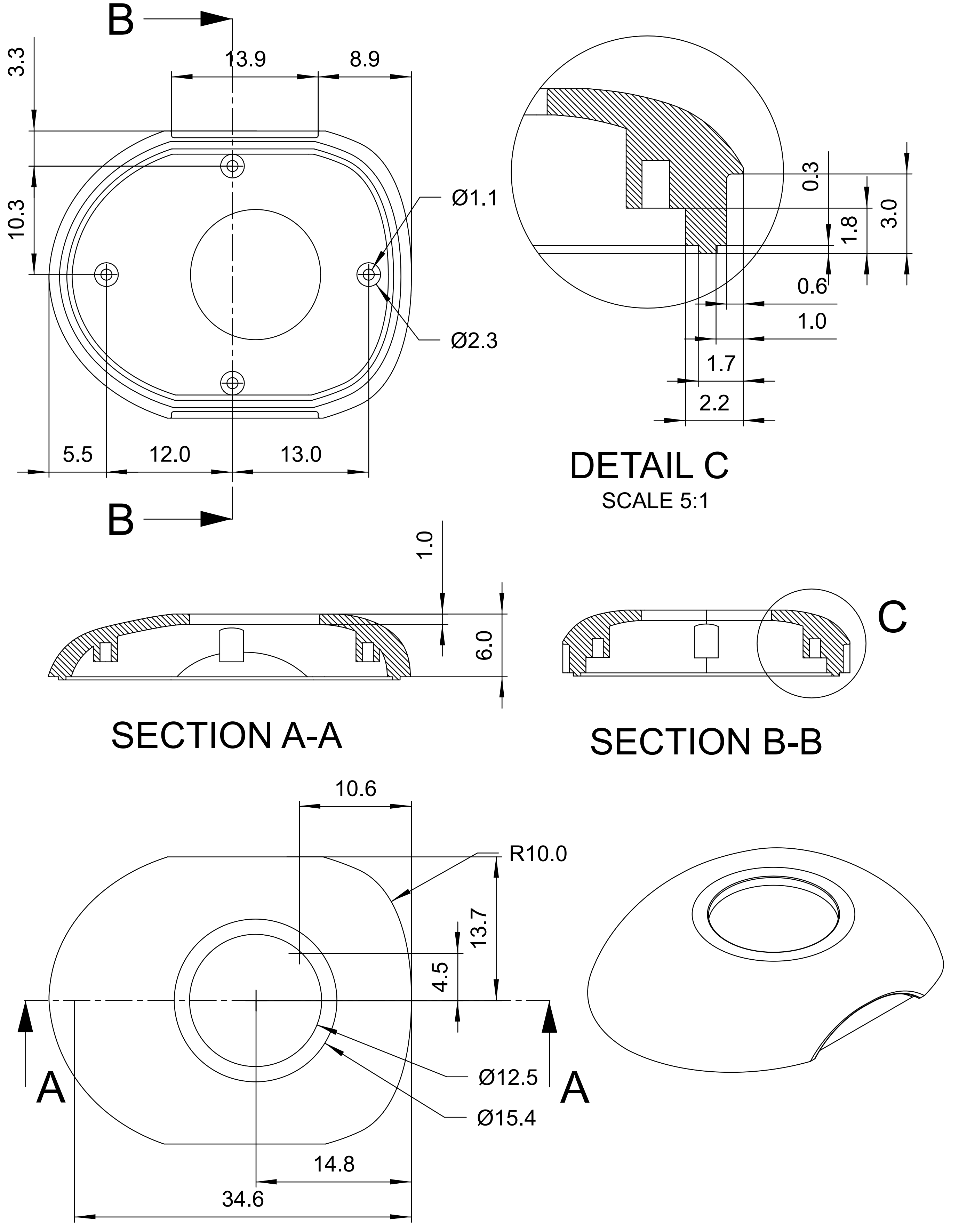
	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish			Revision
			TITLE: BOM - Charger		
	Name	Dato			
DRAWN	QI	May19, 2023			
Material			DWG NO. 006		A4
			Weight:		Scale 2:1

ITEM NO.	PART NAME	DESCRIPTION	Draw No.	QTY.
1	Upper shell	Upper shell	009	1
2	Lower shell	Lower shell	010	1
3	Button	Button	011	1
4	Light shell	Light shell	012	1
5	Grip	Grip	013	2
6	Led lights strip	EKINGLUX 0402 led lights	-	1
7	Push Button Switch	Push Button Switch	-	1
8	Piezo Buzzer	Piezo Buzzer	-	1
9	PCB _ Host Board	Host Microcontroller (MCU); MEMS sensors; GPS; Flash Memory; Algorithm hub; Power management	-	1
10	Battery	Li-Po battery	-	1
11	Wireless charging coil_1	QI Standard wireless charging coil	-	1
12	PCB _ Sensor Board	Sensor Front End; Temperature sensor; Bioimpedance sensor - EDA	-	1
13	Led for PPG	Green led lights	-	5
14	Photodiode for PPG	VEMD8080 Photodiode	-	2
15	Electrode	Stainless steel block for EDA and temperature monitoring	-	2
16	Silicone O-Rings	Silicone O-Rings	-	1
17	Screw	Screw M1.2	-	6

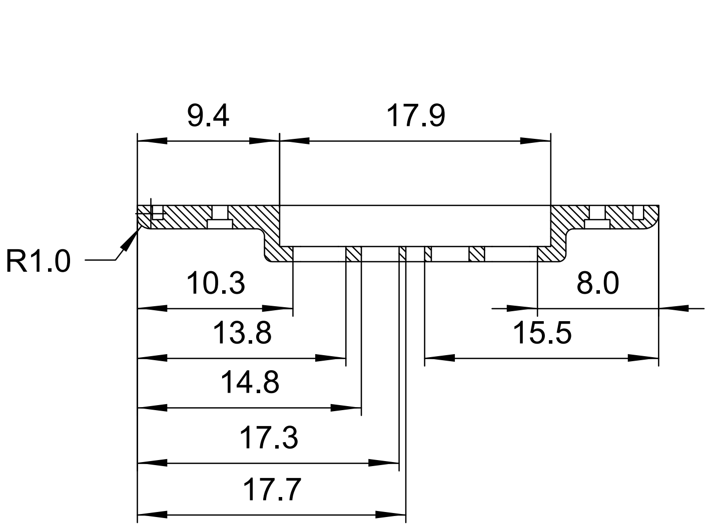
If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish	Do not Scale		Revision
	Name	Dato	TITLE: BOM_1	
DRAWN	QI	May19, 2023		
Material			DWG NO. 007	A4
			Weight:	Scale 1:1

ITEM NO.	PART NAME	DESCRIPTION	Draw No.	QTY.
18	Sock	Sock with hole	014	2
19	Hook and loop	Hook and loop	-	2
20	Pocket	Pocket	015	2
21	Charger_upper	Charger_upper	016	1
22	Charger_middle	Charger_middle	017	1
23	Charger_lower	Charger_lower	018	1
24	Led light	Led light	-	1
25	Screw	Screw M1.0	-	2
26	Screw	Screw M1.4	-	4
27	Wireless charging coil_2	QI Standard wireless charging coil	-	1
28	PCB_charger	PCB_charger	-	1
29	Charging Cable	Charging Cable	-	1

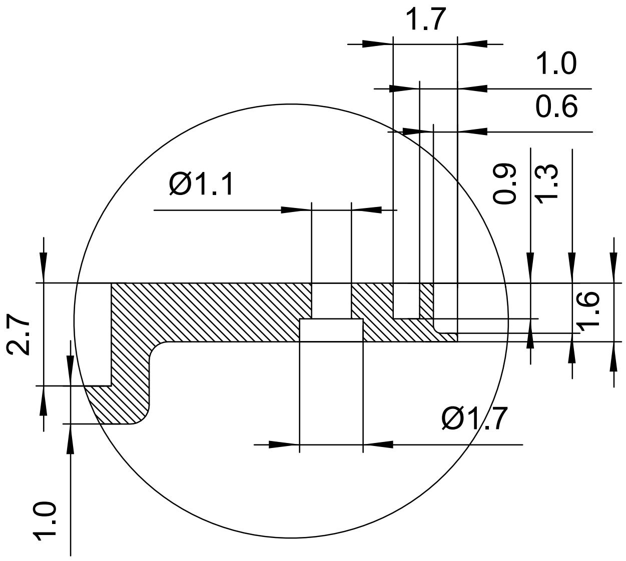
	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish	Do not Scale	Revision
	Name	Dato	TITLE: BOM_2	
DRAWN	QI	May19, 2023		
Material			DWG NO. 008	A4
			Weight:	Scale 1:1



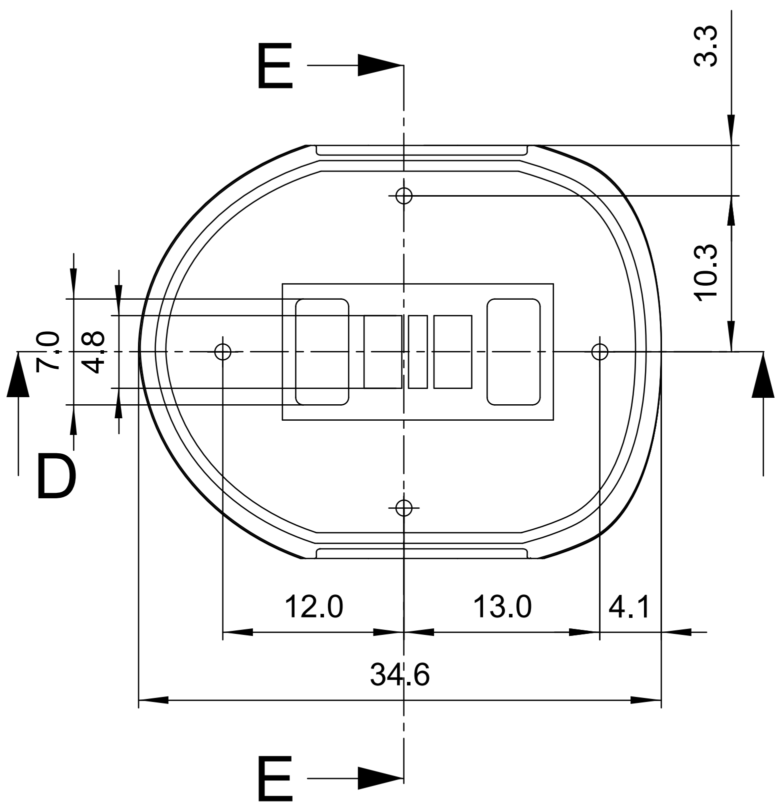
	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish: PM-T1	Revision
	Name	Dato	TITLE: Upper shell
DRAWN	QI	May19, 2023	
Material: Celazole T-Series			DWG NO. 009 — A4
			Weight: 1.75g — Scale 2:1

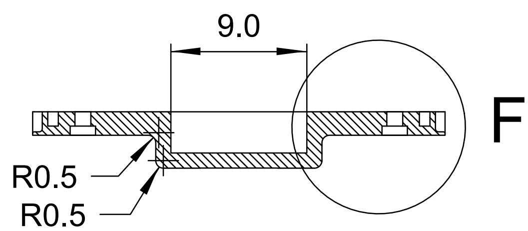


SECTION D-D

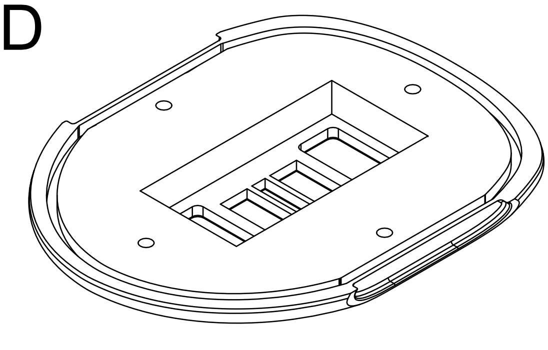


DETAIL F
SCALE 5:1

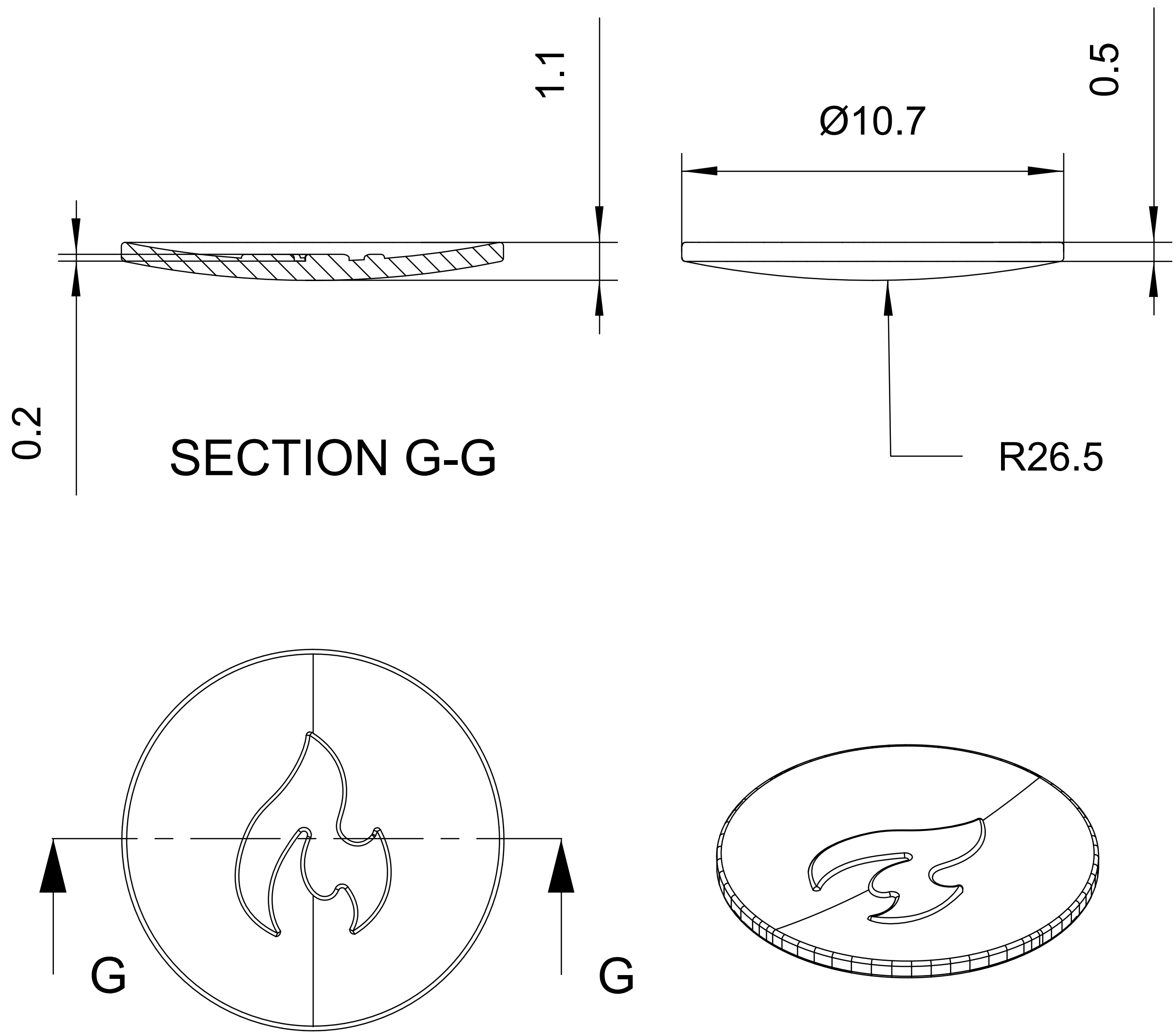




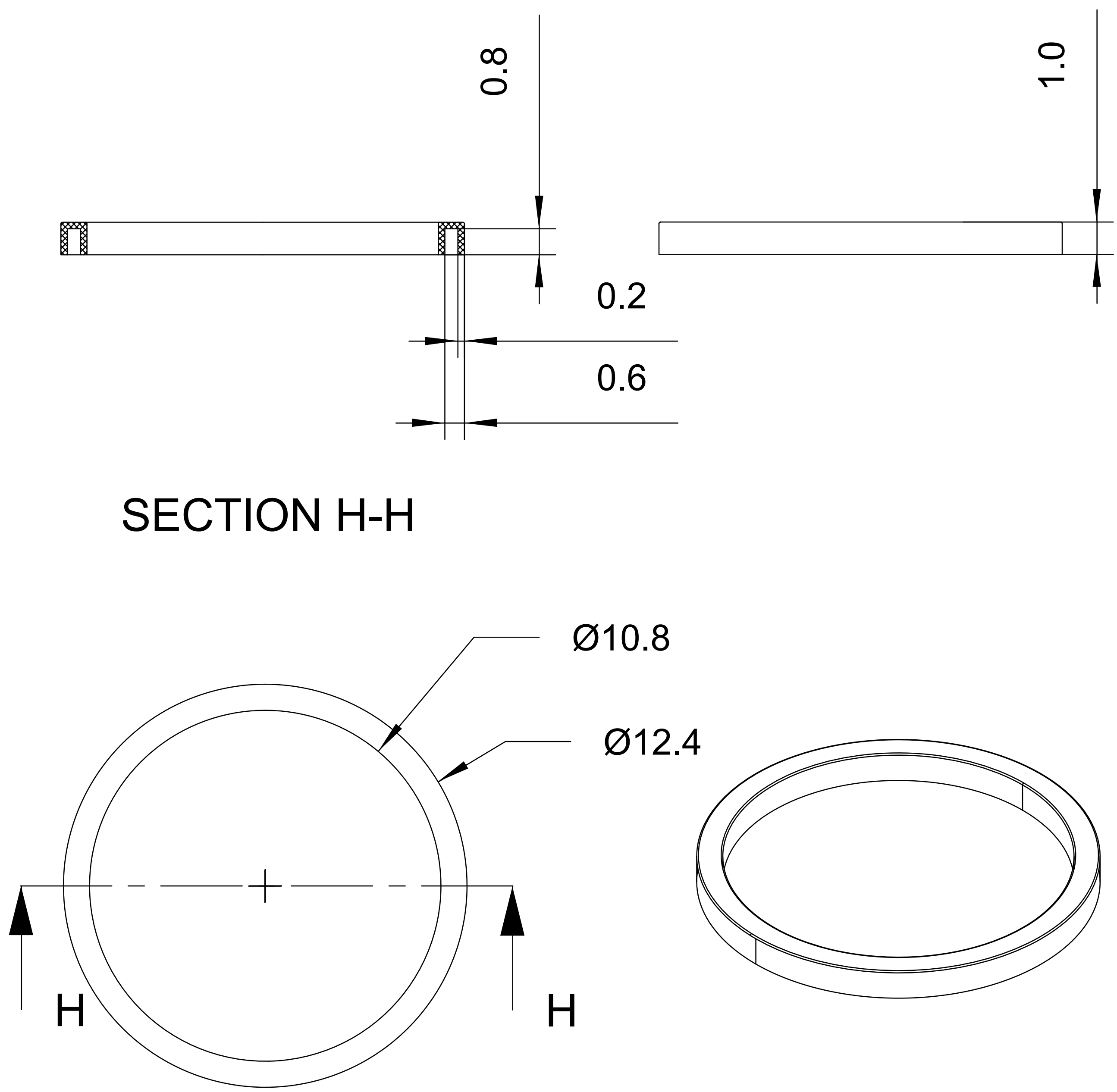
SECTION E-E



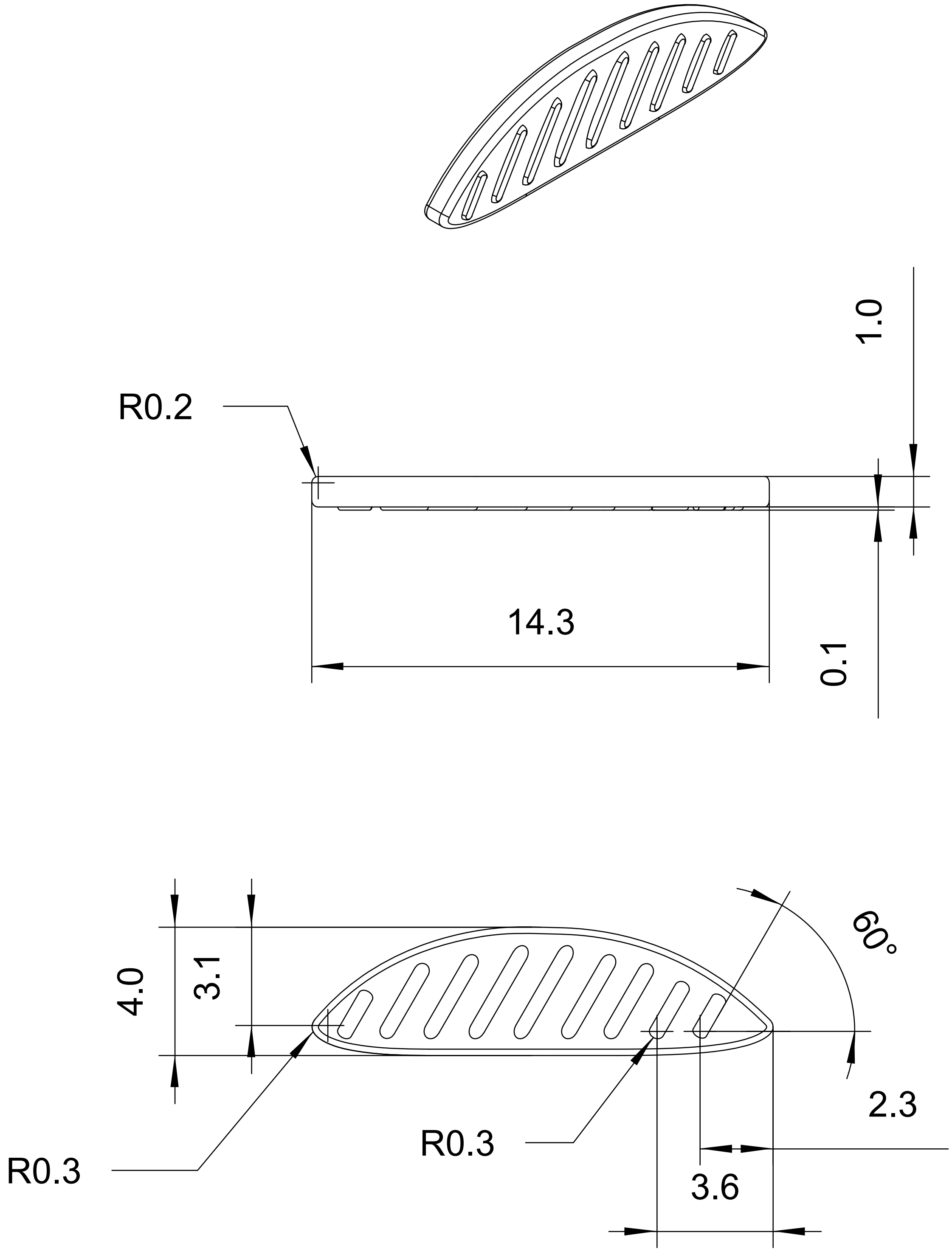
	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish		Revision
		PM-T1	TITLE: Lower shell	
	Name	Dato		
DRAWN	QI	May19, 2023		
Material: Celazole T-Series			DWG NO. 010	A4
			Weight: 1.42g	Scale 2:1



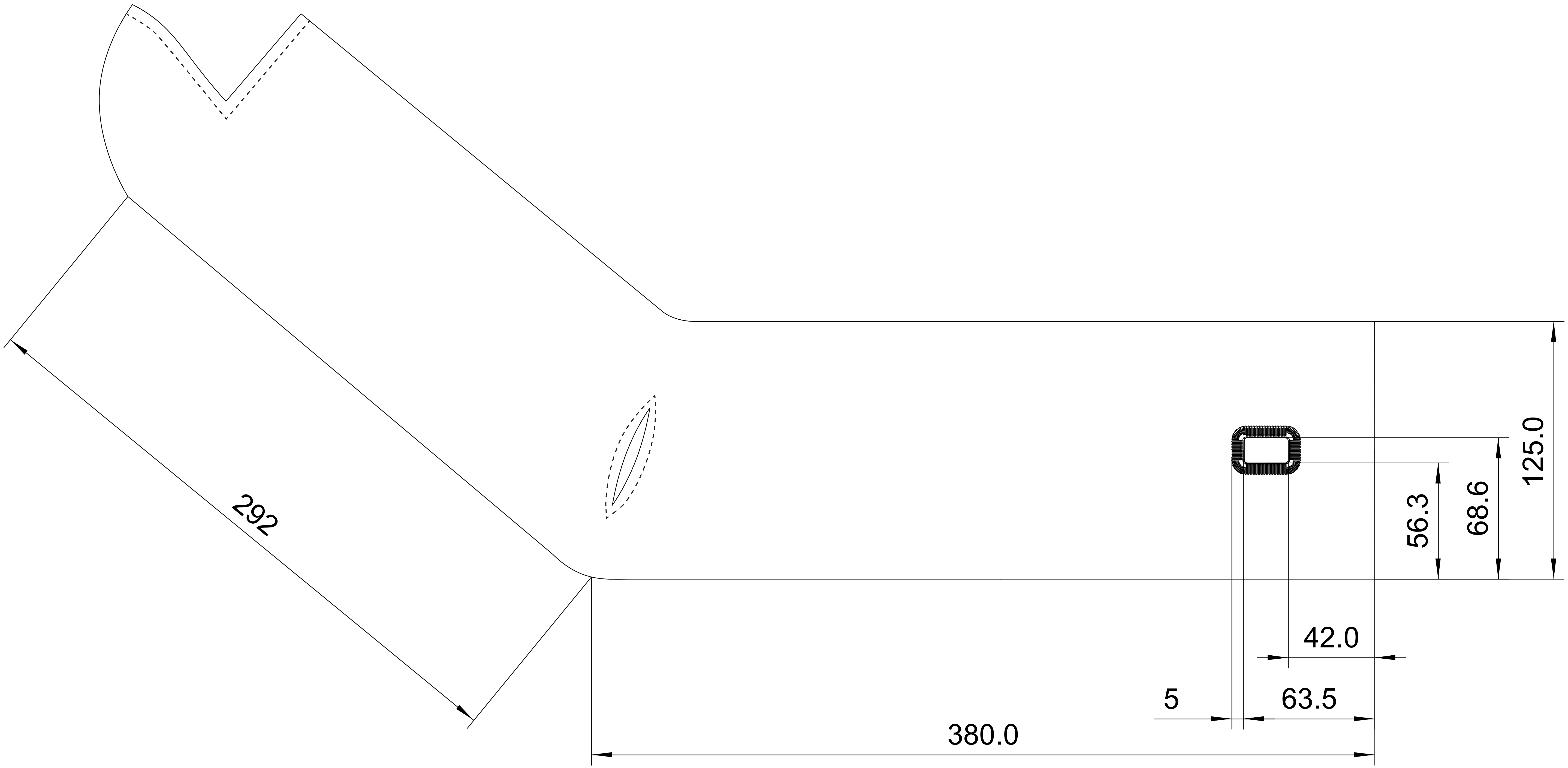
	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish		Revision
		PM-T1	TITLE: Button	
	Name	Dato		
DRAWN	QI	May19, 2023		
Material: Celazole T-Series			DWG NO. 011	A4
			Weight: 0.07g	Scale 5:1



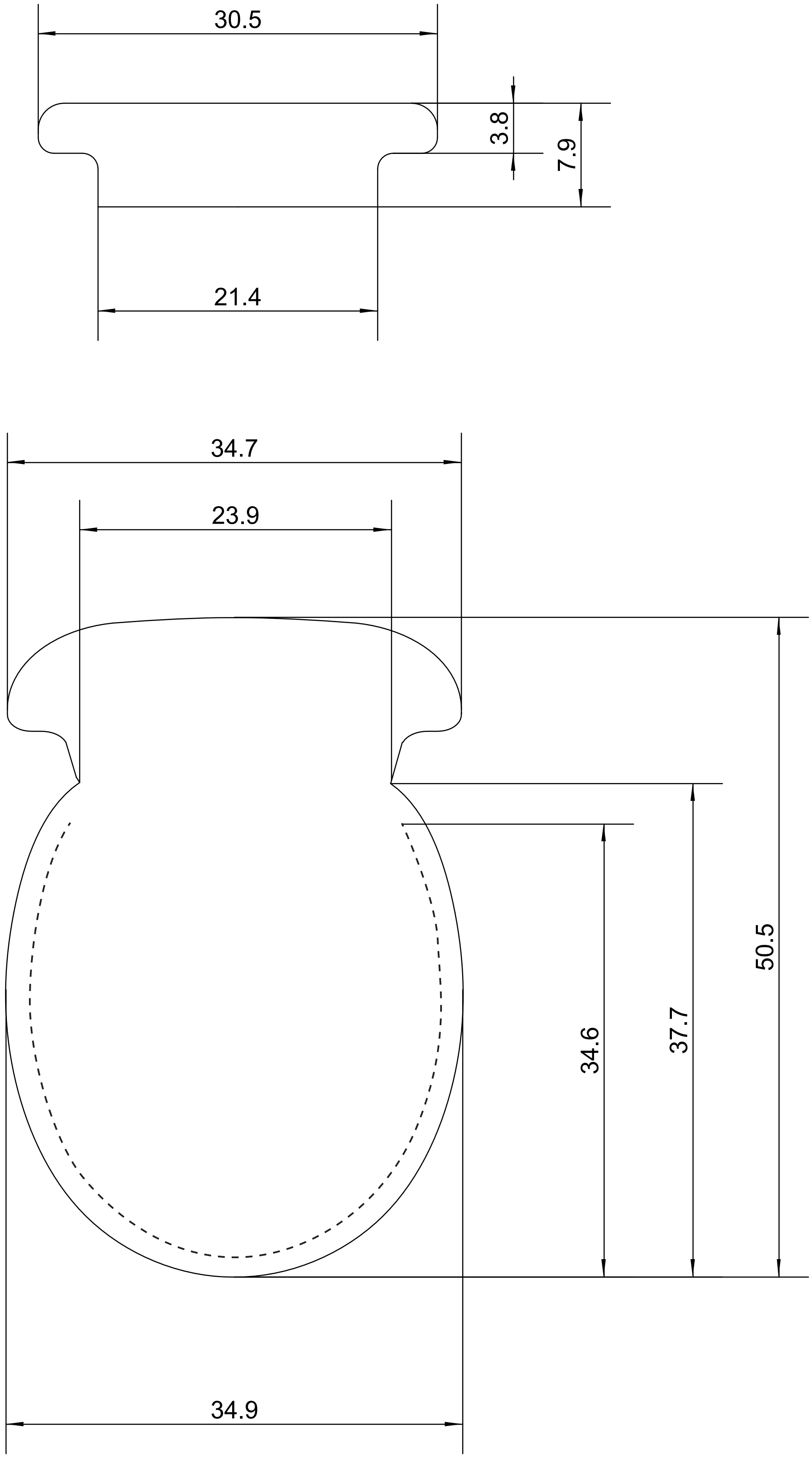
	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish		Revision
		PM-T1	TITLE: Light shell	
	Name	Dato		
DRAWN	QI	May19, 2023		
Material: NEXTREMA® glass-ceramic			DWG NO. 012	A4
			Weight: 0.043g	Scale 5:1



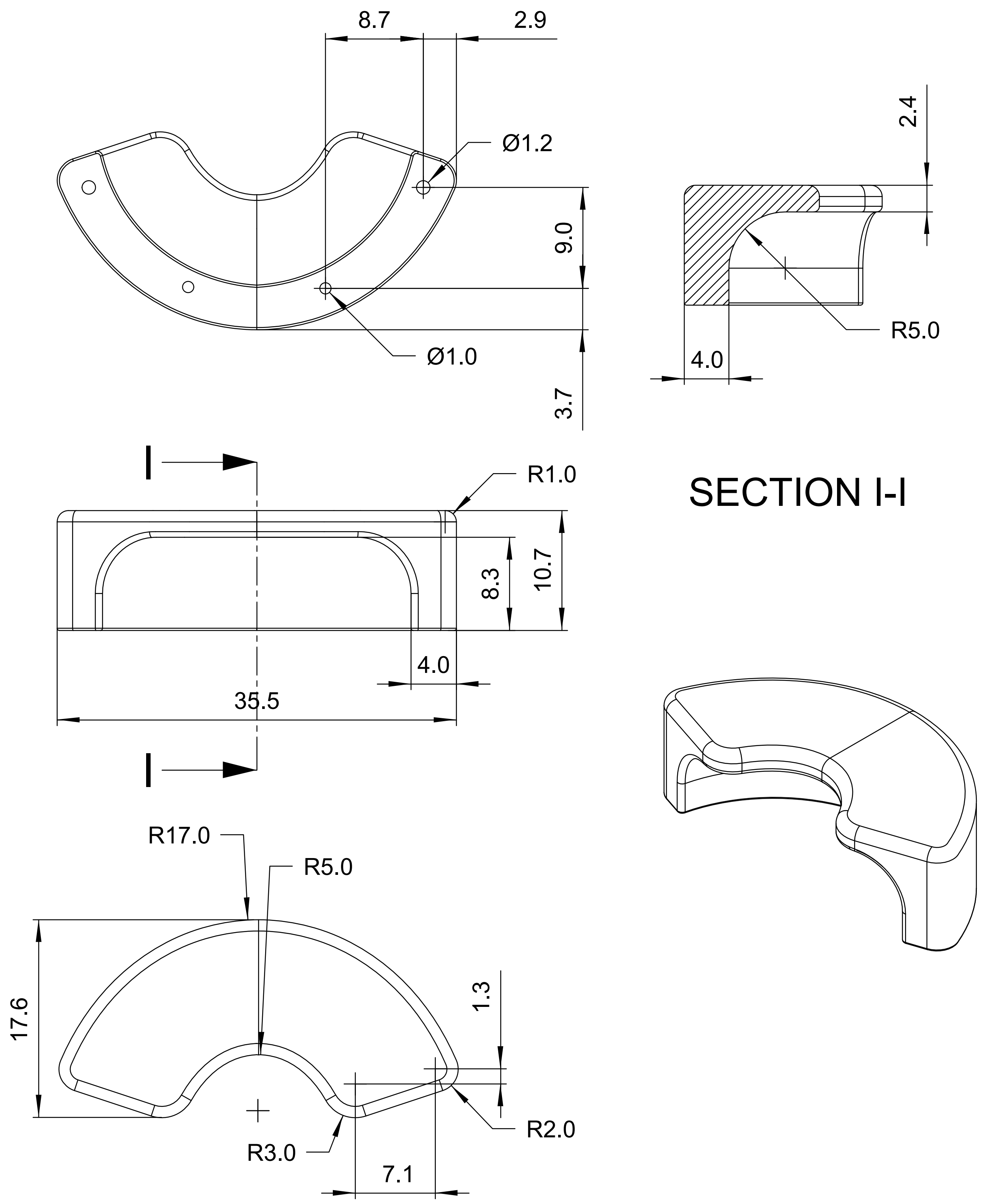
	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish		Revision
		PM-T1	TITLE: Grip	
	Name	Dato		
DRAWN	QI	May19, 2023		
Material: Silicone rubber			DWG NO. 013	A4
			Weight: 0.11g	Scale 5:1



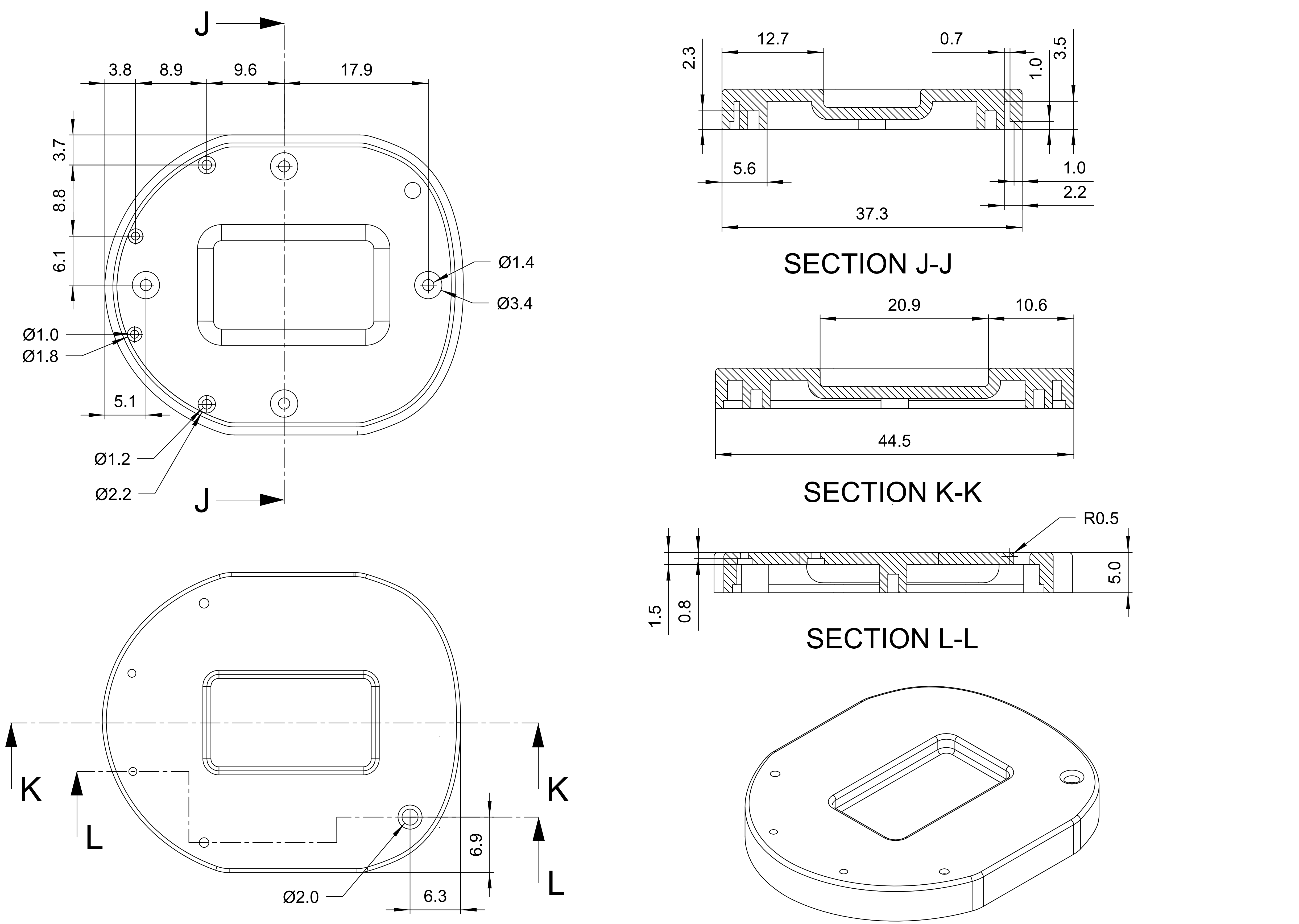
	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish		Revision
	Name	Dato	TITLE: Sock - Sewing template	
DRAWN	QI	May19, 2023		
Material	53% Nylon, 42% Merino Wool, 5% Lycra® Spandex		DWG NO. 014	A3
			Weight:	Scale 1:2



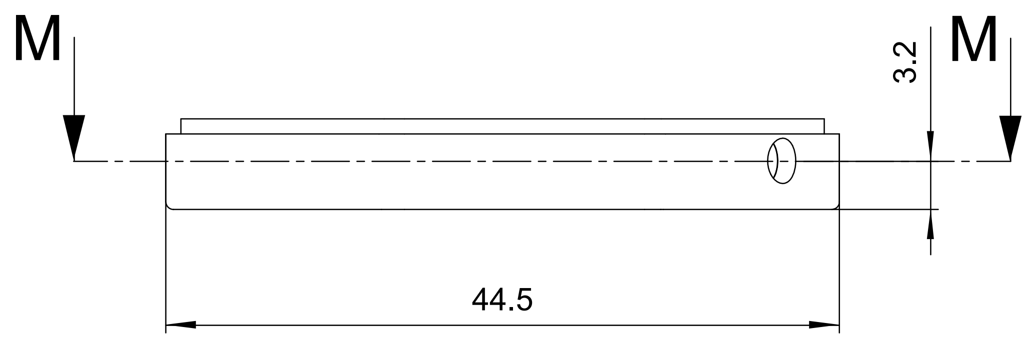
	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish	Revision
	Name	Dato	TITLE: Pocket - Sewing template
DRAWN	QI	May19, 2023	
Material: FR Blending Knitting Fabric			DWG NO. 015 — A4
			Weight: — Scale 2:1

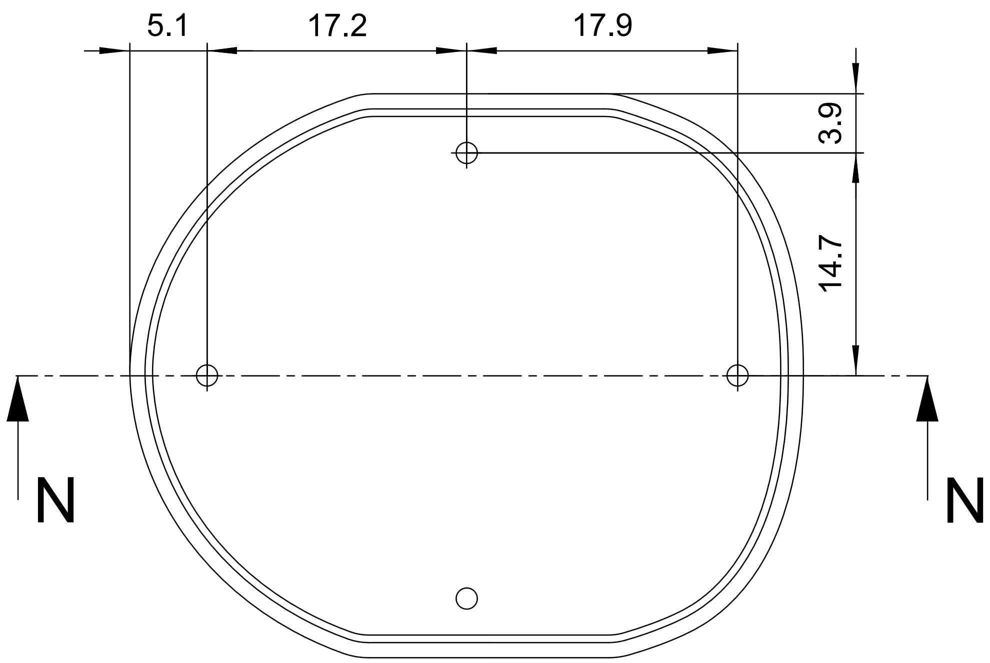


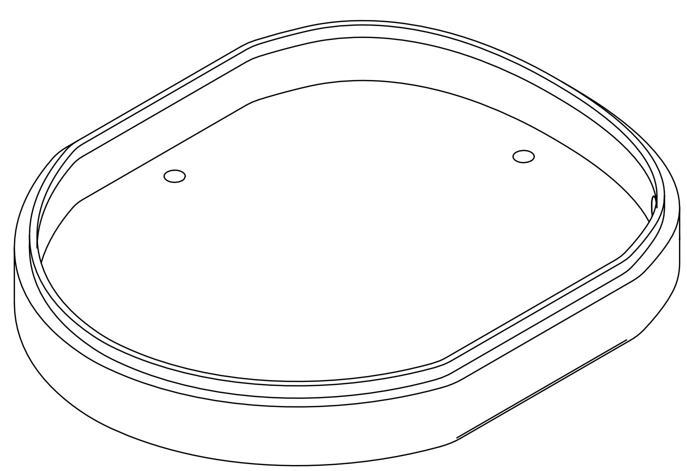
	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish		Revision
		PM-T1	TITLE: Charger_upper	
	Name	Dato		
DRAWN	QI	May19, 2023		
Material ABS			DWG NO. 016	A4
			Weight: 2.1g	Scale 2:1

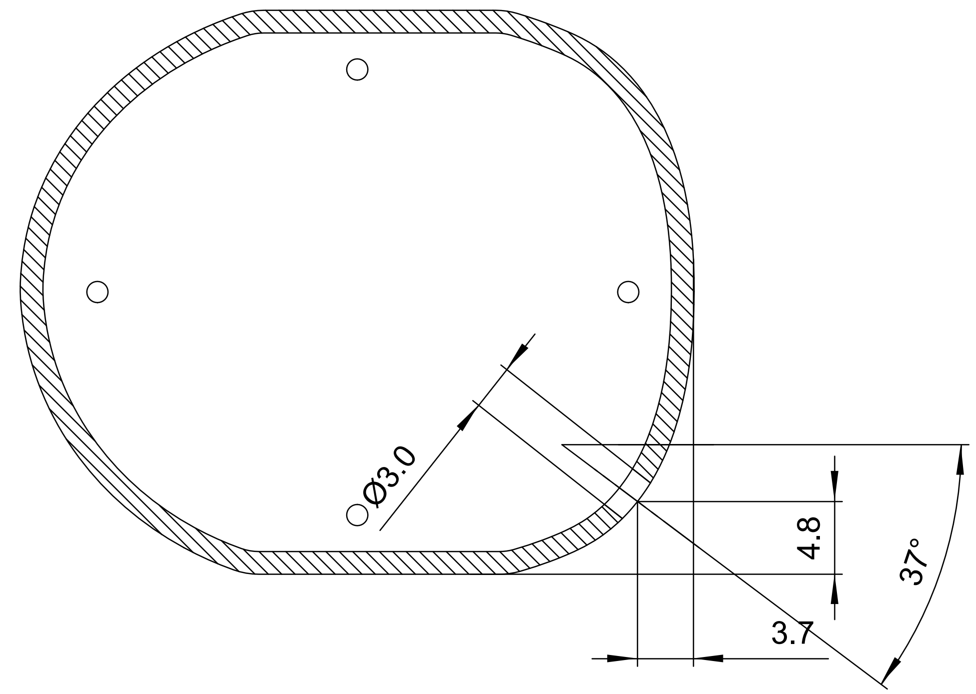


	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish		Revision
		PM-T1	TITLE: Charger_middle	
	Name	Dato		
DRAWN	QI	May19, 2023		
Material	ABS		DWG NO. 017	A3
			Weight: 3.15g	Scale 2:1

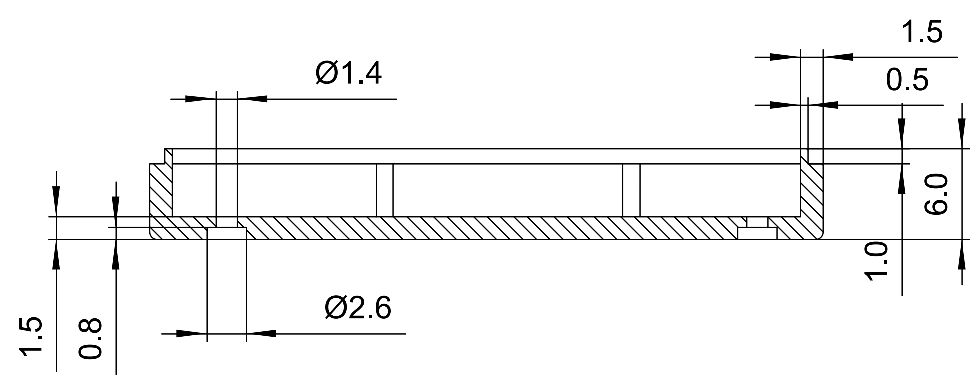






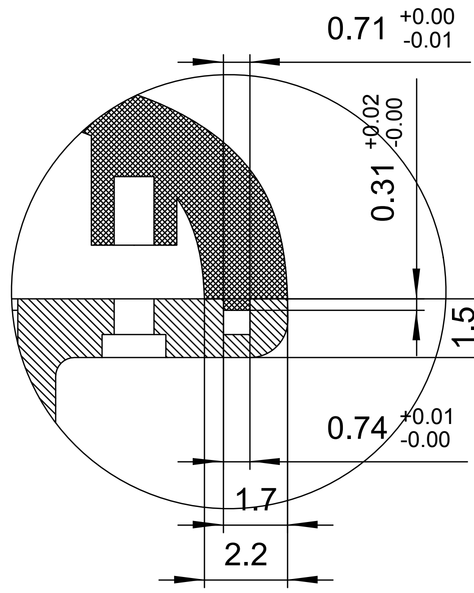


SECTION M-M

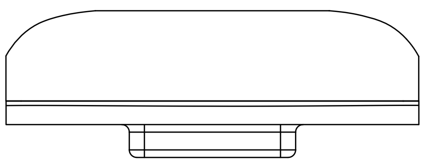


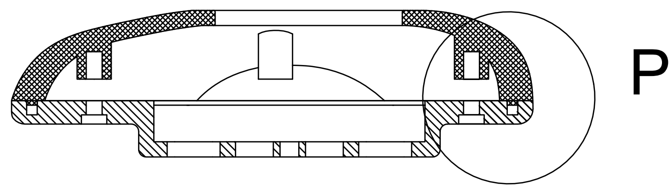
SECTION N-N

	If not specified all dimensions in [mm] Tolerance: DS/ISO 2768-c	Surface finish		Revision
		PM-T1	TITLE: Charger_lower	
	Name	Dato		
DRAWN	QI	May19, 2023		
Material	ABS		DWG NO. 018	A3
			Weight: 2.94g	Scale 2:1



DETAIL P
SCALE 5:1





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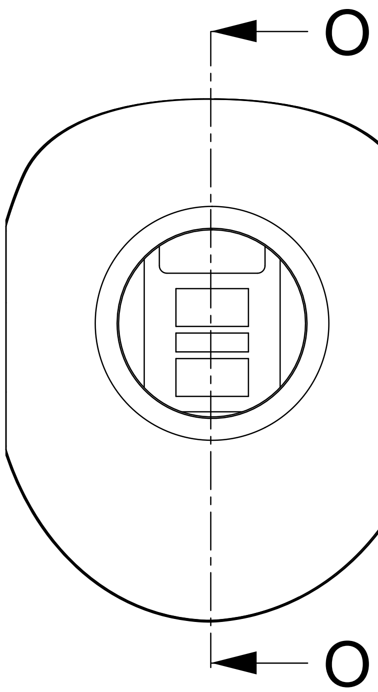

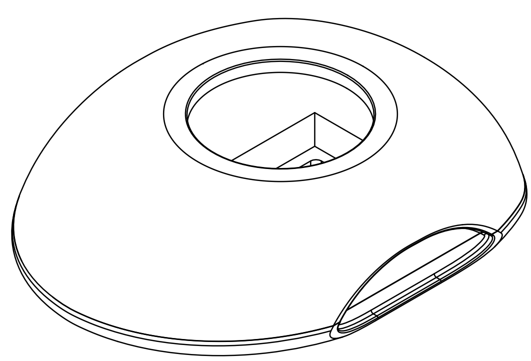

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Lifeline Beacon

Firefighter Safety Equipment

Process report

Qi Ai

MSc04 / ID13

June 2023

Aalborg University

Title page

Title:
Lifeline Beacon

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Abstract

This graduation project involves the development of a wearable device that meets professional standards in the firefighting domain. It aims to enhance the safety of firefighters in their mission execution through proactive protection, without compromising work efficiency.

Firefighters need to perform tasks extremely efficiently, racing against time to save citizens' lives and property. This profession has long been recognized as one of the most dangerous, often confronting highly hazardous working environments and unpredictable risks that threaten their safety. However, their personal protective equipment and some electronic devices present issues that sometimes lead to loss of functionality or even threaten their work efficiency and safety. These problems include low compliance, discomfort, and mobility impact. New products being introduced aim to eliminate these issues.

The project presents an innovative product specifically designed for firefighters, with the key principle of real-time monitoring of firefighters' vital signs and activity level to enable commanders to make dynamic strategic deployments and provide timely rescue assistance, thereby reducing the risk of casualties among firefighters and minimizing the impact on task efficiency. The information dissemination system also involves the firefighters themselves and their teammates, aiming to enhance firefighters' situational awareness and facilitate the rescue of victims. Furthermore, the product's scenario involves relevant personnel before and after a fire incident, aligning with occupational health and safety standards to continuously improve the working safety of firefighters in a proactive and sustainable manner.

Acknowledgement

Thank you to supervisor Mário Barros for the guidance and continuous feedback provided throughout the entire process.
A special thanks to the many firefighters from NOBR Fire Department for their professional knowledge, valuable insights, and feedback. Their contributions are greatly appreciated.

Reading Guide

The project is divided into four parts
1. Product report: presents the final design proposal.
2. Technical drawings: present the specifications of the design proposal.
3. Process report: present the process, thinking and conclusion of the project.
4. Appendix: contains activities and analyzes performed during the project.

For ease of reading and following the process, four types of "Summary" boxes are applied:

- This box indicates that the task provides important insights that require further investigation or are related to the process.

- This box indicates that the task has generated new user needs, requirements, or opportunities related to the solution.

- This box indicates that the task has rejected previous findings or hypotheses, rendering them invalid.

- This box represents the conclusion of the task based on the selected working principle.

References

The references throughout the report are specified directly in the text in accordance with the Harvard method “(author, year), and the illustrations are numbered consecutively: “ill. #: [descriptive illustration text]” and referred to in the text in a likewise manner: “(ill. #)”. Appendix are referred to in the text in a likewise manner: “(app. #)”. All sources and illustrations are fully listed at the end of the report. Illustrations without attribution are the group's own illustrations.

Table of content

Introduction

In our world, something is always burning, with firefighters continuously battling these flames to protect people from the threat of fire. Firefighters safeguard lives and property but face high risk themselves. Motivated by this, my project aims to improve their safety through my design skills and this thesis opportunity. The initial study of the project revealed problems with existing personal protective equipment for firefighters, which prompted my choice of project theme.

Initial study revealed deficiencies in the current personal protective equipment used by firefighters, thus shaping the theme of the project. A thorough analysis of these equipment issues, their implications for firefighter safety, and potential solutions are undertaken, culminating in a comprehensive proposal. Rigorous research into the causes, symptoms, and progression of firefighter casualties leads to the identification of design opportunities to enhance their safety by monitoring vital signs and activity levels. Furthermore, the project delves into the needs of firefighters, both individually and as a team, as well as the broader system requirements. Based on an analysis of the fireground environment, crucial standards necessary for product development are recognized.

Collaborator

This project is developing based on close collaboration with Nordjyllands Beredskab (NOBR), an emergency management agency located in the North Jutland of Denmark. NOBR provides comprehensive emergency, firefighting, and rescue services, consistently dedicated to protecting citizens' lives and property, contributing to the safety and reliability of the North Jutland islands.

The design proposal of the project is developed through close collaboration with the main users, firefighters, to ensure that the product can meet their needs. These firefighters and commanders, coming from NOBR, provide valuable insights and feedback through user interviews and prototype testing, also offering opportunities to participate in drills and real alarm responses.

User feedback plays a crucial role throughout the project, and therefore, this part is thoroughly documented in the entire report. The following sections will briefly introduce a few of the users who provided feedback.

Anders Brosbøl
Team leader,
Operations
manager
20 years

Tommy Johannessen
Fire chief
Smoke divers (9 years)
Incident commander
(31 years)

Martin S. Olsen
Team leader,
incident
commander
10 years

Michael
Smoke diver
9 years

Tom
Smoke diver;
Water diver
7 years part-time

Methodology

Project management

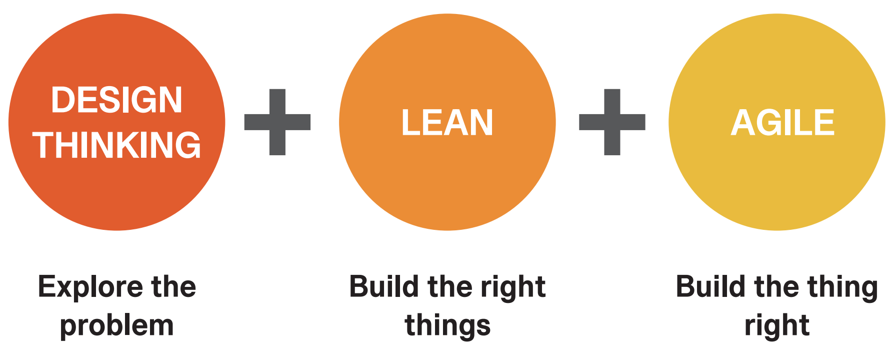
The primary management strategy for the project involves establishing and maintaining clear project goals, as well as formulating daily tasks and milestone plans to ensure the orderly progress of the entire project. To improve work efficiency and effectiveness, I utilize tools such as a "to-do/doing/done list" and "SCRUM" to build and optimize work processes. The use of these tools makes the work progress more explicit and visual, greatly assisting me in monitoring the status of tasks at each stage, and adjusting and improving the project plan in a timely manner.

Design Thinking - Lean - Agile

The entire project process is guided by a systematic approach of Design Thinking - Lean - Agile. The three methods are iteratively used at each stage, but overall, design thinking is primarily used in the early stages of the project to explore and solve problems. Once the solution space is framed, with the selection of the conceptual direction, lean and agile methods are employed more extensively. This is done through iterative testing of beliefs and learning to attain correct results, and by adapting to continually changing information to get things done right.

At the project's inception, it's in the fuzzy front end, using design thinking to view all problems as complex "wicked problems". Before entering the proposal model, different interpretations are questioned and identified, searching for ambiguities and contradictions. The process entails understanding the problem and finding value-creating solutions through iterative learning. This is primarily achieved by understanding users, challenging assumptions, redefining the problem, and creating innovative solutions for prototyping and testing. Additionally, using design thinking to "think outside the box", brainstorming is used to challenge existing assumptions and reshape the problem, fostering idea creation and meaningful innovation. Following the "value probing" approach, it seeks to qualitatively understand "what is valuable", rather than just chasing scale in quantity, to better drive the project's progress and development.

The Lean and Agile mindset in entrepreneurial thinking helps the project progress and focus on the most important things. This mainly aids in accelerating the project and provides a natural mechanism to respond to rapid changes, thereby moving in the right direction.



illus. 1： Design Thinking - Lean - Agile

illus. 2

UNDERSTAND

This chapter comprehends the project background through desktop research combined with user interviews. It includes the impact and significance of the project, problem areas, and preliminary identification of needs. The phase concludes with a project overview and a design brief, summarizing the identified problems, scope, target group, and business potential.

1.1 Context

Who is Firefighter

The target group of the project is firefighters. Therefore, the role of firefighters is considered a key part of the project background and is thoroughly researched as the first step of project initiation.

Duties of a Firefighter

A firefighter is a trained professional who is responsible for responding to emergency situations, particularly fires. Firefighters are typically employed by local fire departments, which are usually part of a city or county government. They work in teams to respond to emergencies, assess the situation, and take appropriate action to protect life and property. In addition to responding to fires, firefighters may also respond to medical emergencies, traffic accidents, natural disasters, and other types of emergencies. Firefighters are trained in a variety of skills, including fire suppression, search and rescue, and hazardous materials response. They also perform regular maintenance on their equipment and participate in ongoing training to maintain their skills and stay up-to-date with new techniques and equipment. (Careerexplorer, n.d.)

In addition to responding to emergencies, fire departments work to prevent fires and other emergencies. So firefighters inspect buildings to make sure they meet fire safety codes, educate the public about fire safety, and participate in community outreach programs to promote safety and preparedness (Duties of a Firefighter, 2015). Clearly, firefighters are an integral and important part of emergency response and community safety.

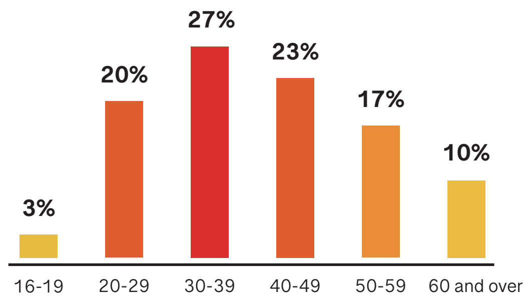
Composition of firefighters

Gender

The firefighting profession has traditionally been dominated by men. According to the National Fire Protection Association (NFPA), as of 2020, only about 9% of firefighters were female. This number has been slowly increasing over time, and efforts have been made to recruit and retain more women in the profession. (Fahy et al., 2022)

Age

According to the newest report that the median age of firefighters is 38.4 years old (Data USA, 2023). Typically, firefighters need to be at least 18 years old to join, and many fire departments have a maximum recruiting age, usually around 35. Once hired, firefighters can continue to serve as long as they can meet the physical, mental and skill demands of the job. Many firefighters serve until retirement age, usually around 55-65 (Pertz, 2023). The figure below shows the proportion of each age group (Fahy et al., 2022) (illus.3).



illus.3: Number of firefighters by Age group

Roles

Firefighters can be classified into five categories based on their roles and employment status. The first category, career firefighters, consists of full-time, paid professionals employed by city, county, or state fire departments or districts. They typically receive benefits such as health insurance, retirement plans, and paid time off. The second category, volunteer firefighters, serve their communities without pay. They can be found in both rural and urban areas but are more prevalent in smaller communities unable to support a full-time, paid fire department. According to the National Fire Protection Association (NFPA), as of 2020, approximately 35% of firefighters in the US were career firefighters, while 65% were volunteers (Fahy et al., 2022). It is essential to consider that these numbers may change over time and depend on factors such as location and organization.

The remaining three categories, which constitute a smaller percentage of the overall firefighting workforce, include: wildland firefighters, who specialize in combating wildfires; industrial or private firefighters, employed by private companies or organizations such as airports and chemical plants; and military firefighters, responsible for firefighting and emergency response at military bases and installations (Careerexplorer, n.d.). While each type of firefighter has distinct responsibilities, training requirements, and challenges, their shared primary goal is to protect life and property.

illus. 4: Numbers

Firefighter casualties

Problem Size

Approximately every 23 seconds, a fire department in the United States is dispatched to combat a blaze across the nation. Substantial advancements in construction materials and techniques, coupled with the enforcement of more stringent fire codes, have led to a significant reduction in fires and fire-related fatalities since the 1970s. However, firefighters contend that as an unintended consequence, the fires they now face are often larger and more severe than those they previously encountered. In 2021, around 60,750 firefighters sustained injuries while on duty, based on the most recent data (Campbell and Hall, 2022). Moreover, firefighters' life expectancy is on average 10 years shorter than that of the general population, and they face a 14% higher risk of succumbing to cancer (Fahy and Petrillo, 2022).

Economic impact

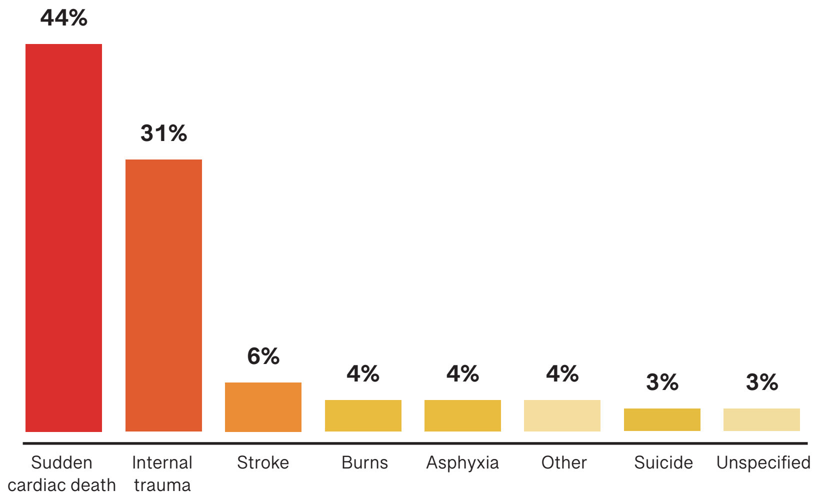
Firefighter injuries not only pose significant risks to their well-being but also entail substantial economic repercussions. The study estimates that the annual cost of such injuries in the United States amounts to roughly $3.1 billion, encompassing both direct and indirect expenses. Direct costs, totaling approximately $1.1 billion, comprise medical bills, workers' compensation, and disability retirement benefits. Indirect costs, which amount to around $2.0 billion, factor in elements like training and overtime for substitute firefighters, diminished productivity, and the effects on morale and mental health. By normalizing the total annual costs with the number of firefighter injuries and firefighters, it is determined that injuries cause a financial loss equivalent to $5,412 per firefighter annually. The average cost per injury stands at $95,031 (David et al., 2017).

“ It's a little bit special job when people go out, and we go in.”

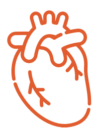
- Anders Brosbøl, Operations manager, NOBR

Firefighter deaths by cause of injury

To further understand the problem area, the reasons behind the firefighter casualties were investigated and dissected in detail. The figure illus. 5 visually represents the proportion of these contributing factors.



illus. 5: Firefighter Deaths by Nature of injury (Campbell and Hall, 2022)



Sudden cardiac death

Sudden cardiac death among firefighters is often caused by a combination of factors, including underlying **heart disease, extreme physical exertion, heat stress, and exposure to toxic substances** during firefighting activities. These factors can strain the cardiovascular system, leading to a sudden cardiac event that may result in death.

Internal trauma/crushing

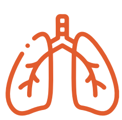
Internal trauma or crushing death of a firefighter can occur due to various incidents on the fireground or during emergency response. Factors contributing to these casualties include **structural collapses, falling debris, vehicle accidents, or being caught or pinned by heavy equipment.**

Stroke/aneurysm

Stroke or aneurysm-related deaths among firefighters can be attributed to a combination of factors, including underlying **medical conditions, physical exertion, and stress** experienced during firefighting activities.

Burns

Firefighter fatalities due to burns can result from direct contact with **flames, extreme heat, or hot gases** during firefighting operations.



Asphyxia

Firefighter deaths due to asphyxia typically occur when they are **unable to access sufficient oxygen** while working in a hazardous environment, such as a burning building or a confined space filled with **smoke or toxic gases**.

Suicide

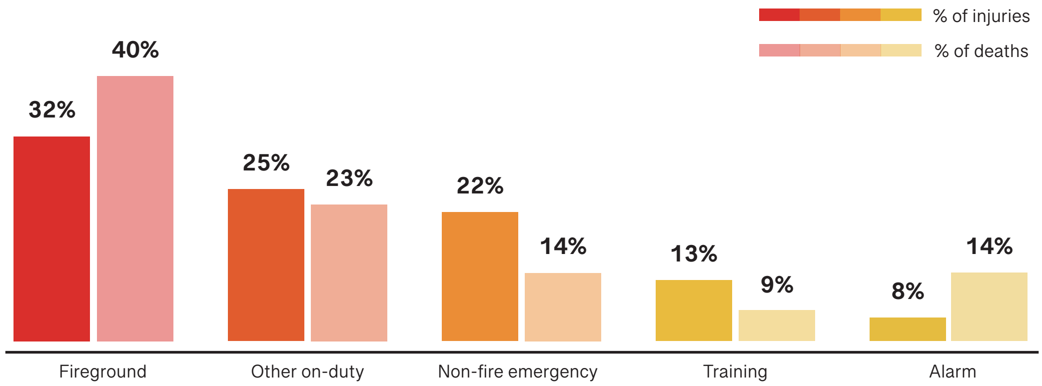
Firefighter suicides can be attributed to various factors, including chronic stress, trauma from witnessing tragic incidents, high-pressure work environment, and mental health issues like depression, anxiety, or post-traumatic stress disorder (PTSD).

Other

Unspecified medical

Firefighter casualties by Type of Duty

According to the National Fire Protection Association (NFPA) firefighter casualty statistics report, injuries and fatalities among firefighters can be classified into five distinct duty categories, based on the activities being performed at the time of injury or death. These categories include: 1) responding to or returning from incidents, which encompasses both fire and non-fire emergencies; 2) non-fire emergencies, covering rescue calls, hazardous situations, and natural disaster responses; 3) training exercises; 4) other on-duty tasks, such as inspections or maintenance duties; and 5) fireground operations, which involve various types of fires, including structure fires, vehicle fires, and brush fires. The chart below depicts the percentage of injuries and fatalities for each duty type. (illus.6)



illus. 6: Firefighter causauties by Type of Duty (Fahy and Petrillo, 2022)

Scoping

Considering the wide range and complexity of firefighters' duties, and the varied and intricate causes of injuries and fatalities while performing each duty, the scope of the project's problem domain must be further narrowed down to delineate solution area. Analysis and evaluation of the overall project background research reveal that focusing on a specific duty category is more meaningful and promising than considering age or gender. In this case, the project selects fireground operations as the focus area, as firefighters face the highest likelihood of injury or death during these tasks, indicating that potential solutions could have a greater impact. Furthermore, this choice is based on the assumption that fireground environments are the most hazardous and complex, which can facilitate the identification of more comprehensive and critical innovative breakthroughs.

Sum up

The initial research provides an overview of the project background, including the primary users and their role scope. Moreover, the impact of the project on the life safety of the firefighter and the resulting economic consequences are presented. To advance the project, the focus is narrowed down to fireground operations. It is worth noting that the age and gender groups will encompass the entire firefighter population. Moving forward, in order to establish a solid foundation for the project, a more in-depth study of fireground operations is required.

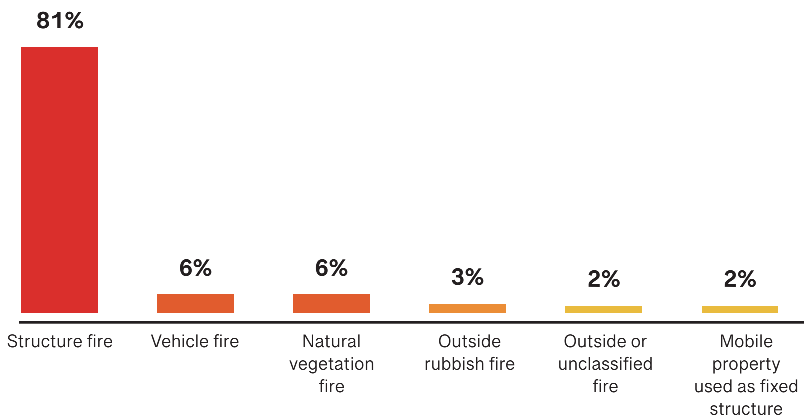
- The user age group spans the entire firefighter population, covering 16 to 65 years old.
- User gender includes male and female.

1.2 Fireground

As the project background is scoped to the fireground, desktop research efforts focus on it in greater depth.

Fireground is a term used to describe the location of an active fire incident, encompassing the area directly involved in the fire as well as its immediate surroundings. In the context of firefighter duties, fireground operations refer to the various tasks that firefighters perform while actively engaged in fighting a fire or managing the scene of a fire incident (Spell, 2020).

Upon further investigation, it has been determined that structural fires represent the primary category of incidents leading to firefighter injuries on the fireground, at 81%. The incident type for a structure fire pertains to a fire event occurring within a building or facility designed for human occupancy or use. The graph below illustrates the various types of incidents and the corresponding percentage of firefighter injuries sustained in each type of fire. (illus. 7)



illus. 7: Fireground Injuries by Type of Incident (Campbell, 2022)

Structure fire

Since structure fires account for a significant proportion of firefighter injuries, it is further studied and it is noticed that structural fires pose unique challenges and threats to firefighter lives compared to other types of fires, such as wildfires or vehicle fires, which can be summarized into the following two main triggers.

Confined spaces and complex layouts
Structural fires occur inside buildings, which often have enclosed spaces and limited entry and exit points. This can make it difficult for firefighters to quickly escape or avoid being trapped by collapsing structures when the situation worsens. Moreover, buildings, particularly large commercial or institutional structures, may have complex layouts consisting of multiple rooms, floors, and compartments. Navigating in these environments can be challenging, especially in low visibility conditions, increasing the risk of disorientation and entrapment. It is worth noting that enclosed spaces within structures can also lead to rapid buildup of heat and combustible gases. This increases the risk of flashover or backdraft occurrences, resulting in sudden, intense fires and explosions, exposing firefighters to serious burn and injury risks. (Havel, 2012)

Building construction and materials
Compared to other types of fires, structural fires are more likely to cause structural collapse. This occurs when a fire weakens the structure of the building, rendering it unstable. Structural collapse can result in severe injuries or fatalities for firefighters (Firehouse, 2008; Havel, 2012). Additionally, the combustion of various building materials, furniture, and personal belongings can release smoke and gases containing numerous toxic chemicals, posing severe respiratory hazards and chemical burns to firefighters (Lakeland, 2023).

- Structure fire poses additional threat.

Environment threats

As the causes of firefighter casualties and the unique threats posed by structural fires are identified, along with a further study on the fireground environment, the potential environmental threats that firefighters may face at the fire scene are categorized and summarized. The purpose is to bring out the problem domain and get an overview of it.

Fire and high temperature

Firefighters are exposed to extreme temperatures and radiant heat from the fire, which can lead to heatstroke, dehydration, and burns. Prolonged exposure to high temperatures can also increase the risk of heat exhaustion and other heat-related illnesses.

Hazardous materials

Fires can involve hazardous materials, such as chemicals, fuels, or explosives, which can pose additional risks to firefighters. These materials can be highly reactive, toxic, or flammable, and require specialized knowledge and training to handle safely.

Smoke and toxic gases

Fires produce a variety of toxic gases, such as carbon monoxide, hydrogen sulfide, methane, and various volatile organic compounds (VOCs). These gases can be highly dangerous when inhaled, leading to disorientation, respiratory distress, or even death.

Limited visibility

Thick smoke and darkness can severely limit visibility on the fire scene, making it difficult for firefighters to navigate and locate victims, exit points, or other hazards.

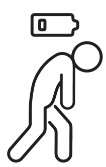
Slip, trip, and fall hazards

Fire scenes can be littered with debris, water, and firefighting foam, making surfaces slippery and uneven. Firefighters must be cautious to avoid slips, trips, and falls that could result in injury.

Collapse or falling object

Fire can weaken building materials, leading to structural failures, collapses, and falling debris. Firefighters must be vigilant in assessing the structural integrity of a burning building to avoid being trapped or injured.

In addition to the inherent threats of the environment itself, the tasks that firefighters carry out also pose threats to them.



High-intensity physical activity under pressure

Firefighting is physically and mentally demanding, and long hours on the fire scene can lead to fatigue, stress, and a reduced ability to make critical decisions.

Sum up

Through research on fireground, it is found that the environment at fire scenes is rather complex, filled with many predictable and unpredictable threats. Furthermore, it can be noted that these environmental threats are interrelated, where one type of threat might trigger another.

- **Fireground environmental threats are interrelated.**

1.3 Firefighter equipment

In order to identify entry points for the project, existing solutions for protecting firefighters from hazards of the fireground are studied.

Always carry equipment

Firefighters usually carry and wear various equipment and tools. Most wearable devices are personal protective equipment (PPE), which is designed to protecting them from physical, chemical and biological hazards through inhalation, skin contact, ingestion or contact through mucous membranes. Complete personal protective equipment and some major device and tools are shown and described below (Park et al., 2014).

Protective helmets

Firefighter helmets provide essential head protection against falling debris and other hazards. Some are designed with a wide rear bill to prevent hot water and hot embers from reaching the firefighter's neck or falling down the inside of their coat.

Face Mask

Firefighting face masks provide protection from the smoke, debris, and embers present in fire operations.

Fireproof Lifeline

It provide a means for rescued persons to escape through an entry route or for rescuers to follow their path.

Fire Axe

It either can be used for smashing windows or doors to gain entry, or to chop holes in a roof for ventilation.

illus. 8: Firefighter equipment (front)

Intrinsically Safety Lamp

It is designed to minimize the risk of equipment explosions so that firefighters can see and operate in dark or low-light, potentially explosive areas.

Hood

Face and neck shrouds for firefighting provide a barrier between the heat and elements and the firefighter. Shrouds offer a better way to beat the heat while still providing adequate heat deflection and inflamed airborne debris.

SCBA

Self-contained breathing apparatus are essential for providing firefighters with clean air in smoke-filled environments and protect firefighters against oxygen deficiency, dust, gases, and vapours.

Portable radios

It is an important communication device between firefighters and commanders outside the fire scene.

Safety Gloves

Gloves are designed to protect firefighters hands against blisters, cuts, scratches, and minor burns during routine firefighting.

Turnout ensemble

The main purpose of the outer shell is to protect the firefighter from direct flame and heat; it also contributes to abrasion and cut protection.

Boots

Firefighting boots are able to handle a variety of conditions. Made of rubber or leather, the boots have steel toes to protect the firefighter's feet from falling debris, glass, and metal.

illus. 9: Firefighter equipment (back)

Portable Fire Extinguisher

It functions by releasing an extinguishing agent intended to cool the fuel, remove or displace the oxygen, or stop the chemical reaction.

Major device and tools

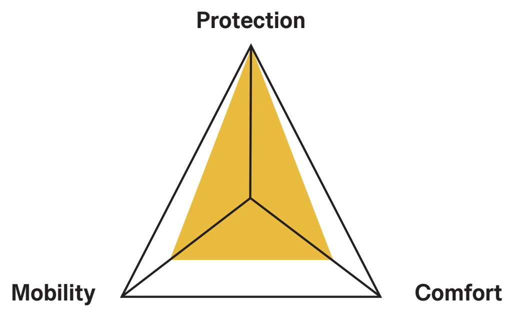
Personal protective equipment (PPE)

Three key elements

Through further research on firefighting equipment, it has been found that mobility, protection, and comfort are key elements in the design of equipment for firefighters. These elements are crucial for ensuring the safety and effectiveness of firefighters as they work in hazardous environments and perform physically demanding tasks. However, these three elements often conflict with one another, and although advancements in materials and design have led to continuous improvements in firefighters' gear, striking the right balance among these elements remains a challenge. From the current personal protective equipment (PPE) used by firefighters, it can be seen that they are primarily designed to prioritize protection, but this often comes at the expense of mobility and comfort. For example, the introduction of heavy materials in firefighting suits to meet thermal protection requirements compromises body balance, triggers physical fatigue, and increases the risk of musculoskeletal injuries and falls (Boorady et al., 2013). This, in turn, can have a negative impact on task efficiency and the life safety of firefighters.

The following diagram illustrates the three key design elements of firefighting equipment and depicts the current compromises in firefighter gear among these three elements. (illus.10)

Firefighters face a range of hazards, including high temperatures, flames, smoke, toxic gases, and falling debris. Their equipment must provide protection from these dangers while also being resistant to wear and tear.



Firefighters need to move quickly and freely in various situations, such as climbing ladders, crawling through tight spaces, and carrying heavy equipment. Their gear must allow them to perform these tasks without hindering their movement or causing fatigue.

Given the physically demanding nature of their job, it is essential that firefighters' equipment is comfortable to wear for extended periods. Properly fitted and well-designed gear can help reduce the risk of injury and fatigue, allowing firefighters to focus on their tasks and maintain their performance.

illus. 10: Three key design elements of firefighting equipment_1

- An appropriate balance between protection, comfort and mobility factors.

- The electronic equipment is single-function and requires the firefighter to manually operate it when using it.
- Two types of protection: active and passive protection.
- Two ways of being rescued: self-rescue and others-rescue.
- Potentially solution: integrate functional devices into firefighters' current personal equipment systems.

Occasional Equipment

In addition to the equipment that firefighters almost always carry, thanks to advances in technology, they also have electronic equipment that enhances the safety and efficiency of their task performance. However, these devices are not considered personal equipment and are generally only carried by firefighters and brought to the scene of a fire in specific and required circumstances. The three shown below are the most common pieces of equipment that firefighters occasionally carry.

illus.11: Dräger Pac 6000

Portable Gas Detector

A handheld device detects and monitors the surrounding environment for the presence of potentially hazardous gases. It includes a sensor array, display screen, and alarm system. Sensors identify specific gases, and the screen shows real-time gas concentrations. The alarm activates when gas levels surpass safe limits, enabling firefighters to take appropriate steps to protect themselves and others and make informed decisions when responding to an emergency. (Dräger, 2023a)

illus.12: Dräger UCF ® FireVista

Thermal imaging cameras (TICs)

Specialized devices assist firefighters in seeing through smoke, darkness, and obscurities during operations and rescue missions. Infrared technology detects temperature differences, enabling firefighters to identify hotspots, locate victims, and navigate hazardous environments (Dräger, 2023b).

illus.13: Dräger Bodyguard ® 1000

Personal Alert Safety System (PASS)

A crucial safety device for firefighters, PASS devices help locate and rescue firefighters who are trapped, disoriented, injured, or incapacitated while working in hazardous environments. If no movement is detected within a preset time (15-30 seconds), an alarm is triggered, producing a loud sound and visual indicators like flashing lights for easier locating the wearer in low-visibility situations. (Dräger, 2023c)

Sum up

This section provided an overview of firefighters' equipment, including personal gear they always wear or carry and electronic devices occasionally brought depending on the situation. These devices are designed to address various or common fire scene threats, enhancing firefighters' safety during tasks in different ways. Protective measures can be categorized into two types: the first offers active protection through threat detection and visual navigation, while the second is to provide passive protection through personal protective devices and mobility detection. Rescue methods for firefighters involve self-response or waiting for others to rescue them.

Regarding the personal equipment firefighters frequently carry, they are designed to prioritize protection, compromising two key factors: mobility and comfort, which negatively impact protective performance.

As for electronic devices occasionally carried by firefighters, they share the design advantages of being compact, lightweight, and easy to carry during firefighting operations. They can usually be attached to firefighters' uniforms or carried with ropes or straps. However, as separate and additional devices, firefighters do not always bring them to the fire scene. Their use is determined by the commander's assessment of the fire incident and conditions. However, fire scene threats are often difficult to predict accurately, and there may always be sudden or unexpected threats. This means that these products may lose their function when not carried and needed.

A potentially feasible solution is to integrate functional devices into firefighters' current personal equipment systems, ensuring their functionality is always available when needed.

1.4 Personas

In order to gain a more comprehensive and in-depth understanding of the topic before defining the problem domain, semi-structured firefighter interviews are conducted (app.1). The purpose is to identify some latent key insights to help lay the foundation for building the value proposition of the concept. Subsequently, the key takeaways collected from the interviews are categorized, analyzed, and summarized. The personas method is used, by creating a representative user that could carry these key pieces of information, guiding the ideation process to focus on what truly matters to the user.

illus.14: Personas

Name: Peter
Age: 32
Occupation: Firefighter - Smoke diver

About
I have distinct personalities. I tend to be realistic individuals, which means I am independent, stable, persistent, genuine, practical, and thrifty. I like tasks that are tactile, physical, athletic, or mechanical.

Goals

Time
I have only 1 minute to put on my suits and depart from the station.

Standard
I have standard-compliant, very good quality, up-to-date equipment and garments.

Portability
I use some equipment that can be hung on my clothes or buckled on the shoulder strap of the SCBA. Often special tools are brought into the workplace only on special occasions; most of the tools are in the fire truck.

Boundary

Technology accessibility
I often use some electronic equipment to detect the environment or to navigate, and I can master the operation of technical products.

Price
I think my department is willing to buy new expensive equipment if it makes work safer.

Behaviour

Autonomy
I need to be able to assess the situation and make my own decisions flexibly and quickly on the specifics of the incident. I train in this ability in firefighter school by simulating fires.

Team
I have teammates and we will walk together and perform missions collaboratively.

Pains

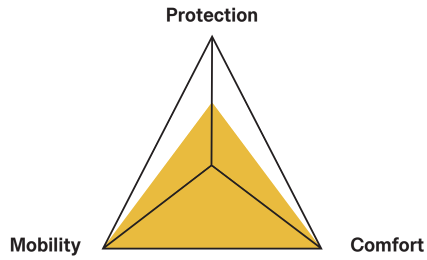
Communication
We use radios to communicate and detect the positions. However, wearing a helmet and mask, the sound of breathing and various noises on the fire scene made it difficult for me and the commander to hear each other clearly.

Weight
I have the heavy equipment and tools on my back and body.

Visibility
My flashlight only provides about 50cm of visibility in the foggy environment and I could not even see my hands.

Through the analysis of current firefighting equipment, it has been found that they are designed to prioritize protection, which results in compromises to the two key factors of mobility and comfort. Subsequently, questions related to these three design factors for firefighting equipment were answered first-hand by firefighters during interviews. The compromises and priorities of these elements are depicted in the following diagram. (illus.15)

" While protection is undoubtedly crucial, I prioritize mobility and comfort. Gear that hinders movement can affect my mission and hinder escape in a fire. If a device is uncomfortable, I might avoid using it, even in high-risk situations. "



illus.15: Three key design elements of firefighting equipment_2

How much does firefighter equipment weigh?

If Peter works as a craftsman, according to At-guideline D.3.1., he might lift a maximum of 20 kg close to the body and may walk a maximum of 20 m with the load. One step = 1m. According to AT, the transport route must be level, tidy and well lit. The surface must be stable and not slippery. Now, peter needs to put on his equipment to carry out the mission.

Peter now puts on his fire suit, boots, helmet and radio in his pocket, and is now weighed down by 9.6 kg.

With the SCBA (11.6 kg), the weight impact is now 21.2 kg. The light and thermal camera for searching people are not included (approx. 2 kg).

In the high-rise package, Peter has to carry up two hoses (17.2 kg), which are now weighted with 38.4 kg.

Peter brings a door hammer (14.4 kg) to open any locked doors. He now weighs 52.8 kg.

illus.16: firefighter equipment weigh

Sum up

Firsthand key information is obtained through user interviews, including user goals, key behaviors, and their pain points. Furthermore, the project's development will not be overly restricted by the introduction of high-end technology and price. This information serves as a foundation for the project's development.

- Fire response timeline.
- Standard for firefighter equipment.
- Firefighting team and fire scene scenario.

- Firefighters have a certain degree of autonomy in decision-making.
- All of a firefighter's equipment is portable.
- Very heavy equipment that firefighters need to wear.
- Visibility at a fire scene is extremely low.
- Communication devices between firefighters and commanders do not work well.
- Mobility and comfort are very important to firefighters.

1.5 Fire response timeline

Through research on firefighting response, combined with interviews of firefighters, visits to fire departments, and personal participation in actual firefighting responses, the entire firefighting response timeline and corresponding scenes and actions for each time segment are listed on the right page. It is important to note that this is a standard timeline, and the actual order of actions may vary depending on the specific incident. Additionally, the entire timeline includes some detailed action scenarios. Some important details from each scenario are elaborated on below.

Fire response

Call processing time is the duration from receiving the call to dispatching the first unit, including alarm answering and processing time, ending when the assigned unit's alarm goes off. Turnout time is the time from dispatch until a unit changes its status to "responding," as firefighters put on PPE and leave the station. Travel time, or First Engine Arrive on Scene Time, is the duration from a unit's response until its arrival on scene.

Fireground

On the fireground, before the oxygen supply in the SCBA cylinder is exhausted, firefighters must leave the hazardous environment to replace or refill the cylinder to avoid inhaling harmful substances or experiencing oxygen deficiency. Typically, SCBA cylinders can be used for **15 minutes to 60 minutes** or longer. However, the actual usage time may be shorter due to factors such as increased breathing rates during intense physical activities and the need to maintain a safety buffer to ensure the wearer can safely exit the hazardous environment (Chase, 2023). Additionally, SCBAs are often equipped with an oxygen monitor (illus.17), and firefighters are trained to monitor the air supply and work within the limitations of the equipment.

illus.17: oxygen monitor

Overhaul

Overhaul is one of the final steps in the firefighting process. A report on counting activities that injured firefighters states that **8%** of firefighter injuries are caused by overhaul activities (Campbell, 2022). The significant number of injuries during this period indicates that the danger is not only limited to the environmental threats inherent to the fire scene but also depends on whether firefighters wear complete personal protective equipment (PPE) correctly (Feisty, 2013). As a result, an important factor that has been noticed is the potential **low compliance** of some firefighters.

Researchers found the leading reasons for low-compliance with PPE usage are:

During Overhaul

- **Limited awareness or training:** Some firefighters may underestimate the risks of the overhaul phase, believing the danger has passed and not feeling the need to wear full PPE. Additionally, firefighters without adequate training on the importance of wearing full PPE are more likely to wear PPE incorrectly.
- **Fatigue, discomfort, or inconvenience:** Firefighters may be fatigued after long hours of work and may remove parts of their PPE to feel more comfortable.

Other situations

- **Firefighter identity:** Adherence to group cultural norms (e.g., being a "real" smoke-breathing firefighter) instead of following established safety standards.
- **Goal seduction & time:** In certain situations, firefighters prioritize being "first-in" over their own safety, e.g., violating driving protocols or not taking time to put on PPE to reach the incident more quickly. (FireCompanies, 2017)

Sum up

The entire timetable for firefighters facing a fire is presented, providing a more comprehensive overview of the scenarios and actions involved in their firefighting tasks.

- **Low-compliance with PPE usage.**
- **Firefighters have only an extremely short time to put on their equipment.**

FIRE RESPONSE

illus. 18

illus. 19

illus. 20

1. Call processing time
120 sec (95%)

2. Turnout time
60 sec for EMS;
80 sec for fire responses

3. Travel time
240 sec (90%)

FIREGROUND

illus. 21

illus. 22

illus. 23

4. Search
Firefighters Enters fire site to search buildings.

5. Rescue & Evacuate
Rescue and evacuate trapped or injured persons.

6. Extinguish
Fire source extinguishment operations.

AFTER THE MISSION

illus. 24

illus. 25

illus. 26

7. Overhaul
Return to the fireground, check and make sure all fire sources are extinguished, and eliminate any potential hazards.

8. Cleaning equipment
Collect the equipment in a dissolvable washing bag for cleaning.

9. Body clean
Clean the body and change into a clean uniform on a fire truck or at a fire station.

1.6 Fire scene scenario

Composition of a firefighting team

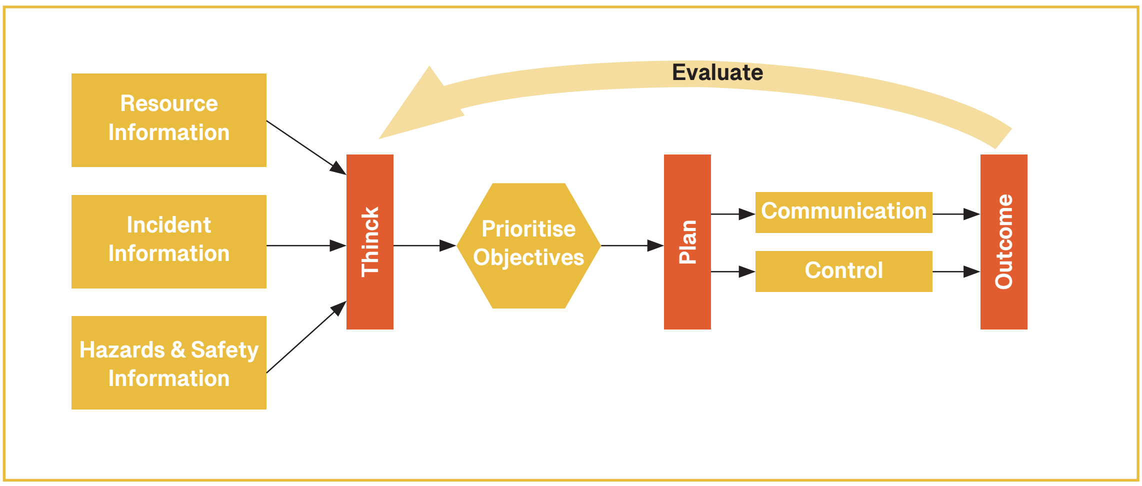
A firefighting team typically consists of 3 to 6 firefighters, depending on the department's staffing and operational guidelines. The team usually includes an officer who also assumes the role of **Incident Commander (IC)**, critical in managing and coordinating emergency response. They have extensive experience and training in handling emergencies.

The remaining members may have specific roles such as **driver/engineer**, who operates the fire apparatus and pumps, and firefighters, also called **smoke divers**, who perform various tasks, including fire suppression, search and rescue, and ventilation. There are usually at least two smoke divers who will always be walking together and doing these tasks in tandem, one of them being the host, which means, they always have teammates on the fireground. If someone on the team says he has to go out, the rule is that everyone else has to go out at the same time.

Incident Command Responsibilities

The Incident Commander remains at all times responsible for the overall management of the incident and will focus on the command and control, deployment of resources, tactical planning and coordination of the sector operations and running the incident itself, while ensuring the safety of the firefighters involved. In command, they rely on a number of other people to give them up-to-date information about what is happening in all areas of the incident. Afterwards, the Incident Commander can create a plan for tackling the incident based on this collected information. Thus, the IC must establish effective arrangements for communications. Information is one of the most important assets on the incident ground; information must be gathered, orders issued and situation reports received.

The figure below is the decision-making model of the incident commander. It is a cyclic process control model that assists commanders in achieving their operational objectives. (illus.27)



illus.27:Managing Incident: Decision-making Model

Some critical information include:

- **Incident information:** The type and the size of the fire, its spread, and the potential for escalation.
- **Resource information:** The number and type of personnel, equipment, and apparatus already on the scene, as well as those en route to the incident.
- **Hazards & Safety information:** Life safety of firefighters and trapped persons; potential hazards and risks such as nearby chemical storage, hazardous materials, or environmental concerns.

As shown in illus.27, the incident commander must be able to assess the incident priorities to determine the strategy and tactics that will be used. The incident priorities are simple and straightforward:

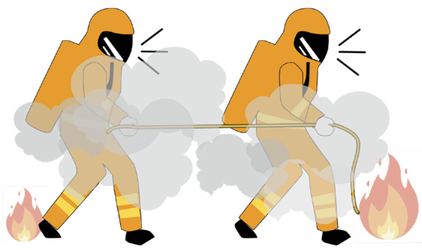
1. Life safety
2. Incident stabilization
3. Property conservation

These three priorities are in rank order and must always be addressed in this fashion and must be considered at all types of incidents.

Communication on the fireground

Effective communication between firefighters and incident commanders is critical to successfully managing fire incidents and ensuring the safety of all involved. Regular updates on the fire situation are necessary for the incident commander to maintain a comprehensive understanding of the incident, allowing them to assess, analyze, and relay pertinent information to the firefighters for strategic decision-making. Besides, the incident commander often receives vital information from **Command Support**, a senior fire officer who provides guidance and assistance. This allows for collaborative discussion of tactics. A monitoring officer, while not always required to be physically present at the incident, can contribute valuable advice through radio communication. Their presence is especially critical when specific risks arise, such as potential danger to the public. (illus.28)

Some communication methods are listed below, and the illus depicts the communication scenario on the fire ground:



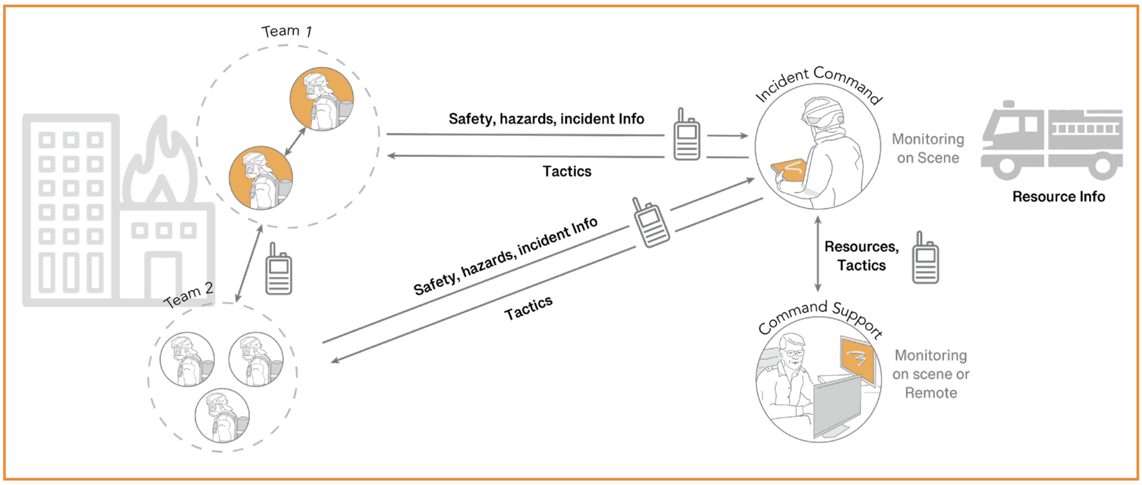
Within a team

Face-to-face:
Firefighters within a team speak directly to teammates.

Signals and visual cues:
- Hand signals
- Rope
- Tag
- Flashlight signals

Overall fireground

Radios: Firefighters use portable radios as the primary means of communication during an incident. These radios typically operate on specific frequencies or channels, allowing different teams of firefighters to communicate with each other and with the Incident Commander (IC).



illus. 28: Fireground communication

Sum up

Firefighters and commanders have different sets of information and must communicate with each other. Despite the current shortcomings of the Land Mobile Radio (LMR), it remains a necessary and sole solution for real-time communication of critical information.

- Their current radio system cannot be affected by other means of communication.

Project overview

Project background
Firefighters face a high degree of danger when performing their duties. While protecting the safety of lives and property, their personal safety is equally important. They need to race against time, responding quickly and effectively to various situations. This project aims to design a product that does not interfere with the work efficiency of firefighters and improves their safety on the fireground.

Problem definition
Firefighters wear personal protective equipment and carry electronic devices to mitigate threats in fire situations, enabling them to perform their duties more efficiently and safely. However, these devices sometimes fail to function correctly. The problems with these devices are framed below in two key points.

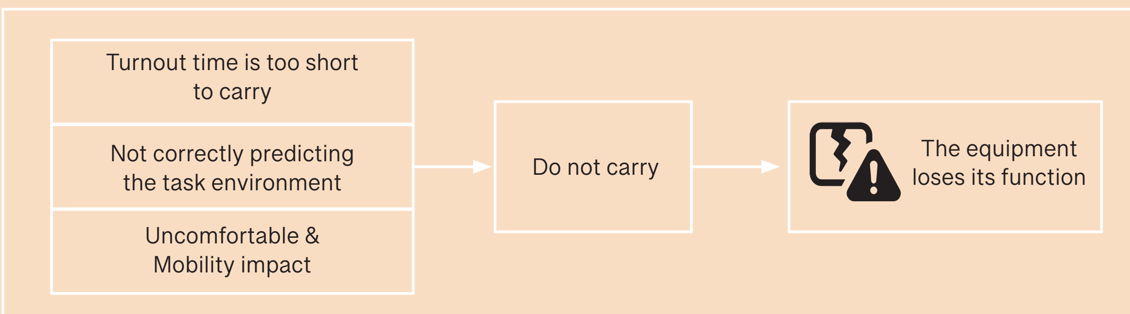
A potential solution is to integrate functional devices into firefighters' current personal equipment systems, ensuring their functionality is always available when needed without adding wear time and hassle to carry.

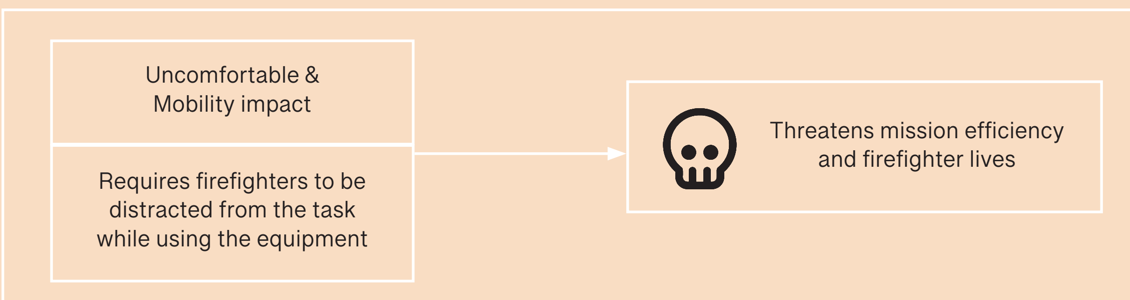
Project scope
The project will first focus on improving the safety of firefighters when they are executing tasks on the fireground, which is the most risky and fatal part of their responsibilities.

Target group
The project is looking at a global target audience encompassing all firefighters who share similar tasks and the common need for enhanced work safety. Therefore, the age range of our user group is expected to be from 16 to 65, including both males and females.

Challenges
The project faces multifaceted challenges. The complexity of the fireground environment is difficult to fully comprehend. Creating and executing real testing environments might pose significant hurdles, and the expectation of an outcome being a tech-integrated smart product raises the bar for achieving a fully functional prototype.

Business potential
Available data shows that there are approximately 1,063,400 active, volunteer, and paid firefighters in the United States and around 365,000 professional firefighters employed in the EU. This considerable user base quantifies the potential impact of our project. A product that innovatively integrates high-tech technologies can penetrate this enormous market through a blue ocean strategy.





Design brief 1.0

Vision

Firefighters can perform fireground missions more safely

Problem statement

How to develop a solution that can help reduce the risk of casualties to firefighters during fireground operations, without compromising their duty efficiency?

Design criteria

Based on preliminary research and understanding of the project background, some design requirements have been collected and organized as follows, with their sources traceable to the cited pages. These may be validated, become obsolete, or be redefined as the concept evolves. The final, refined product requirement list will be updated accordingly.

The solution should

Cover the entire user group of firefighters.	P11
Be able to handle the special threats of structural fires (Confined spaces, complex layouts and structural collapse).	P12
Not affect the integrity of the protection of existing firefighter protective equipment.	P16
Not require firefighters to be distracted to operate it while on duty.	P17
Be compliant with Personal Protective Equipment standards.	P18
Give firefighters some autonomy in decision-making.	P18
Maintain functionality in low visibility conditions.	P18
Reduce dependence on their radio system.	P18
Be portable by firefighters.	P18
Not add much weight to the firefighter.	P19
Be comfortable.	P19
Not impact the mobility of firefighters.	P19
Not increase the turnout time.	P20
Not impact their current radio system.	P23


10

IDEATE

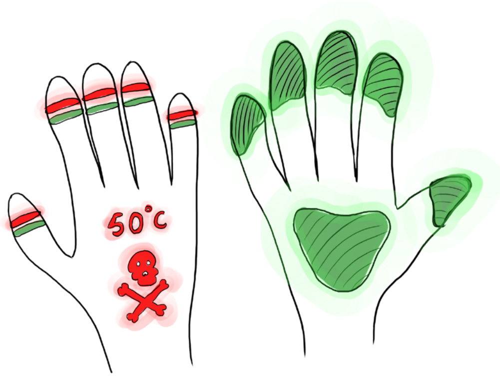
This chapter carries out several rounds of idea generation based on collected design guidelines and the delineation of problem areas. It employs inspiration and brainstorming methods, and uses sketches and mock-ups to visualize and materialize ideas, thereby aiding in obtaining key insights from users. Additionally, market analysis and firsthand observations are conducted to navigate the concept direction. The phase concludes with a design requirement list.

illus.29

2.1 Concept synthesis 1.0

Ideation Round 1

With the design criteria collected in the first chapter, the first round of ideation activities is launched, focusing on adhering to two core goals: the first is to free up both hands, and the second is not to increase the turnout time. Based on user interviews and the current price level of firefighting equipment, concept development will not be particularly limited by technical and cost constraints. As a result, some ideas are generated and visualized through sketches. They all share the common feature of integrating technology capable of addressing certain fire scene environmental threats into the current personal protective equipment system of firefighters. It should be noted that this round of concept creation is carried out before the technology search, with the aim of not being hindered by the feasibility of the technology and more likely to achieve radical innovation. Therefore, during the concept evaluation stage, the feasibility of technology will also be one of the evaluation factors. At the same time, various technologies that have the opportunity to be introduced into firefighters' equipment to enhance their work safety are studied.



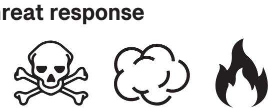
illus.30: Concept 1

illus. 31

Concept 1

Firefighter protective gloves capable of detecting various environmental threats. When it detects high temperatures, toxic gases, and harmful substances, it can alert firefighters through some indicator lights and images. By providing a reactive protection method, firefighters can gain a clearer understanding of the fire scene environment, enabling them to take appropriate action to avoid injury, such as avoiding touching surfaces with detected toxic substances. In addition, firefighters can use arm movements to pre-detect environmental conditions before their body enters the area. (illus.30)

Threat response



Inspiration source - observation

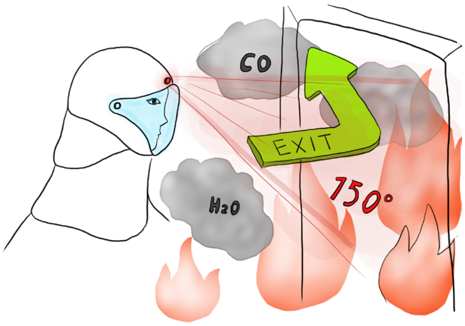
Firefighters often need to use their hands to perform many tasks, so their hands come into contact with various substances. Moreover, the hand is the most flexible body part, and some hand movements can increase the contact range of firefighters in the environment. (illus.31)

Technology

Indicator lights, temperature sensors, hazardous substance sensors, gas sensors.

Evaluation

Firefighter gloves, in order to provide sufficient protection, already use very heavy and thick materials. If these technology components are integrated into the firefighting gloves, it will make them even heavier, making it difficult for firefighters to use their hands to perform any tasks.



illus. 32: Concept 2

illus. 33

Concept 2

An integrated helmet and face mask product for environmental detection and navigation. Firefighters can see various useful information on the face mask, such as building layout, exit locations, various environmental threats, and data analysis. Through proactive protection, firefighters can clearly understand the entire environment in extremely low visibility conditions, such as thick smoke and fire scenes, and have the opportunity to escape smoothly even in buildings with complex layouts. (illus.32)

Threat response

Inspiration source - thermal imaging cameras

Using technology to enable firefighters to navigate and detect information in low visibility environments. (illus.33)

Technology

AR technology, various threat substance sensors, etc.

Evaluation

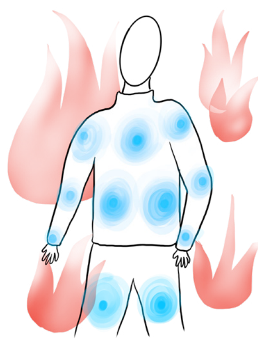
Research shows that the weight of a head-mounted display (HMD) can exceed 600 grams. Integrating it into an already heavy helmet will cause a significant increase in helmet weight and volume. In addition, AR devices have not yet been tested for reliable operation under harsh conditions on the fire scene.

Concept 3

A firefighting suit that can automatically adjust the internal temperature of the clothing based on the environmental temperature. By using a cooling system embedded in the clothing to maintain the temperature inside the firefighting suit, firefighters are protected from the threat of flames and high temperatures, reducing the risk of heat stress. (illus.35)

Threat response

illus. 34



illus.35: Concept 3

Inspiration source - observation

Firefighters face the scorching heat of flames in a fire-filled environment, and an automatically cooling firefighting suit would provide them with better protection. (illus.34)

Technology

Temperature sensors, cooling system

Evaluation

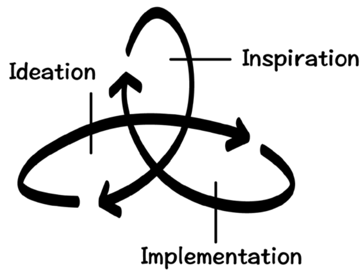
Research shows that integrating liquid cooling technology into clothing will result in an additional weight of 3-7 kilograms and a significant increase in volume. This will lead to a bulkier firefighting suit, placing a greater physical burden on firefighters and hindering their movement.

Sum up

Through this round of ideation, it is found that the likelihood of realizing some far-fetched ideas without an assessment of technical feasibility and opportunity is very low. It is important to note that when integrating technology into firefighters' personal protective equipment, the focus should be on the volume and weight brought by the technical components, as well as the ability to accommodate new technologies without affecting the original protective functions of the equipment. Moreover, the fire scene environment needs to be further studied to understand the possibilities of technology being applied in the field.

Ideation Round 2

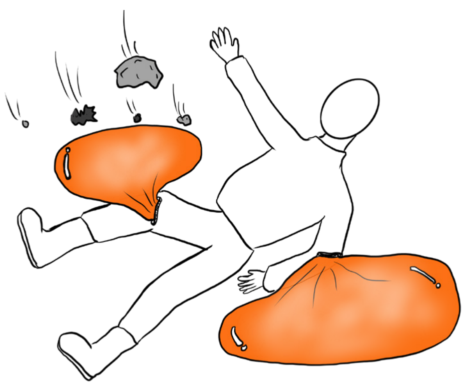
In the second round of idea generation, the focus is on "hiding" the product within the firefighters' existing personal protective equipment and addressing other environmental threats at the fire scene that are not covered in the first round of ideation. Moreover, in this round, the core activities of design thinking are employed - an iterative approach of inspiration, ideation, and implementation (Brown, 2008) (illus.36). Since the inspirations in the first round are all related to the fire scene itself, this round use creative thinking to "borrow" solutions from outside the project context. In addition, the solutions are externalized not only through sketching but also through the creation of mock-ups and received feedback from the primary users - the firefighters - to help evaluate the concepts.



illus. 36: 3 Core activities of design thinking

illus. 37

Inspiration - Airbag
An airbag is a passive safety device designed to protect vehicle occupants in the event of a collision. It consist of a flexible fabric cushion, an inflation module, and various sensors that detect impacts. In the event of a collision, the sensors trigger the inflation module, rapidly filling the airbag with gas to create a protective barrier between the occupant and the vehicle's interior (Bellis, 2019) (illus.37).



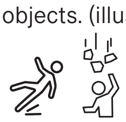
illus. 38: Concept 1

illus. 39

Concept 1

Inflatable cushions are embedded in multiple positions of the firefighter turnout ensemble. When the firefighter falls, or when objects fall or splash that may hit the firefighter, the corresponding air cushions on the coat will automatically inflate, providing a protective buffer for the firefighter and preventing injury from falling objects. (illus.38)

Threat response



Mock-up test
Using balloons to simulate the inflatable cushions, users can experience the feeling of the cushion blocking contact with surfaces with both eyes open and closed. (illus.39)

Feedback
“ **Positive**

- The air cushion can effectively block my contact with some surfaces and falling objects, and I believe it can also provide protection when I fall.

Negative

- The sudden release of the air cushion may hinder my subsequent task execution and movement.
- The release of multiple air cushions may cause me to feel squeezed while working in an extremely confined space. ”

illus. 40: Deformation roller shoes

Inspiration - Deformation roller shoes
Deformation Roller Shoes are designed for convenience and versatility. They are innovative hybrid footwear that combines the functionality of traditional shoes with the excitement and mobility of roller skates. These shoes feature a retractable wheel system, which allows the user to switch between walking or rolling modes with ease. However, users need the practice to master balance and coordination (Deczynski, 2021) (illus.40).

illus. 41: Concept 2

illus.42

Concept 2

Some flexible, fine teeth in various shapes and materials are embedded in the sole of the shoe. By monitoring and analyzing the type and condition of the ground, the corresponding fine teeth will automatically pop out to change the pattern of the sole. In this way, the shoe's performance on that surface is improved, thereby reducing the likelihood of firefighters falling. (illus.41)

Threat response 

Mock-up test
A sole assembled from different shapes of saw teeth is presented to the user, helping them understand the concept. (illus.42)

Feedback
" **Positive**: I believe that different materials and shapes of textures can enhance the grip of the sole.

Negative: I think I would need some time to adapt to the new sole, as a sudden change in the sole might affect my balance and cause me to fall due to not being used to the new sole texture. "

Sum up

The second round of concepts addressed two additional threat risks that are not considered in the first round, and by quickly testing mock-ups with the user, firsthand feedback including key insights is obtained, allowing for a rapid assessment of the concepts.

After two rounds of brainstorming, it is found that all concepts aimed to reduce firefighters' casualty risks by addressing one or multiple environmental threats in fire scenarios, and the approaches included threat detection. Most of the outputs are relatively out-of-the-box ideas with low feasibility. Upon reflection, the possible reasons for this could be an incomplete analysis of available technologies and insufficient learning about existing market solutions. Therefore, it is necessary to further research some new existing solutions. Additionally, by examining the outputs of these two rounds, it may be necessary to view the problem from another perspective and reframe the solution space.

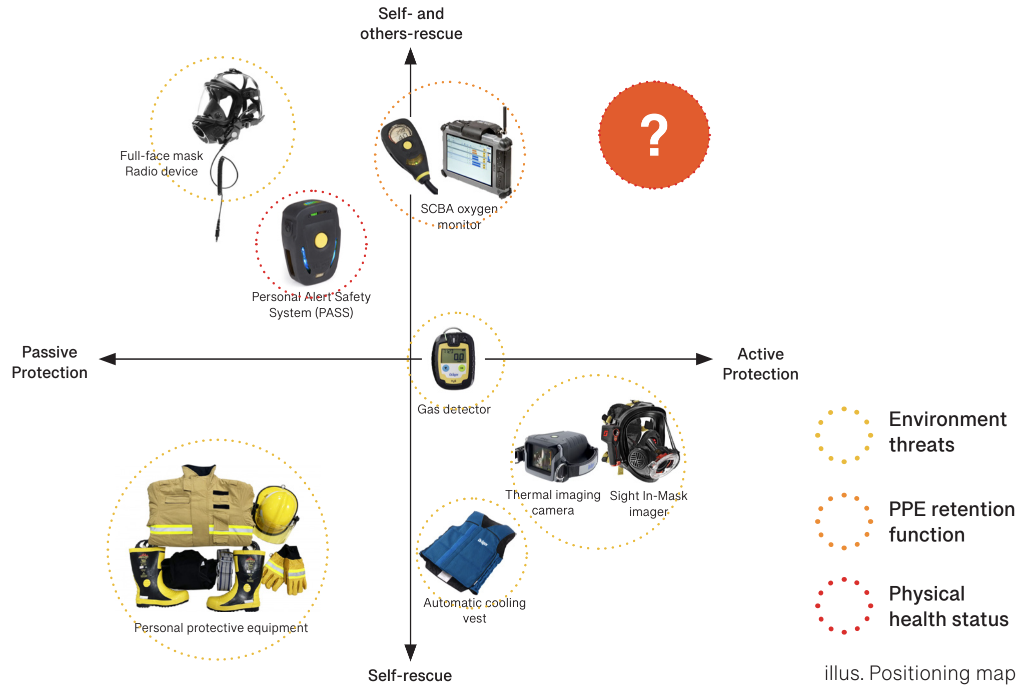
However, from these resulting concepts it is possible to note that the automatic operation of the equipment is a possible solution to avoid distraction of the firefighters from the task.

- The equipment works automatically to avoid distracting firefighters from the task.
- These ideas concern only the individual firefighter and do not take into account the entire team.

2.2 Positioning

Market gap

In order to further develop new concepts, other existing market solutions for enhancing firefighter safety through advanced technologies are explored, and together with the previously identified equipment, are placed on a positioning map. The two types of protection and two types of rescue identified in Chapter 1 are used as two pairs of key attributes to categorize and position these solutions, with the goal of finding opportunities for new concept development from market gaps. Through a systematic analysis of these devices, it is found that the solutions involved could be classified into three main categories because they are designed to address different risks threatening firefighter safety. These three categories are marked in the chart below with different colored circles. In addition, a market gap is identified and marked (illus.43).



illus. Positioning map

illus.43: Positioning map

New equipment with state-of-the-art technology

illus.44

Dräger FPS ® -COM 5000
By integrating a radio system into the face mask, firefighters' hands are freed, while digital noise reduction technology filters out any interference or potential feedback that may reach the microphone inside the mask. This allows firefighters to communicate with commanders without any disturbance, even in the noisiest environments (Dräger, 2023d).

illus.45

3M™ Scott™ Sight In-Mask Thermal Imager
Advances in thermal imaging technology have now shrunk the size of the components. Scott Sight's revolutionary design integrates a lightweight camera and a tiny display in the firefighter's mask, allowing the thermal image to be always visible, with hands-free operation (Gigazine, 2017).

illus.46

Dräger Comfort Vest
The cooling action of the vest is derived from 20 individual PCM elements (Phase Change Material) integrated into the inner lining. At a skin temperature of 28 °C, the content of the PCM elements gradually become liquid by absorbing the excessive heat. This reduces skin temperature by approx. 3 – 4 °C (Dräger, 2023e).

Reframing

With the market gap identified, this can be seen as an opportunity for new concepts. Therefore, the next round of ideation activities intends to focus on this gap. Before that, it is necessary to have a more explicit understanding of this gap to be able to reframe this new solution space.

Self- and others-rescue

For firefighters, self-rescue and being rescued by others refers to the importance of self-protection and teamwork in dangerous and often unpredictable firefighting environments. This means that firefighters and their team need to be aware of risks and take appropriate measures to protect themselves and their colleagues. Therefore, the key aspects of this concept are the following two points:

Self situational awareness

Firefighters must be constantly aware of their surroundings and the ever-changing conditions of a fire scene. This helps them make wise decisions, anticipate risks, and avoid putting themselves and others in danger.

Effective communication & teamwork

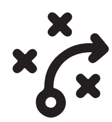
- Team members need to be aware of each other's condition so they can rely on each other for support and rescue when necessary.
- Commanders need to keep abreast of the condition of firefighters in order to adjust strategic deployments and, where possible, deploy Rapid Intervention Teams (RITs) to rescue trapped, injured, or disoriented firefighters in emergency situations.

Active protection

Compared to passive protection, active protection focuses more on the approach and timing of risk management, rather than the specific protective measures themselves. The active protection can include both proactive and reactive forms, which involve conscious efforts and actions taken to manage risks, hazards, and potential threats (Bandara, 2023). The following are key differences between the two approaches to active protection.

Proactive protection

Proactive protection involves anticipating potential risks and taking preventive measures to minimize or eliminate them before they can cause harm. This approach focuses on planning, preparedness, and prevention.



Reactive protection

Reactive protection involves responding to risks, hazards, or threats after they have occurred or become imminent. This approach focuses on mitigation, containment, and recovery.

Sum up

Through a more comprehensive market analysis, it is realized that previous concept creations were limited to solutions aiming to improve firefighter safety by responding to fire threats alone, overlooking other problem areas and thus limiting the solution space.

According to the market positioning of the current solution space, whether it is proactive or reactive protection, and no matter what type of threat risk response, a new solution needs to be able to monitor and communicate the monitored information to the firefighter's teammates and the incident commander.

- Three risk response strategies to enhance firefighter safety are identified.
- Solution-framing: Improve firefighter safety by monitoring life-threatening risks and conveying this information to the team.

2.3 Concept synthesis 2.0

Among identified three types of risks, environmental threats and physical health risk factors have already been clarified in the first chapter (Section. 1.1 and 1.2). Therefore, the risk factors related to maintaining the functionality of PPE is studie. It should be noted that since there are already solutions on the market for monitoring the oxygen function of SCBA equipment, possible concept development opportunities will be aimed at other personal protective equipment, such as helmets, fire suits, gloves and boots.

PPE retention function

Through research, it has been discovered that firefighters' personal protective equipment may not maintain functionality for various reasons, posing a threat to their life safety (NIST, 2016). Three main reasons are summarized as follows:

Abrasion and damage

Regular use, harsh conditions, and exposure to high temperatures and hazardous materials can weaken the materials. Additionally, punctures, cuts, or abrasions can damage the equipment's integrity, reducing its ability to protect the wearer.

Improper maintenance

Firefighter PPE requires proper maintenance, cleaning, and inspection to ensure it remains in good working condition. If not maintained appropriately, the equipment's performance may be affected.

Low compliance

If firefighters are not using and wearing personal protective equipment correctly, the equipment will not be able to perform its intended functions. (Causes can be found in Section 1.5)

From the listed risk factors, it can be identified that in a fire scene, the most promising risk management strategy involves monitoring equipment abrasion and damage. The major consequences for damaged equipment can include heat, smoke, or chemical infiltration. A potential solution is embedding sensors in the inner layers of various equipment to monitor environmental threats. However, this may create bulkier devices and impact mobility, the same issue faced in the first round of ideation. It especially negatively impacts highly flexible equipment like gloves.

Further evaluation revealed that firefighter suits might be the best option, as they cover most of the body and can distribute weight and volume of the various monitoring systems, minimizing the negative impact on firefighters' mobility.

Mock-up test

A mock-up is created, but it is realized that several different types of sensors need to be connected to a host for programming, data collection and power supply etc. Therefore, the mock-up consists of multiple sensor pods wired to a host pod and tested with the user. (illus.47)

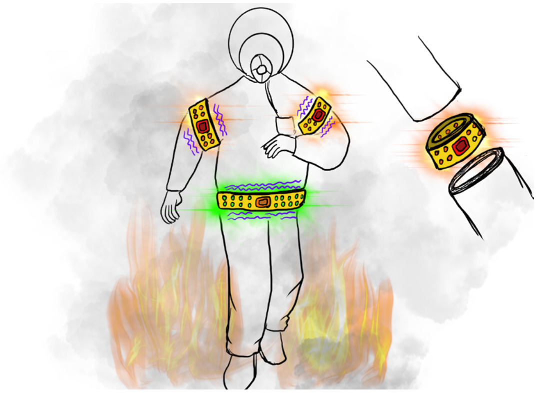
Feedback

“ **Positive:** This distributed approach does help to even out the weight and volume of the equipment.

Negative: It looks complicated and feels difficult to manage, I think some connecting wires should be avoided. ”

illus. 47

Two directions



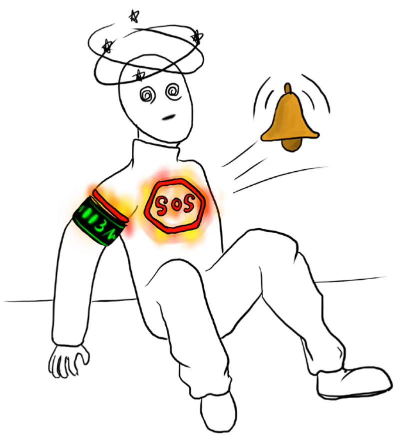
illus. 48

Direction 1 - Reactive protection

Concept

Three integrated ring-shaped devices are embedded in the two arms and waist area of the firefighter suit. Both the inner and outer layers of the devices serve as monitoring functions. The device part on the surface layer of the suit detects environmental threats, while the inner layer of the device part monitors the environment inside the suit, thus checking for any damage to the suit. When the device detects abnormal environmental conditions, it alerts the firefighter through flashing lights and vibrations. The flashing lights can also draw the attention of fellow firefighters, allowing them to provide support and assistance. In addition, incident commanders outside the fire scene can receive real-time data from all monitored devices. (illus.48)

Response: environmental threats, PPE retention function



illus. 49

Direction 2 - Proactive protection

Concept

The firefighter suit is embedded with a vital signs monitoring system, screens, and indicator lights. When firefighters wear the suit, their health status is monitored in real-time, and the data collected is transmitted to the incident commander outside the fire scene. Additionally, the screens on the suit display monitoring results of the firefighter's vital signs. If a firefighter's physical condition becomes problematic, warning lights will appear on the suit and an alarm will sound, alerting fellow firefighters to initiate a rescue. (illus.49)

This concept is defined as proactive protection based on the assumption that a firefighter's vital signs will change before injury or death occurs, thus preventing casualties by monitoring these signs.

Response: Physical health status

Sum up

A new round of concept synthesis is carried out. Two concept directions are ultimately created targeting the three identified risk response strategies. The first is a reactive protection scheme that monitors environmental threats and equipment function retention. The second is a proactive protection scheme that monitors the vital signs of firefighters. However, the second direction is based on assumptions that require further research to understand each type of injury and the timeline it takes from injury to death. Moreover, it is necessary to figure out how the monitored information is transmitted to the firefighter's teammates and the commander.

- The way of the monitored information is conveyed.
- Timeline of firefighter casualties on fireground.

- The solution should be embodied as much as possible in an integrated product.
- The equipment needs to be maintained.
- The equipment needs to be durable enough to withstand the wear and tear on the fireground.

2.4 First-hand observation

In order to evaluate, select, and develop concepts, participation in alarm missions and training is carried out, and many subtle and important observations are collected (app.2). Some key observational details combined with the answers to interviews with firefighters are summarized below, according to the timeline of fire scene responses.

illus.50: Observations

Observation

Alarm

While having breakfast, the firefighters respond to the alarm, hurriedly don their PPE in under 60 sec, and prepare to depart on the fire truck. PPE is set up for quick dressing; for instance, gloves are attached to jacket hooks, and pants are prepositioned over boots.

Travel time

The tight space in the fire truck's back seat restricts stretching.

Fireground

Before executing their duties, firefighters and commanders familiarize themselves with the incident details and strategize in the command room. The room displays the fire location and building layout on screens.

- **Communication**

During task execution, the commander communicates with firefighters using a Land Mobile Radio (LMR). He remains unaware of the building's internal situation until a firefighter relays information via radio. Although the current radio system is not working well, it is a necessary and only solution for real-time communication of important information.

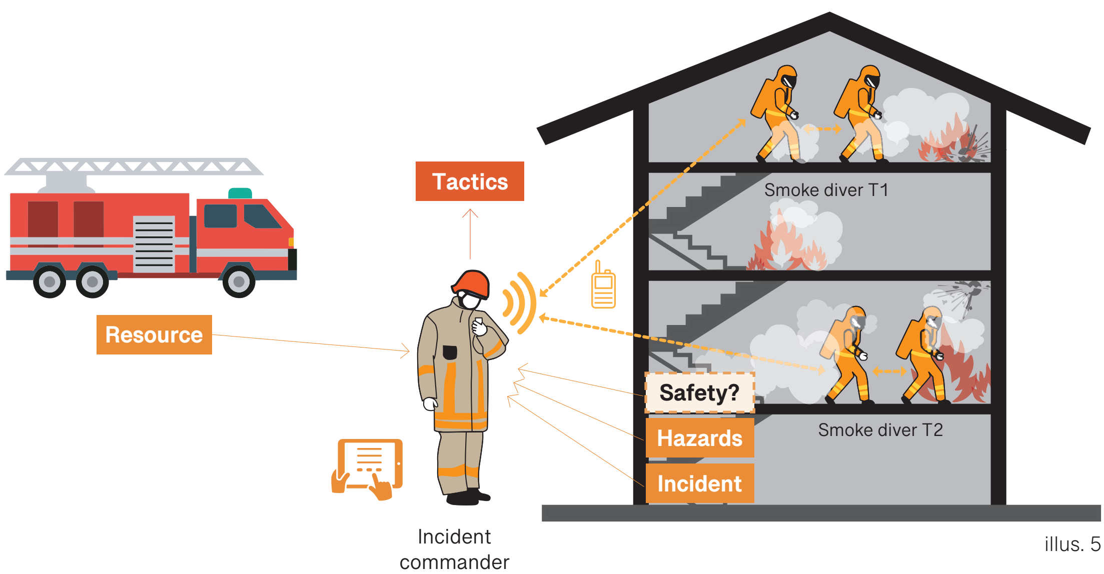
- **Communication content**

Communication between the commander and firefighters primarily revolves around the incident and strategy. Discussion on physical conditions or minor injuries is not common unless a firefighter perceives their limit reached (illus.51). Firefighters are trained to push their boundaries, which boosts efficiency and stamina. However, real fire situations can influence their judgment due to external factors. Hence, it is crucial for the commander to be aware of their vital signs for dynamic strategy and immediate rescue.

Firefighters often make independent decisions post receiving basic instructions from the commander, relying more on their peers at the fireground.

- **Resource**

The commander outside the firegound operates from a command vehicle, noting down structural details, vehicle location, and additional notes on a whiteboard. A tablet is also at their disposal.



illus. 51

Between the missions
The number and timing of tasks that firefighters need to perform are unpredictable. They may need to proceed to a new task immediately after one ends, without adequate rest and recovery time.

In the time between tasks at two sites, firefighters will not take off their SCBA gear, to be ready for the next task at hand. However, the oxygen cylinder on their back causes discomfort while sitting in the rear seat.

They use water and chocolates stored under truck seats for hydration and energy. Moreover, fire trucks are equipped with various tools and devices, available for use when needed.

After the mission
Post non-hazardous tasks, some firefighters remove their upper outer garments on the truck or after leaving the fire scene.

Back at the fire station, they tidy up all the tools used, put them back in their places, clean and charge the equipment. Some consume protein drinks and micronutrient supplements for muscle strength and to replenish lost nutrients by sweating.

illus.52: Observations

Expert knowledge

illus. 53

" Firefighters often face extremely high-temperature environments, such as apartment roofs with 200 or even 300 degrees. They need to get close to the fire source and climb upstairs to extinguish the fire, which makes them sweat profusely. Dehydration affects their focus, decision-making, and increases the risk of injury. Losing 2% of body water can result in a 20% decline in physical condition. Therefore, I always advise them to recover fully before taking on the next task.

In addition, another sign that needs to be aware of is elevated heart rates, which cause fatigue and illness, so replenishing elements like calcium and magnesium is vital (illus.53). These elements are as important as water intake, and help address issues caused by sweating, such as muscle support.

Monitoring vital signs continuously can provide valuable insight into firefighters' physical condition, ensuring timely intervention, which is undoubtedly a huge advantage. On the fireground, detecting a firefighter's compromised physical condition allows for backup, reducing casualties and potentially saving lives. "

- Tommy, fire chief - NOBR

Sum up

The key points summarized show that the need for monitoring firefighters' vital signs is significant and urgent. However, before choosing this direction, the solution space is reflected and it is found that the three types of response strategies proposed in the previous section are interconnected. Whether it is environmental threats or the functional loss of personal protective equipment, firefighters' vital signs can be directly affected and can be reflected in an intuitive, dynamic numerical response. Therefore, this is a result-oriented solution that can reflect all the risks firefighters face on the fireground, thereby having the opportunities to make a larger impact.

- The direction of improving firefighter safety by monitoring vital signs is chosen.

- The physical condition of firefighters is not usually included in fire communication.
- Firefighters often push their limits and may sometimes be unable to make correct judgments about their physical condition.
- Firefighters rely heavily on their colleagues in a fire.
- The commander on the scene uses a tablet.
- Long-term monitoring of firefighters' vital signs is more conducive to making appropriate strategies and personnel deployment.

- Vital signs important to firefighters.

2.5 Concept validation

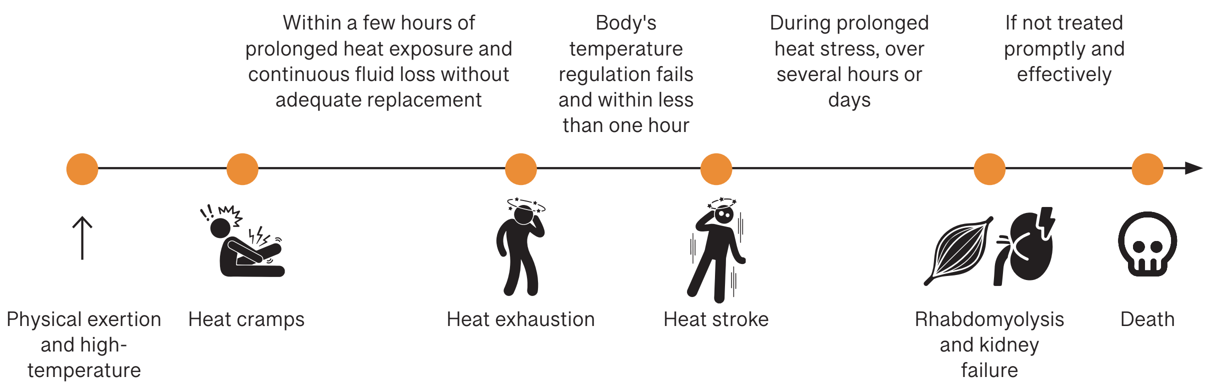
With the selection of the concept of vital signs monitoring, research is conducted to analyze and interpret the working principle of this concept. Firstly, to gain a deeper understanding of which vital signs are key for firefighters, the threats faced by firefighters on the fireground are further studied (app.3). The types of casualties or symptoms caused by these threats and the casualty timeline are drawn, so that the vital signs reflected by these symptoms can be identified. Additionally, another important purpose of the research is to verify the proactive protection features of the concept and find the points or stages at which the product might intervene to help reduce firefighter casualties.

Timeline of firefighter casualties

The timelines of a type of injury very unique and common to firefighters, and two leading causes of death are selected and presented below, reflecting the vital signs identified as important for firefighters. These timelines interpret in detail the stages, states, and physical changes experienced by firefighters from injury to death.

Heat stress

Firefighters face a unique risk of heat stress due to the intense physical exertion and high-temperature environments involved in their work. Moreover, the insulating properties of personal protective equipment (PPE) can inhibit sweat evaporation and cooling, exacerbating the situation (Avsec, 2019). Below is a typical timeline for the progression of heat stress when firefighters are performing tasks on the fire scene (Serban, 2019; CDC, 2020) (illus. 54).



illus. 54

Heat cramps

These are involuntary muscle spasms, usually caused by a significant loss of salt and water, typically through **sweating**.

Heat exhaustion

Symptoms can include heavy sweating, weakness, dizziness, nausea, headache, and a fast, weak pulse.

Heat stroke

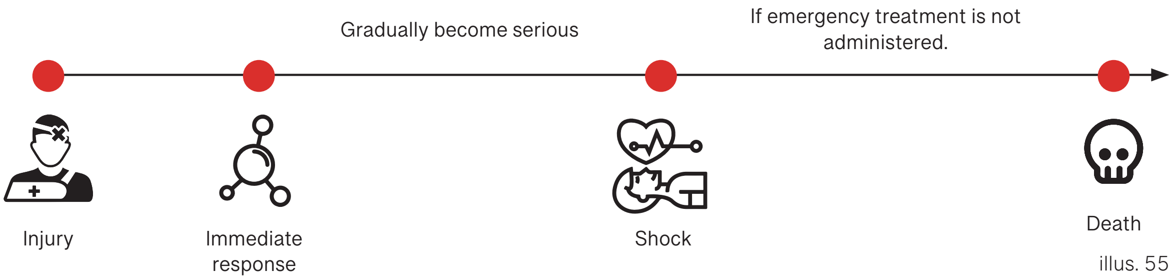
Symptoms may include an extremely **high body temperature**, red and hot skin (but not sweating), **rapid pulse**, headache, dizziness, nausea, confusion, unconsciousness, and even seizures.

Rhabdomyolysis and kidney failure

The body can start breaking down muscle tissue, leading to a condition called rhabdomyolysis. This can result in kidney damage or failure, and brain damage, which can be life-threatening.

Internal trauma

Internal trauma refers to injuries that occur inside the body, often as a result of a severe impact or force, and involve vital organs or internal structures (Timothy, 2020). The general progression of internal trauma from injury to death can be summarized as follows (illus.55). It should be noted that the exact length of time from injury to death in internal trauma can vary widely depending on the individual's physical health and the severity of the injury.



illus. 55

Injury

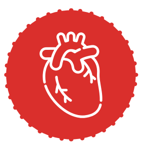
This is the initial trauma, in the context of firefighting, internal trauma could be caused by a fall from a height, being hit by falling debris, or an explosion.

Immediate response

This includes the release of adrenaline (which **increases heart rate to boost circulation**), the clotting of blood to prevent excessive bleeding, and the triggering of pain signals.

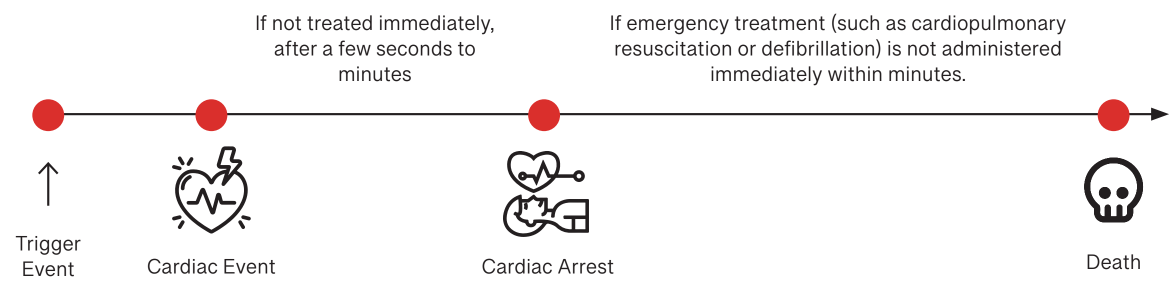
Shock

This is a life-threatening condition that requires immediate medical attention. Signs of shock include **cold and sweaty skin, irregular heart rate, rapid breathing**, dull or glassy eyes, and confusion or loss of consciousness.



Sudden cardiac death

Sudden cardiac death (SCD) is an unexpected sudden death due to a heart condition that occurs within one hour of symptoms onset. Research shows that the leading cause of sudden cardiac death in firefighters is coronary heart disease, a type of underlying heart disease. They face unique threats in their work, including physical exertion, heat stress, exposure to smoke and other toxic substances, and sources of psychological stress, which can exacerbate this disease (Yang et al., 2013). Following are some key stages leading up to sudden cardiac death (Clevelandclinic, 2022) (illus. 56).



illus. 56

Trigger Event

This is caused by usually severe physical exertion or severe emotional stress, but here, it can be caused by any threat on the fireground.

Cardiac Event

Refers to any major cardiovascular event that affects the function of the heart. These events include various conditions, such as a heart attack (myocardial infarction), angina, heart failure, arrhythmia. Possible symptoms include chest pain, **shortness of breath, breaking out in a cold sweat**, or fainting.

Cardiac Arrest

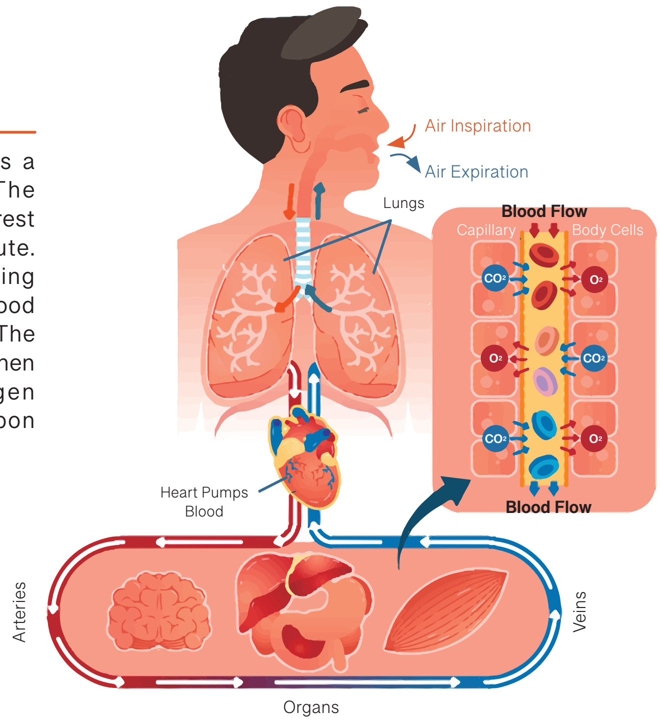
The heart suddenly stops beating effectively and no longer pumps blood, leading to **a lack of oxygen supply** to the brain and other vital organs, causing a loss of consciousness.

Important vital signs

The threats faced by firefighters on the fireground, the casualties or symptoms they cause, and the vital signs they affect, are systematically linked, finding the relationships between all these factors and depicting them in a diagram to provide an overview of all key elements and the reasoning process (Johns Hopkins, 2023) (illus.57; 58). It is worth noting that due to the complex physiological interplay in the human body, various vital signs influence each other, and the relationships indicated by arrows in the diagram are the most direct and significant ones.

Respiratory Rate (RR)

It is the number of breaths a person takes per minute. The normal range for an adult at rest is 12 to 20 breaths per minute. The main function of breathing is to deliver oxygen to the blood and remove carbon dioxide. The respiratory rate will increase when the body needs more oxygen or needs to expel more carbon dioxide, and vice versa.



illus.57:Respiration mechanism (Medictests, 2023)

Heart Rate (HR)

It is the number of times the heart beats per minute. The heart rate of a healthy adult at rest is usually between 60 and 100 beats per minute (bpm). The job of the heart is to pump oxygenated blood from the lungs to other parts of the body. When the body's cells need more oxygen, the heart rate increases to pump more blood, thereby providing more oxygen to the body.

Oxygen Saturation (SpO2)

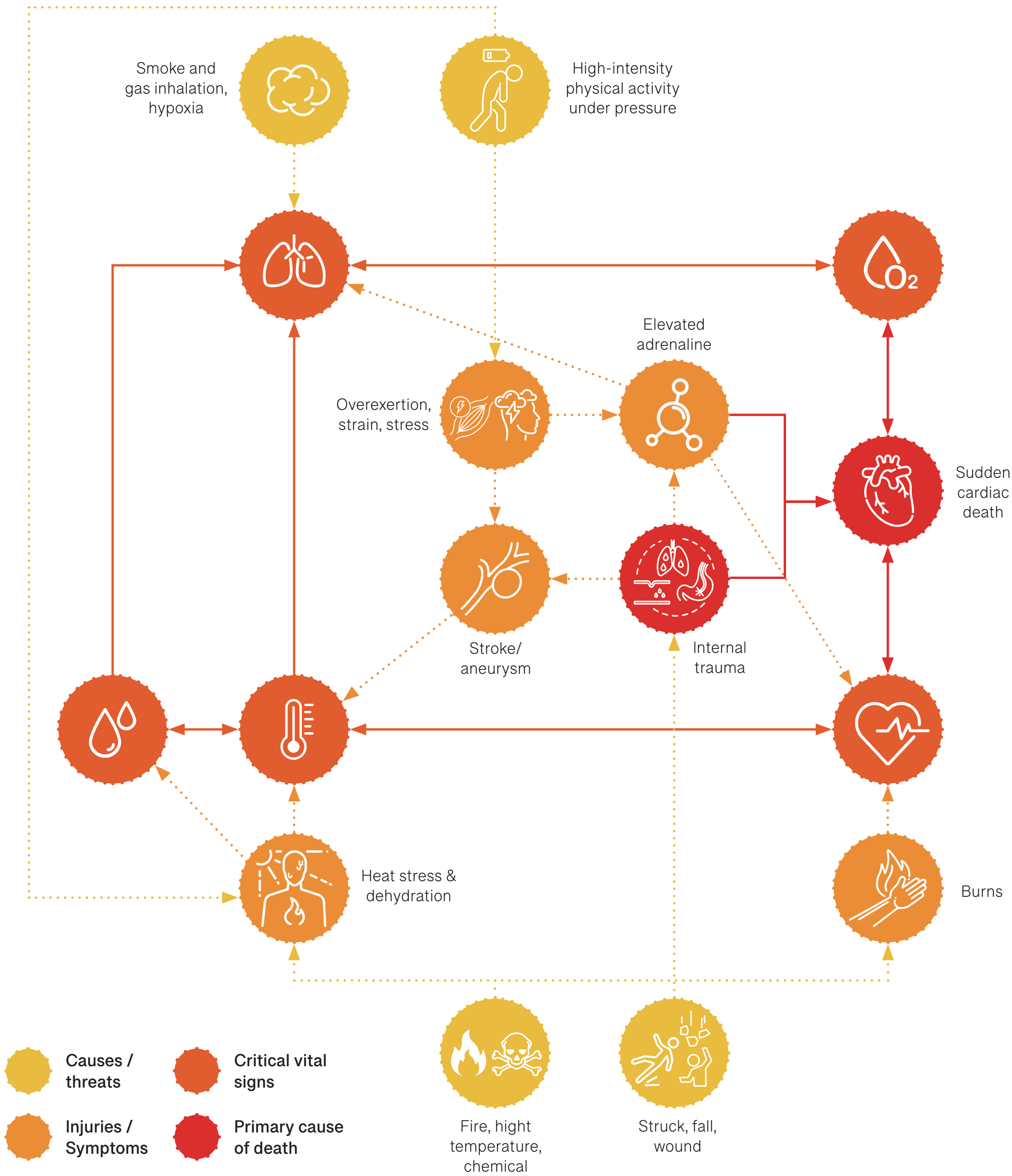
It is a measure of the amount of oxygen carried by red blood cells in the blood. In healthy individuals, oxygen saturation should be between 95% and 100%. It is influenced by the respiratory rate and the efficiency of gas exchange in the lungs. When the respiratory rate increases or becomes more efficient, more oxygen can be absorbed into the blood, thereby increasing the level of oxygen saturation. Conversely, if the respiratory rate decreases or becomes less effective, oxygen saturation will decrease.

Body Temperature

It maintains a relatively constant internal temperature through a process called thermoregulation. Normal body temperature is usually between 36.5–37.5 °C (97.7–99.5 °F). When body temperature rises (such as during a fever or in a hot environment), the heart rate and respiratory rate may increase to help the body cool down.

Sweating

It is the main method of thermoregulation. When body temperature rises, the body produces sweat to help cool down. The evaporation of sweat from the surface of the skin has a cooling effect. However, excessive sweating can lead to dehydration, which causes a reduction in blood volume and an increase in heart rate.



illus. 58

Sum up

The need for vital signs monitoring is confirmed through user interviews and observations. The ongoing research further verifies the significance of this concept and the effectiveness of its proactive protection feature. In particular, the process of identifying important vital signs underscores the necessity for firefighters to receive timely treatment. Research findings indicate that between the stages of injury and death, timely treatment for firefighters can prevent further injuries or even death. Therefore, real-time monitoring of firefighters' vital signs is essential as it provides the possibility of timely rescue. In addition to vital signs, the timeline shows that firefighters' activity levels are also critical, which is one of the important manifestations of their injuries.

- **Important vital signs for firefighters are identified.**
- **Firefighter activity levels need to be monitored.**
- **Monitoring should be real-time.**

2.6 Monitoring technology

With the identification of key monitoring content, the usability and feasibility of the technology are immediately evaluated to confirm the opportunity for concept development. Furthermore, the technology's requirements for specific body positions will also serve as a basis for further development of the concept. This section will present the selection and considerations of technology for these monitoring contents. When technology is being studied and selected, the focus is on several key indicators, including wearability (small size and light components), non-invasiveness, and low energy consumption (app. 4).

Heart rate & Oxygen saturation monitoring

Blood oxygen saturation is a very critical vital sign for firefighters. Research on available technologies shows that very few are non-invasive and can be used in wearable devices. Thus, the method of Photoplethysmography (PPG) is selected, which is the most commonly used and reliable method for non-invasive, continuous monitoring blood oxygen saturation levels.

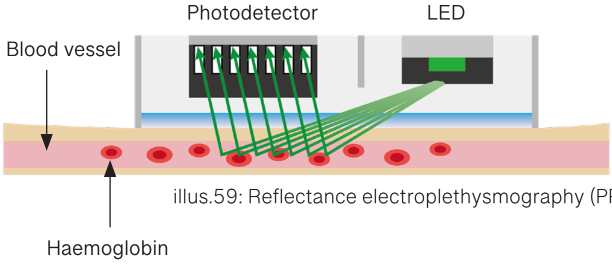
It is a simple and low-cost optical technique that measures the changes in blood volume in the microvascular bed near the skin surface with each heartbeat, based on the optical properties of human components such as absorption, scattering, and transmission at specific light wavelengths. This principle means that the technology can also measure heart rate (pulse rate) at the same time.

PPG devices consist of a light-emitting diode (LED) that emits light and a photoelectric detector that detects the emitted light. The device can be divided into transmission and reflection types based on the positions of the LED and the photoelectric detector.

Transmission Photoplethysmography (PPG)
For the transmissive type, the photodetector is located on the other side of the LED, with skin tissue in between. Since the transmissive type measures the light intensity attenuated after passing through the skin tissue, it is mainly used for measuring PPG at the distal parts of the body, such as fingers, toes, and earlobes, where the skin tissue is relatively thin. In addition, to ensure that the light can effectively penetrate the tissue, the transmissive PPG device must be in close contact and usually needs to be "clamped" on the skin. A loose fit may allow ambient light to interfere with the signal, or the light from the device may not sufficiently reach the detector.

Reflectance electroplethysmography (PPG)
For the reflective type, the photodetector is located next to the LED. The photodiode measures the intensity of unabsorbed light reflected from the tissue in reflective optical measurements (illus.59). In theory, a reflective PPG device can be used anywhere on the body where there is a microvascular bed, and the skin and underlying tissue allow sufficient light to penetrate and reflect. But it is advisable to use it where a good pulse can be detected, and the device can be placed securely and in good contact with the skin. In addition, research shows that excessive pressure applied by the device on the skin can restrict capillary blood flow, thereby reducing the reliability of the measurement. However, there is no specific information about the pressure range that should be applied to the skin for successful measurement. (Park, 2022)

Evaluation
From the perspective of the working principles and requirements of two types of Photoplethysmography (PPG), the reflective type is more suitable in concept. This is because the transmission type is too restrictive in the selection of the body position, and more importantly, it is not suitable for long-term wear. However, research results have discovered that the reflective PPG technology has some pressure requirements for accurate measurement, but this parameter cannot be found through desktop research. Therefore, experiments need to be conducted for this chosen technology to find the specific requirements for successful measurement.



illus.59: Reflectance electroplethysmography (PPG)

- Reflective PPG technology is selected for heart rate and oxygen saturation monitoring.

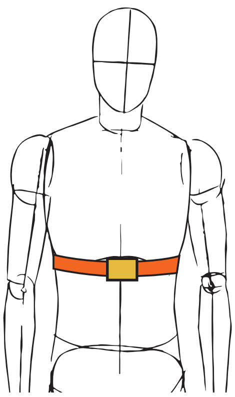
- Feasible body position for PPG technology.
- Pressure requirements for reflective PPG measurement.

Respiration monitoring

While searching for techniques for monitoring respiration rate, it is discovered that Photoplethysmography (PPG) could also be used to measure this vital sign indirectly through several mechanisms (Da Costa, 2019; L'Her et al., 2019):

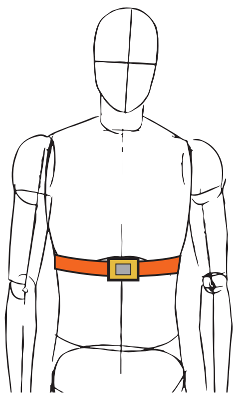
- Respiratory Induced Intensity Variation (RIIV): Respiration affects the cardiovascular system. Inspiration decreases intrathoracic pressure, increasing venous return and thus the PPG signal. Expiration does the reverse, reducing the PPG signal. These changes stem from blood volume variations in the microvascular bed of tissue influencing the PPG signal.
- Respiratory Sinus Arrhythmia (RSA): Respiration impacts heart rate variability. The heart rate rises during inhalation and falls during exhalation, a pattern known as RSA detectable in the PPG signal and useful for estimating respiration rate.
- Impedance Pneumography: Changes in chest or abdomen volume during respiration alter the PPG signal's path length. These changes can be monitored and associated with the respiratory rate.
- Cardiogenic Oscillations: Minor oscillations in the PPG waveform correlate with respiratory activity and can be used to determine the respiration rate.

There are also some wearable sensor technologies specifically for respiratory monitoring (Da Costa, 2019), but generally each technology involves a specific monitoring location, they are listed and described below:


illus. 60

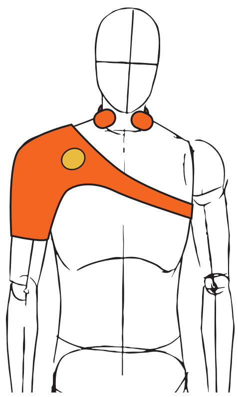
Pressure Sensor

A sensor containing an electromechanical membrane (EMFit) is attached to the belt so that the expansion of the chest during breathing exerts a force on the sensor and produces a voltage change proportional to this movement.


illus. 61

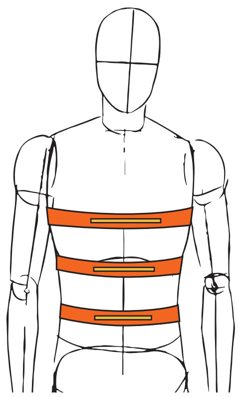
Acceleration sensors

Accelerometers can be used to capture respiratory motion during inhalation and exhalation events, and EMFit's sensors are used to evaluate MEMS (micro-electromechanical systems) high-resolution capacitive accelerometers while detecting respiratory rate.


illus. 62

Acoustic sensor

Lung sounds are monitored using acoustic transducers, and acoustic signals associated with respiration are typically acquired through transducers in the throat (near the carotid region) and suprasternal notch. The technology includes a real-time wheeze detector consisting of a wireless sound collection module, a wearable mechanical design, and a host system.


illus. 63

Resistive sensor

The solution consists of a resistive stretch sensor made of a conductive material and a polymer mixture. These components connect to three different girdles: upper chest, lower chest, and abdomen. Events of expansion and relaxation of the chest or abdomen cause changes in the resistance of a stretch sensor with this sensor configuration.

Evaluation

There are various technologies for monitoring respiration rate, each requiring different monitoring locations. The choice of technology should align with the concept's requirements. Notably, photoplethysmography (PPG), used for measuring heart rate and blood oxygen, can also estimate the respiration rate. Thus, the precise location of respiration monitoring is not a primary concern in concept development.

Sweat monitoring

To find the most suitable sweat monitoring principle, some possible technologies are studied and evaluated, and finally, Electrodermal Activity (EDA) is selected.

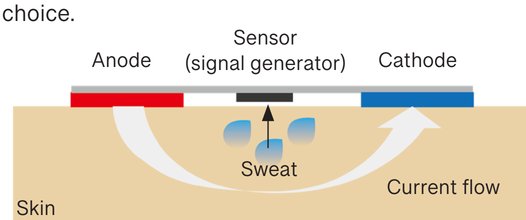
Bioimpedance or EDA provides a non-invasive approach to measure skin conductivity, a metric that fluctuates in response to sweat gland activity. The process involves generating a safe, minor electrical current, measuring the subsequent voltage drop, and calculating the body's impedance. This system relies on three crucial elements: a bioimpedance sensor, a signal generator, and a pair of electrodes (illus.64).

These sensors can be incorporated into wearable devices that sit on the skin's surface. As sweat production increases, these devices detect variations in electrical impedance, facilitating data collection. This data can then be utilized to analyze factors such as sweat rate, sweat composition, and hydration status (Farnsworth, 2019; Liaqat et al., 2022). For optimal sweat collection and analysis, it is crucial that the sensors maintain close contact with the skin and are ideally located in areas with high sweat production (Chung et al., 2019). However, it is equally important to consider the user's comfort and mobility when determining the device's location.

Furthermore, EDA technology offers additional benefits beyond physical measurements. By tapping into the sympathetic nervous system's responses, EDA can provide indirect measures of stress, fatigue, mental state, and emotions (Liaqat et al., 2022). This feature is particularly beneficial for firefighters who regularly experience significant physical and mental stress.

Electrodes material
The selection of electrode material is critical for the effectiveness of EDA measurements. Several materials, including Ag/AgCl gel, carbon nanofiber, carbon rubber, gold, and stainless steel, are viable options. For long-term EDA measurements, dry electrodes are the most convenient (Kusche, 2018). However, the selection process should also factor in the device's operational environment.

In the high-temperature context of firefighting, electrodes with low thermal conductivity are desirable. After examining various material properties, stainless steel emerged as the optimal choice.



illus. 64: EDA

Temperature monitoring

The following two techniques have been found to be reliable and used in medical temperature measurement through research.


illus. 65: Infrared Sensor


illus. 66: Thermistor

Infrared Sensor
Infrared sensors measure body temperature quickly and non-invasively by receiving infrared radiation emitted by the human body. They convert the captured infrared radiation into electrical signals, which are then processed by a microprocessor to obtain temperature readings. They can measure temperature without direct contact, however, they are often larger, more expensive, and consume more power than other types of sensors (illus.65).

Thermistor
A thermistor is a type of resistor whose resistance significantly changes with temperature. Most digital medical thermometers use thermistors to measure temperature. However, thermistors need to maintain as direct and consistent contact as possible with the heat source in order to accurately measure temperature. The metal used in digital thermometers that come into contact with the skin is usually stainless steel, because it is durable, corrosion-resistant, easy to disinfect, and safe to touch the skin. In addition, because thermistors are small in size, low in cost and low in energy consumption, they are commonly used in wearable devices. (TE Connectivity, 2023) (illus.66)

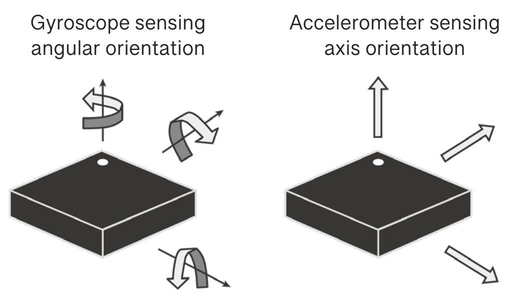
Evaluation
Given that other sensor systems require skin contact, the non-contact temperature measurement of infrared sensors doesn't have a selection advantage here. Therefore, considering factors like cost, size of the technical component, and measurement accuracy, thermistor technology is chosen.

However, it's worth noting that while temperature monitoring technology can measure surface temperature of any part of the body, this can be influenced by many factors and may not always accurately reflect core body temperature.

Movement monitoring

Due to slowed movement, abnormal movement, and immobility, these symptoms may appear after a firefighter is injured. Therefore, in order to more accurately understand the physical condition of the firefighter, movement, as a non-vital sign but still important, is monitored. Research has found that accelerometers and gyroscopes are commonly used technologies to monitor motion. The former measures the rate of change of speed, and is used to detect motion in different directions. The latter measures angular speed, or the speed at which something rotates around an axis, and is used to measure rotation and direction. There is a type of sensor on the market that encompasses these two technologies, called MEMS sensors (Analog, 2023) (illus.67). These sensors can detect gravitational acceleration, so they can be used to detect activities and abnormalities, such as unstable gait, falls, or concussions, and can even monitor the posture of the subject when they are still.

Additionally, MEMS sensing can be used to complement optical sensors, as they are susceptible to motion artifacts; when this occurs, information from the accelerometer can be used to make corrections.

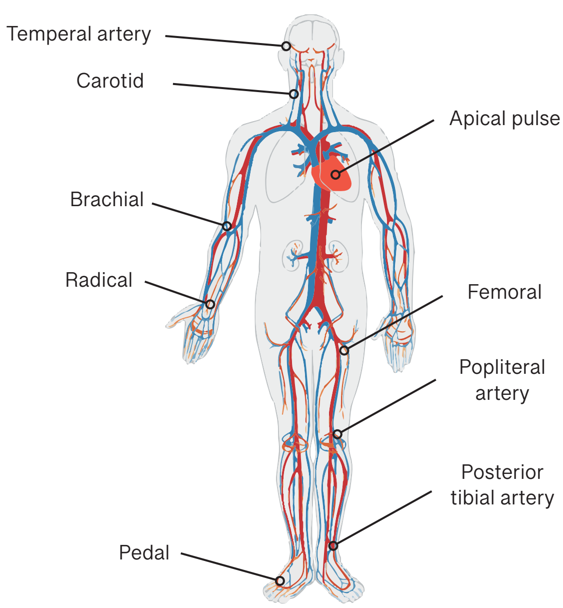


illus. 67: MEMS sensor

Sum up

Through research and evaluation, various monitoring technologies, other than breathing monitoring technology, have been identified. Due to the technical limitations of the sensors, they currently cannot achieve the accuracy of medical measurements, but they are sufficient for monitoring changes in body signs, meeting operational needs of the concept. Apart from PPG technology, which tends to be used where the pulse is pronounced (illus.68), other monitoring can be applied to most parts of the body.

Since these important vital signs need to be monitored by different technologies, for better management and maintenance, all monitoring technologies should be able to be integrated together, used on a single body part. Therefore, PPG technology, which can simultaneously measure heart rate and oxygen saturation, is prioritized for respiratory monitoring. The selection of the optimal body measurement site should balance monitoring requirements, comfort, and mobility impact.



illus. 68: Pulse points

- **The sensor system must be in contact with the skin.**

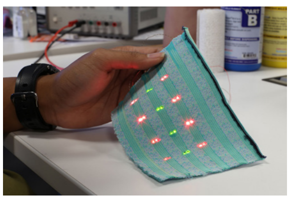
- **Electrodermal Activity (EDA) technology is selected for sweat monitoring.**
- **Thermistor technology is selected for skin temperature monitoring.**
- **MEMS sensor is selected for movement monitoring.**

2.7 Concept synthesis 3.0

As the monitoring technologies are confirmed, a new round of ideation is executed. Since other vital sign monitoring technologies do not require specific body locations, the body location considered here is based on the PPG technology for monitoring heart rate and blood oxygen, mainly targeting positions close to pulse points. In addition, as the conceptual foundation of the product is wearability, some potential wearable methods are identified and incorporated into the new concepts.

Here, three concepts are created, primarily aimed at exploring all wearable methods and potential wearable positions for the product, while starting to consider some approaches to alerting. Key insights into all potential solutions are sought and gathered through mock-up testing to assist in further concept development (app.5).

illus. 69: Hood



illus. 70: embedded in clothing

illus. 71: Concept-redesign

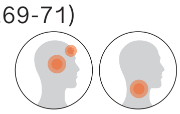
illus. 72: Mock-up test

Concept 1

Redesign - Permanently embedding in existing PPE

The concept is to integrate monitoring technology into the existing personal protective equipment (PPE) of firefighters by redesigning these pieces. Thereby eliminating the need for additional equipment and turnout time, as the product is already part of the PPE.

A hood could be a good choice, as it involves two prime locations for vital signs monitoring. Sensors could be embedded in the upper area of the hood for the forehead or temples. For the carotid area, sensors could be integrated into elastic material to enable skin contact. Moreover, LED strips embedded in the hood are able to alert firefighters and their companions. However, the downside is that this concept only works on the fire scene, and the benefits of monitoring cannot extend to the daily life of firefighters. ((illus.69-71)

Monitoring position 

Alert method 

Mock-up test

Allow users to experience the impact the concept might have on them by tightening the cloth around their forehead and neck respectively. (illus.72)

Feedback

" **Positive**: I like the concept that I do not need additional equipment.

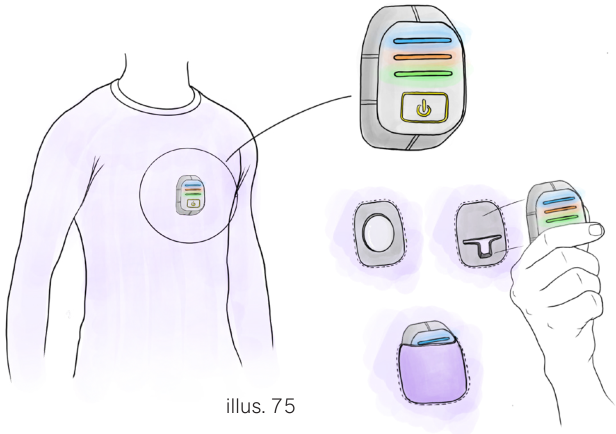
Negative

- I can accept the forehead location, but it may be affected by the helmet.
- I do not like it when the material around the neck is too tight, it makes me feel uncomfortable and anxious.
- In fact, I do not always wear a hood on the fire scene, only in wildfires is it required.
- The fire scene environment usually gets any personal protective equipment dirty, so we need to clean them often. Can this concept withstand the cleaning system of firefighting equipment? "

Evaluation

The greatest obstacle faced by the concept of permanently integrating devices into firefighters' existing PPE is the issue of cleaning and necessary maintenance.

illus. 73



illus. 75

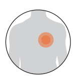
illus. 74

illus. 76: Mock-up test

Concept 2

Patch & Pouch - Removable box

The concept is to attach the product to the user's clothes in an easily removable manner. The user can wear it before an alarm is triggered, hence not adding to the turnout time. Two methods can be chosen: one is through a disposable patch, and the other is by installing a small pouch at the wearing position on the clothes, where the product can be fixed in this area. However, as the monitoring technology requires contact with the skin, it implies that the pouch needs to be placed inside the clothes, or a hole needs to be made in the clothes on the inner side of the pouch. (illus.73-75)

Monitoring position 

Alert method 

Mock-up Test

A box was attached to the user's apical pulse position, mainly to let the user experience the feeling of placing the product at this position. (illus.76)

Feedback

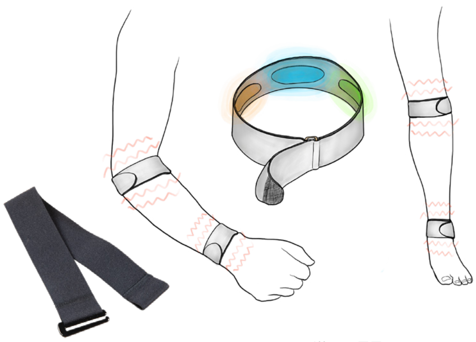
" **Positive**: I like the removable wearing method. When it is assembled, I can forget it, but it can still be flexibly removed when I do not need it. Another potential advantage is that it will not affect the cleaning system of the clothes.

Negative: Compared with the patch, I prefer the small pouch assembly method. I can not accept sticking something to my skin all day, just as I do not like using band-aids, it makes me feel as if I am a patient."

Evaluation

A removable installation method is beneficial for cleaning and maintenance, making it a feasible wearable method. Compared to single-use patch, the small pouch approach is more sustainable and more favored by users.

- Permanent embedding solutions are not conducive to cleaning and maintenance of equipment.



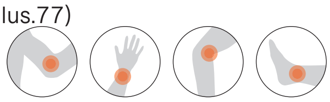
illus. 77

illus. 78: Mock-up test

Concept 2

Daily Wearable strap

The sensor box becomes a daily wearable device through an adjustable strap, adding no extra turnout time. Firefighters can wear it on one of four body positions according to their preference. Considering that the product will be worn under the firefighting suit on the fire scene, it will alert colleagues through sound alarms in case of abnormalities and vibrate to remind the wearer. (illus.77)

Monitoring position 

Alert method 

Mock-up Test

During user testing with straps of the same length, it is noted that the circumference of different parts of the human limbs varies significantly, which cannot be accommodated by a single product. Therefore, three different users are interviewed about their preference for wearing location. (illus.78)

User 1

“ I really like this idea. Before executing a task, if you have health issues, maybe heart problems, you can know whether you are ready for the task.

I like to put it on my ankle. If you can make it softer and more comfortable, that would be great.

But be aware that the strap can not be too tight, otherwise the blood can not flow back to the body heart. When you sweat a lot, your veins will protrude.”

User 2 and User 3

“ We like to wear it on the wrist, I think most firefighters would make the same decision. Because most of us are used to wearing something or a watch on our wrist, it is nothing new for us, so we can more easily adapt and accept it, and wear it all day. ”

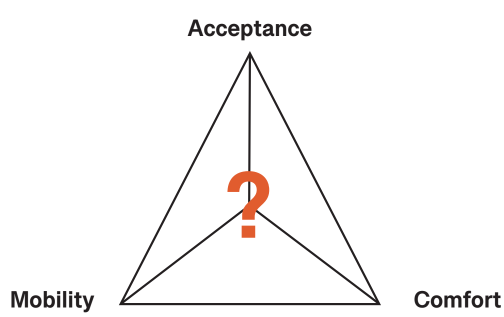
Evaluation

Different users may have different preferences for the location of the wearable, although two out of the three interviewed users expressed a preference for the wrist.

Sum up

The concepts are tested, which helps to further narrow down the solution space in terms of monitoring location and wearing methods. However, there are still two wearable methods that have been evaluated as viable, including the pocket and strap methods. Therefore, they are considered for parallel development. In addition, an important finding is that besides different preferences, user acceptance is also a crucial evaluation parameter. (illus.79)

As for the monitoring location, further exploration is needed. The aim of this round of ideation is to present potential solutions to users and probe their insights through mock-up testing. The concepts presented are very limited and do not comprehensively display all possible solutions.



illus.79: Three key elements

Table of requirements 1.0

Following several rounds of concept synthesis and further research into the project theme, the concept direction is clarified. Some new design requirements are identified and updated in the requirement list, and the sources can be found on corresponding pages. Meanwhile, some requirements collected in the first chapter are abandoned.

Fundamental

Not affect the integrity of the protection of existing firefighter protective equipment.	P16
Be compliant with Personal Protective Equipment standards.	P18
Not add much weight to the firefighter.	P19
Be comfortable.	P19
Not impact the mobility of firefighters.	P19
Not increase the turnout time.	P20
Be durable enough to withstand the abrasion on the fireground.	P35
Be maintainable.	P35

User

Cover the entire user group of firefighters.	P11

Usability

Maintain functionality in low visibility conditions.	P18
Be portable by firefighters.	P18
Be worn in a removable way.	> 47
Be an integrated product.	P34

Monitoring

Enable long-term monitoring of firefighters' vital signs	P37
Provide real-time monitoring.	P41
Have heart rate, oxygen saturation and respiration monitoring via reflective PPG technology.	P42
Allow the sensor system to come into contact with the skin.	P42
Have sweat monitoring via EDA technology	P44
Have skin temperature monitoring via themistor technology	P44
Have movement monitoring via MEMS sensor	P41 P45

Interaction

Not require firefighters to be distracted to operate it while on duty.	P17
Be able to work automatically.	> 31
Give firefighters some autonomy in decision-making.	P18
Reduce dependence on their radio system.	P18
Not impact their current radio system.	P23
Be able to convey monitored information to firefighter teammates and commanders.	P33
Be able to let firefighters know their physical condition.	P37

CONCEPTUALISE

This chapter primarily employs lean and agile methodos, iterating through building, measuring, and learning stages to advance the project. The main objective is to test hypotheses of the key features of the concept. After a pivot occurs, the final concept direction is clarified. The phase concludes with a flowchart that explains how some of the key features of the concept operate.

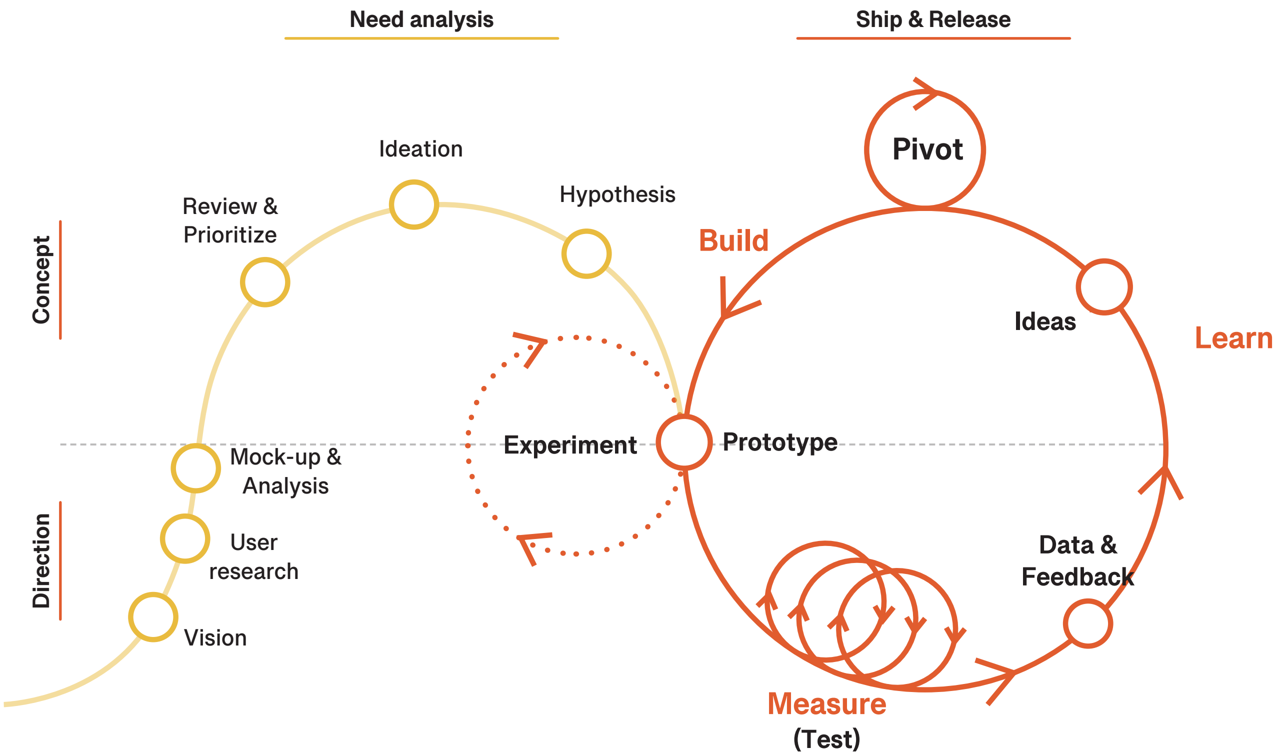
illus.80

3.1 Concept breakdown

Since the concept direction has been determined, key features of how the concept should work are organized and categorized into two categories, including fundamentals and key functionalities. A few of them have been figured out in the Ideate chapter with the concept development, but most are still missing. An overview of these key features follows, describing both completed and not-yet-understood information as well as their priority to guide the progress of the project.

Fundamentals	Requirement summary	Need to be figured out
Time	All developments of the concept must be time-oriented. The most crucial point is that the equipment should not increase the turnout time.	How can it not increase turnout time? Any other potential time-related impacts? How can these impacts be mitigated?
Portability	An equipment used by firefighters must be portable, allowing it to be functional when and where needed.	Be worn in a removable way. Where is it worn? How is it worn?
Comfort	The equipment must be comfortable, without impeding their mobility or adding excessive weight.	The choice of concept technology was based on weight considerations. How is comfort ensured? How is mobility not compromised?
Standard	The equipment must be durable enough to withstand the environment of a fire scene and comply with relevant standards.	What is the nature of the fire scene environment? What standards should be met? How are these standards met?
Maintenance	An equipment used by firefighters must align with their cleaning and maintenance systems.	How can it be maintained?

Key functionalities		
Data collection	The successful monitoring of key data forms the foundation of the concept's critical functionalities.	Monitoring content Monitoring technology What it the monitoring requirement? Where is it placed to monitor? Any other data that need to be collected?
Work automatically	The device needs to operate automatically, without distracting firefighters during their duties.	What triggers does it automatically run?
Information convey	Monitored data should be conveyed to individuals who can rescue firefighters or contribute to their safety, without interfering with existing radio systems.	To whom should the information be conveyed? How is the information conveyed? When is it conveyed? How can dependence on and impact on radio systems be minimized?
Dismiss manually	Firefighters need a certain level of autonomy in decision-making. They should be able to understand their own physical condition and determine if they require rescue themselves.	How can firefighters be informed about their physical condition? How can firefighters manually dismiss the trigger?



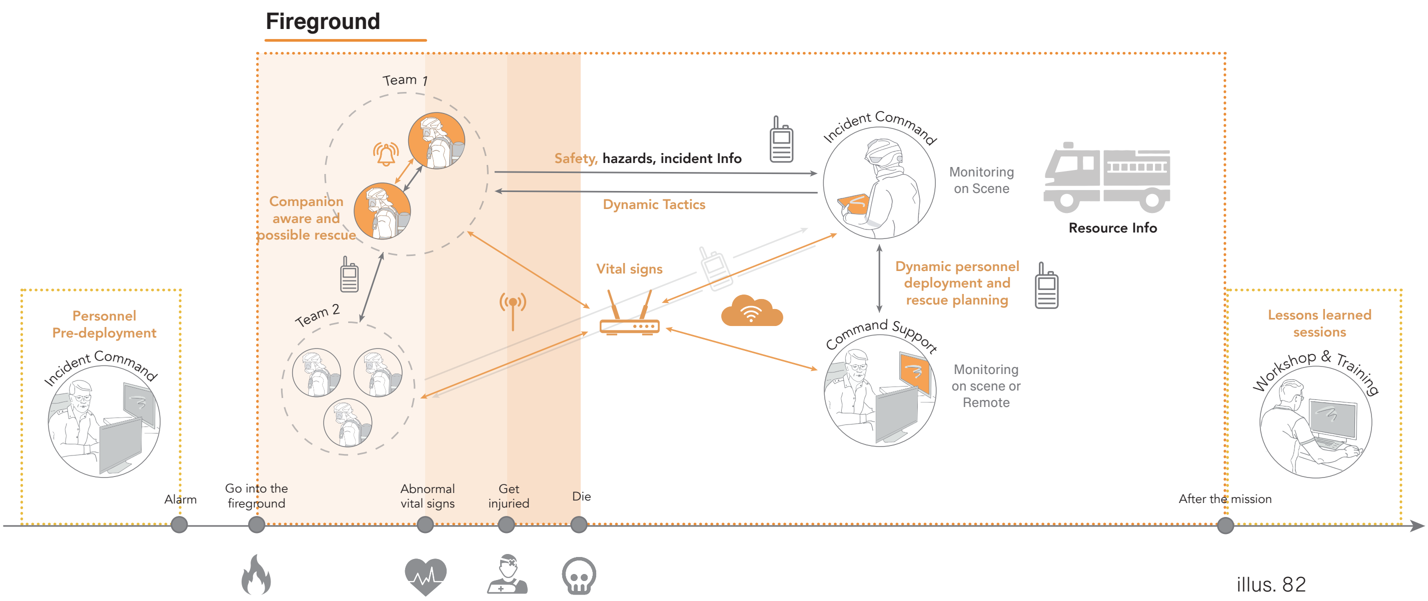
illus. 81

The diagram illustrates the project's progression, where the direction of the concept is clarified, design requirements are collected and categorized, and the problem domain and solution space are defined through concept synthesis. Therefore, this chapter primarily adopts the lean start-up approach to facilitate a rapid iterative process for hypothesis testing. The process is guided by the feedback loop of BUILD-MEASURE-LEARN, aiming to build the right things and build the thing right using lean and agile methods (Blank, 2018).

This project development phase emphasizes agility and speed, focusing on addressing the most important matters while continuously evolving the product through iterations and incremental steps. This iterative process involves transforming the key features of the concept into a Minimum Viable Product (MVP), followed by data collection and feedback through experimentation and prototype testing. Continually learning and reviewing the MVP to respond to design requirements, adapt to rapid changes, and decide whether to pivot or retain features. This iterative process helps deliver incremental value in a faster and more efficient manner, driving continuous development of the concept and ultimately achieving project success. (illus.81)

3.2 Information convey

Analysis of firefighter casualty timelines reveals a progression from initial vital signs issues, injury, to death, indicating that intervention at any stage in this process can provide an opportunity for firefighter rescue. Therefore, it is necessary to convey the firefighter's vital signs and activity level to the commander and colleagues. The following illustration provides an overview of how the concept impacts and how information is conveyed. (illus.82)



illus. 82

Information system

From the illustration XX, it is clear that the concept primarily operates on the fireground, but beyond that, the concept also has opportunities to create additional positive value before alarms and after fireground tasks. Assuming that firefighters are already wearing vital sign monitoring equipment before the alarm, the commander can make appropriate personnel deployments during or even before responding to the alarm. This can, to some extent, reduce casualties among personnel whose physical conditions are problematic or unsuitable for the task at that time, while also improving task efficiency. Furthermore, firefighters' monitoring data can be collected for post-fireground task lessons learned sessions or training schedules, thereby continuously improving firefighter job safety in a positive and sustainable way. This also aligns with the guidelines provided by the Occupational Health & Safety Standard ISO 45001, released in 2018, which advocates enhancing occupational health and safety performance by preventing work-related injury and ill-health, and by actively working to provide a safe and healthy workplace (ISO, 2018).

Data transmission

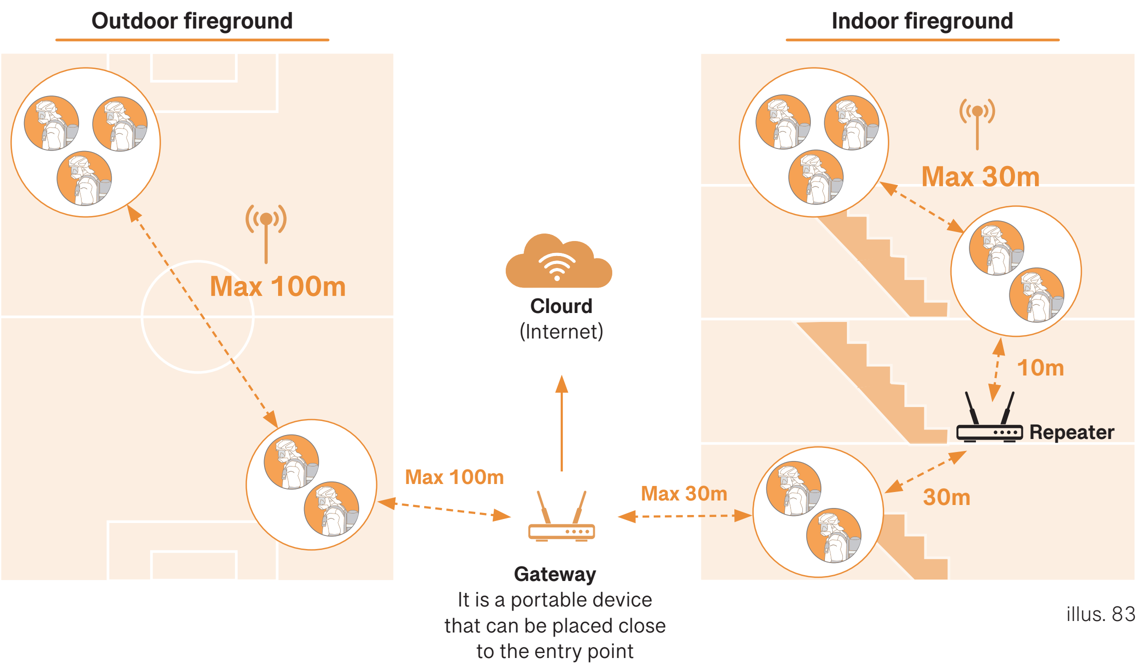
The monitored data needs to be transmitted in the information system. Research indicates that Wireless Sensor Networks (WSNs) have potential for real-time vital sign monitoring during firefighting operations. Firefighters carry a sensor box, and each node transmits data wirelessly, forming a mesh network for direct communication from the fire scene to an external command center, without a traditional router. The data is sent to a commander-accessible gateway, connecting the WSN to networks like the Internet for real-time data access (Dash and Peng, 2022). This allows continuous monitoring of firefighter health and safety, enabling quick emergency responses and informed decisions. Moreover, with the firefighter's consent, the data can be used for learning and improvement sessions after the mission, thus expanding the impact of the project.

The chosen protocol, Zigbee, is commonly used in wireless sensor networks due to its low power consumption. It operates at a frequency of 2.4 GHz without interfering with firefighter land radio systems. The outdoor signal transmission range can reach up to 100 meters. Indoors, the range may decrease to 10-30 meters due to obstacles like thick walls or signal interference. If the distance between sensor nodes exceeds the effective range or if obstacles interfere with the signal, a repeater is required to extend the network's range. (Acosta, 2018; Henderson, 2022) (illus.83)

In addition, considering Proximity firefighting suits used in extreme temperatures have an aluminum layer, a calculation is conducted on 2.4 GHz radio wave signal penetration. Results shows that an aluminum layer up to 1.68mm does not disrupt signal transmission. Typically, the aluminum layer in such suits ranges from 0.25 to 0.5 millimeters (app.6). However, most firefighting suits do not contain aluminum.

Location
In addition to transmitting the monitored information through the system, the location of firefighters is crucial information to be communicated to teammates and commanders outside the fire scene. This allows them to locate the firefighters for effective real-time rescue. However, as GPS signals inside buildings may be weak, the project has integrated GPS with barometers to improve location accuracy. Barometers utilize the characteristic of atmospheric pressure changes with altitude to detect changes in the floor level of firefighters inside buildings. As for communication among teammates, since the product is worn inside firefighters' clothing and does not have visible light indicators, after assessing sensory warning methods, it was concluded that alarms are the best way to communicate emergencies within the team.

Reminders
For firefighters, understanding their physical condition is essential. Vibration can serve as a solution, using different vibration frequencies to allow firefighters to comprehend their physiological status in non-emergency situations and make appropriate behavioral adjustments to prevent further deterioration of their health status.



illus. 83

- The decibel requirement for the alarm.

- The benefits of concept play can be enhanced by products worn by firefighters on a daily basis.
- Incident commanders and workshop personnel should be able to access the information.

- Information is conveyed to commanders via Wireless Sensor Networks (WSNs).
- Information is conveyed within the team through alarms.
- In non-emergency situations, the information is communicated to the firefighters themselves via vibrations.
- Firefighters can be located using GPS and barometers.

3.3 Fire environment

In product development, understanding firefighters' heat environments is vital to define design requirements and future test protocols. The International Association of Fire Fighters (IAFF) has established a four thermal classes, and firefighting environments are categorized as routine, hazardous, extreme, and critical. This classification provides valuable temperature-time targets for manufacturers. Also, the heat levels and temperatures that some common devices can withstand in fire scenes are summarized.

Firefighters wear thermal protective clothing during firefighting, which does not immediately expose skin to high temperatures despite sudden fire dynamics. Thus, electronic devices used by emergency personnel must withstand much hotter conditions than those causing skin burns (Donnelly et al., 2006). Here, temperatures posing burn hazards to skin in fire scenes are also described below.

Thermal Class

Class 1

Routine: Elevated temperature, no direct thermal radiation
Flux to 0.5 kW/m²

Class 2

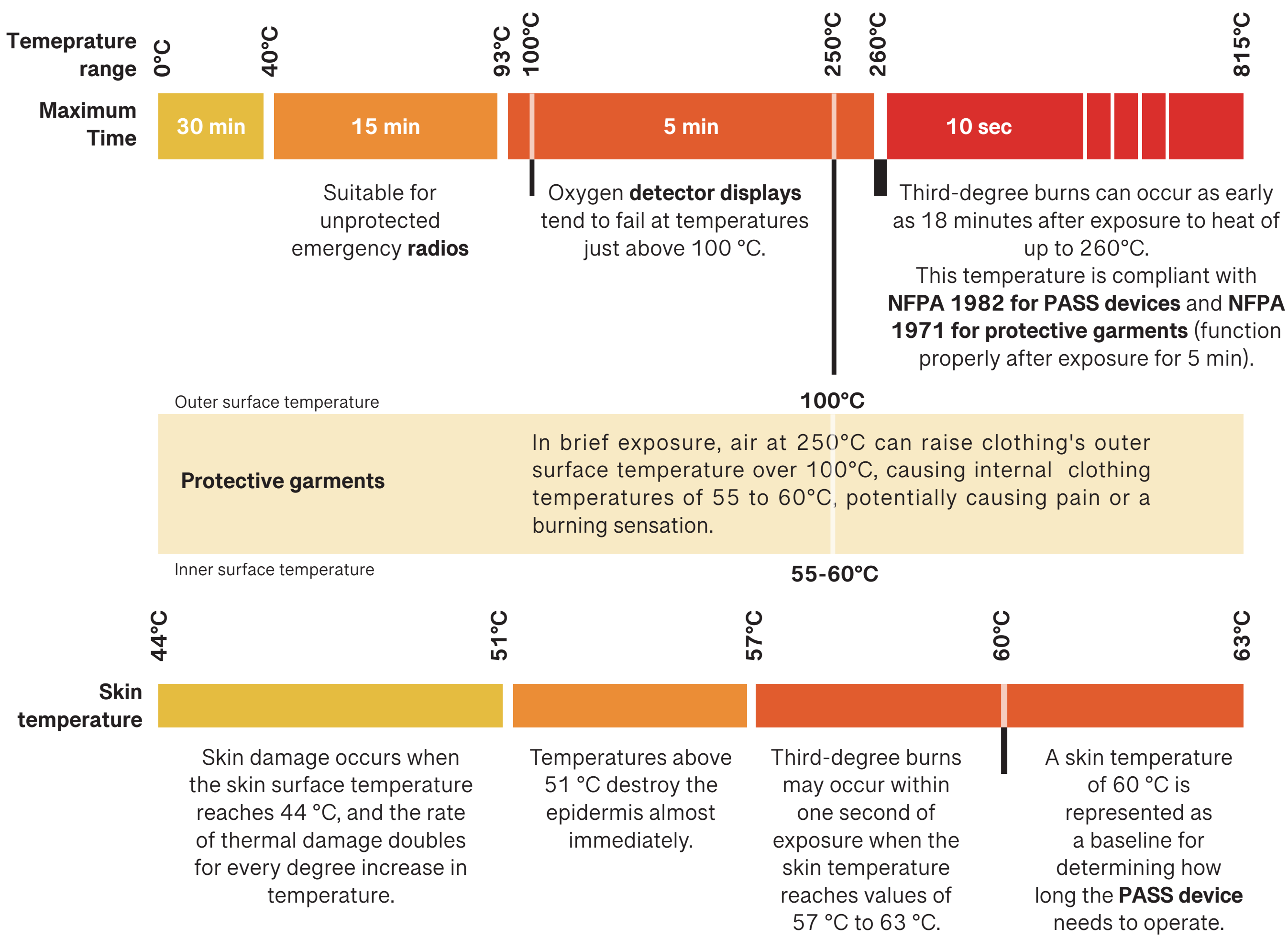
Hazardous: Small fire in a room, elevated temperature and direct thermal radiation
Flux: 0.5 to 1.0 kW/m²

Class 3

Extreme: Totally involved fire; Rescue, retreat from flashover or backdraft
Flux: 1.0 to 1.75 kW/m²

Class 4

Critical: Flashover or backdraft; Could be encountered briefly
Flux: 1.75 to 42 kW/m²



Fire environment requirements

Since the concept is to design a safety device for firefighters to use on the scene, it should align with PASS (Personal Alert Safety System) devices, which serve similar purposes - working when firefighters face threats and extreme environments. The primary difference is that PASS devices are worn outside the fire suit, while the concept is worn inside, leading to different environmental requirements. However, PASS devices' Thermal Class and alarm standards can still serve as references.

Thermal Class requirement

Research shows that since PASS devices must function in potentially rescueable situations, their requirements depend on the life-sustaining ability of firefighter suits in harsh conditions. As firefighters cannot perform search and rescue operations under Thermal Class IV conditions, PASS standards should be based on Class III. Therefore, our product, even inside the fire suit, should strive to match this Thermal Class. Also, the product should function properly at a skin temperature of 60°C, the baseline for PASS devices' operational duration, assuming the protective suit remains intact.

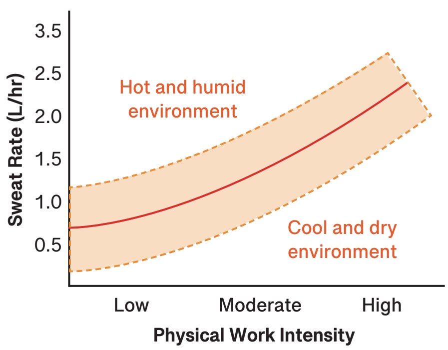
Alarm requirement

The report also mentions the alarm requirements for Personal Alert Safety System (PASS) devices. At a temperature of 160°C, PASS devices need to operate with a 95 dBA alarm for 30 minutes at a spherical radial distance of 3 meters, suited for heat level II operations. At 260°C, they must operate with a 95 dBA alarm for 20 minutes at a 3 meter spherical radial distance, for heat level III operations (Donnelly et al., 2006). Therefore, the product also need to meet these requirements.

Environment inside of garment

As the product is worn inside the firefighter's suit, research has extended beyond the hot environment firefighters face at the scene, to the conditions within the suit itself. It is found that the interior of the protective gear worn by firefighters on duty can become very humid, potentially approaching 100% relative humidity under intense conditions. This high level of humidity is mainly due to the suit's insulation and poor breathability, along with the moisture produced by the firefighter, primarily through sweating. Studies show that heat and humidity further increase the rate of sweating (illus.84). In fact, a firefighter can lose between 75 to 110 ounces of sweat per hour, nine times that of a regular exerciser.

Additionally, research has noted that the fire suit can limit the wearer's sensory perception. It dampens sound and makes it harder to feel heat or other physical sensations, making it more challenging for firefighters to assess their physical condition. (Smith et al., 2015) This further supports the concept of aiding firefighters in understanding their bodily status.



illus. 84

- The device needs to function at a skin temperature of 60 degrees Celsius.
- The material of the device should be able to withstand a high temperature of 260 degrees Celsius for at least 5 minutes.
- The alarm should be able to reach 95 dBA.

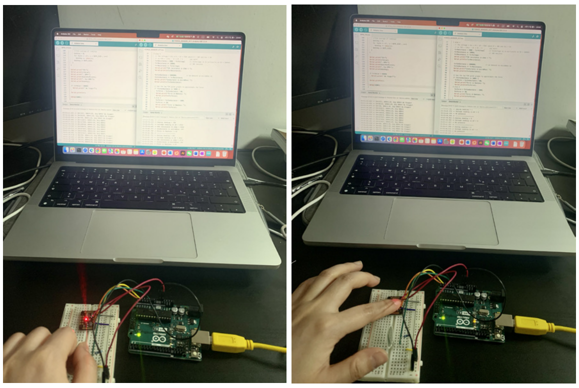
illus. 85

- The environment inside the fire suit is very humid.

- The firefighter's suit has a muffling effect.

3.4 Technology experiment

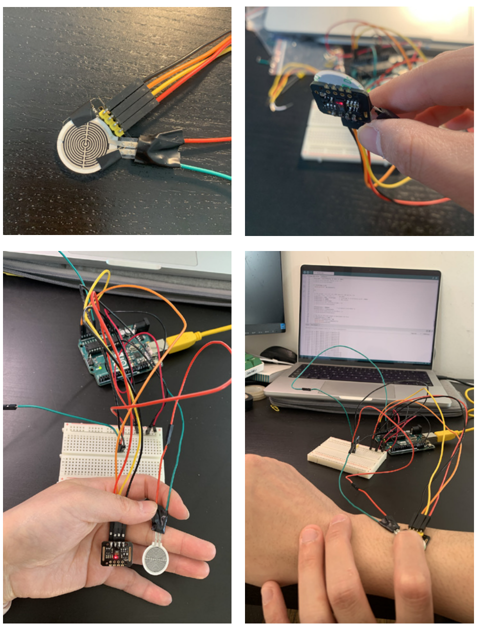
Technology validation



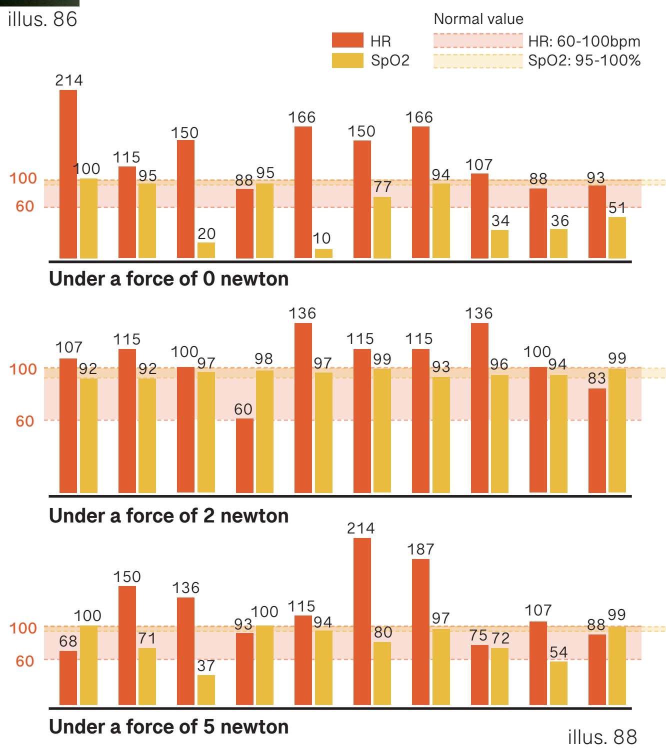
illus. 86

The study results reveal that reflective PPG technology demands a certain pressure range for precise measurement, but this parameter is not found through desktop research. Therefore, experiments regarding this technology are carried out to determine the specific requirements for successful measurement, which would allow for further product development. The technical feasibility of PPG sensors has been confirmed before setting up the experimental prototype. (illus.86)

Pressure experiment



illus. 87



illus. 88

The main objective of the experiment is to identify the range of pressures that PPG technology can accurately measure. Consequently, an experimental prototype is created, where a pressure sensor is mounted on top of a PPG sensor. The experiment involves placing the configured prototype on the skin, applying varying forces to it, and simultaneously recording the applied force and data results measured by the sensor through software (app.7). (illus.87)

The experiment applied pressures ranging from 0 to 7 Newtons. The initial 10 measurements from three different force levels (0N, 2N, and 5N) are presented in three charts. A force of 0 Newtons implies a gentle touch of the sensor to the skin, potentially involving some displacement. A force of 2N suggests the sensor can be lightly fixed to the skin, with minor deformation on the skin surface. 5N indicates that the sensor is pressed onto the skin, causing more noticeable deformation on the skin surface.

The charts show that a force of 2N produces optimal results, with the collected data almost entirely within the normal range. Thus, it can be concluded that both excessive and inadequate sensor displacement and pressure can affect measurement accuracy. Therefore, product design must overcome these factors. (illus.88)

It is important to note that the low-quality sensors used for the experiment led to certain inaccuracies in the data, and faulty data has not been recorded. Moreover, the experiment employed PPG sensors with a combination of red and infrared LEDs. Further study of the technology shows that this type of sensor is suitable for transmission PPG measurement, but for wearable device applications, it can easily be affected by motion artifacts. In contrast, green LEDs with shorter wavelengths better align with the project's requirements. Therefore, green LEDs have been chosen as a technical component of the product. Concerning the number of LEDs, considering the low cost of LEDs and the larger measurement area afforded by more LEDs, the quantity will be considered based on the product construction design. Furthermore, the study results suggest that having photodetectors on both sides of the LEDs can further improve monitoring accuracy due to light scattering. However, all these product specifications determined through research still require technical testing.

Prototype test

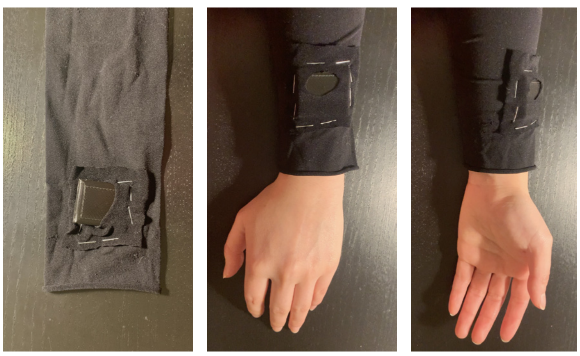
Clip

illus. 89

Clip with strap

illus. 91

Pocket



illus. 90

Pocket with strap

illus. 92

Based on the conclusions from the final round of concept synthesis (Section 2.7), both the strap and pouch are evaluated as feasible solutions. However, as experiments reveal, for accurate measurements, the device needs to be fixed in one position on the skin and avoid displacement during monitoring. Therefore, to find the right direction for product development, prototypes are made and tested.

Two prototypes for integrating the product into clothing are first created: one where the product is clipped to the clothing through grooves on the product's edges, and another where a small pocket is sewn into the clothing and the product is inserted. However, testing reveals that both product configurations do not stay in place when the wrist is rotated. Yet, with a strap, the product can be secured. Consequently, a strap is considered to be a part of the product design. (illus.89-92)

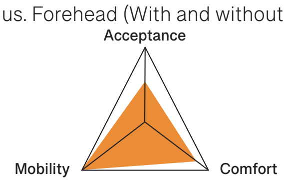
Additionally, two types of solution are identified: one in which the product is seen as a separate device with a strap, and another where the product is integrated into clothing and a strap is added at the integration point through a redesign.

- Measurements using the PPG technique require securing the device to the skin and avoiding displacement.
- The product construction should include a strap.

3.5 Position test

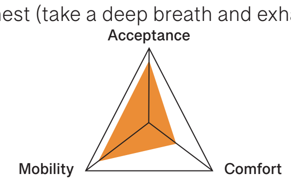
With the testing of technology, it has been found that the product must be fixed at the measurement location and a strap is a good solution. Thus, prototype of potentially viable positions are made and test with users. The tests focus on three key factors: acceptance, comfort, and impact on mobility. Here, acceptance is a subjective parameter while the other two are objective. Therefore, the test method requires users to perform possible actions and states while wearing the product. At the same time, after tightening the strap, users' feelings about the product being placed in different positions, and whether the product obstructs or affects the execution of movements are recorded (app.8). The test results are summarized and visualized by the indicator triangular cup as follows.


illus. Forehead (With and without helmet)



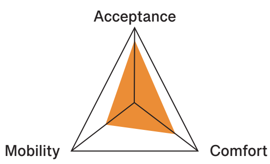
illus. XX


illus. Chest (take a deep breath and exhale)



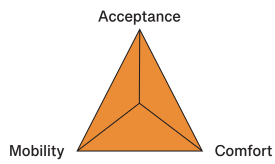
illus. XX


illus. Arm (Flexed and Unflexed)



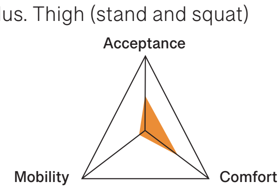
illus. XX


illus. Wrist (turning)



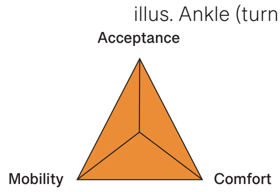
illus. XX


illus. Thigh (stand and squat)

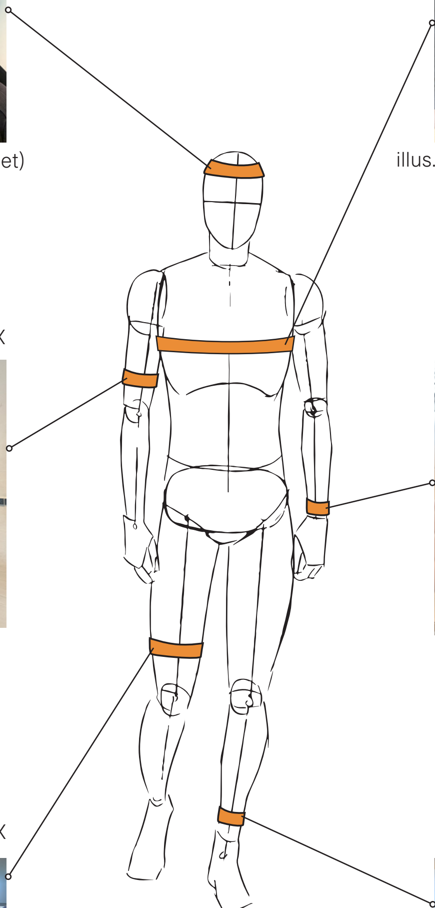


illus. XX


illus. Ankle (turning)



illus. XX


illus. 93

Forehead

illus. 94

The prototype includes a cotton strap with an adjustable length, into which a sensor box embeds. As the forehead position does not involve joint movement, the main consideration is whether it gets affected by a helmet. Testing shows that the helmet does not cover the forehead, however, users have some reservations about wearing a strap in this position. Yet, if it integrates into their hood and increases comfort, users would show more acceptance.

Chest

illus. 95

The prototype includes a thin rubber strap with adjustable length. The chest position primarily tests the user's feeling of being constricted by the strap during deep inhalation and exhalation. During prototype testing, it reveals that at the chest position, the strap must be tightened, otherwise, the product moves during inhalation and exhalation. However, a tightened strap decreases user comfort.

Arm

illus. 96

The prototype includes an elastic strap. During arm extension and elbow bending, there is a noticeable change in muscle relaxation in the arm. Therefore, despite the strap being elastic, it still affects comfort to some extent. Additionally, the strap causes a slight sense of obstruction when the elbow bends.

Wrist

illus. 97

The prototype includes a strap with adjustable length via a fastening tape. The user states that wearing a strap in this position does not affect any movements and it is very acceptable to have something there.

Thigh & Anklet

illus. 98

The prototype consists of a Velcro strap that is adjustable in length but not elastic, and it is used for testing both the thigh and ankle positions.

Thigh
During the prototype testing at the thigh position, it reveals that when the user squats, the strap significantly obstructs the user's action and causes a very noticeable discomfort. This might be because when the leg is active, the leg muscles noticeably relax, and a non-elastic strap hinders muscle relaxation.

Ankle
During the prototype testing at the ankle position, users report that, just like at the wrist, wearing a strap in this position does not affect any movement and does not cause any discomfort.

illus. 99

Sum up

Due to time constraints in creating prototypes, different strap features are embodied in different prototypes, leading to less stringent experiment design. Despite this, position testing provides vital insights for concept development and narrows down the solution space. Notably, wider straps offer more comfort than thin ones, and adjustable, elastic straps accommodate muscle movement better, enhancing comfort and minimizing movement impact.

Test results indicate that the wrist and ankle are optimal for wearing the product with a strap. Both locations have similar product requirements, suggesting a single product could meet both needs. For further concept development, the wrist is temporarily prioritized. Observations show that firefighters often do not wear gloves before entering a fire scene, allowing more opportunities to wear the product, such as en route to a fire. The ankle, due to clothing integrity, is typically less accessible, especially in the confined space of a fire truck's back seat. (illus.99)

- **Scenarios affecting mobility are identified.**
- **The wrist is tentatively chosen as the monitoring location.**

3.6 User experience test

Usability - Efficiency

The previous test results show that the strap must be adjustable. Given that time is vital for firefighters, anything designed for them must be easy to use. At the same time, a product that is not user-friendly may reduce a firefighter's desire to use it, affecting its usability. Therefore, to further develop the product, the best usability method must be found to construct the product's expression. The tests in this section mainly focus on the efficiency of operations that users may have with the product (app.8).

Putting on and taking off

Prototypes of straps with different tightening methods are created to test the primary operations that the first user, the firefighter, performs when using the product, including how easy it is to tighten and loosen the strap. This serves as a key consideration for evaluating solutions. Additionally, other detailed insights from user experience testing are collected and used as reference indicators for comprehensive solution evaluation. The test results are represented by a score from 1 to 5, and key user feedback is summarized as follows.

illus. 100

1 Buckle-1

"Operating the buckle with one hand is not easy, and there is a risk of pinching the skin when fastening."

illus. 101

5 Buckle-2

"It is easy to operate, and if paired with an elastic strap, allowing me to adjust the length of the strap while wearing it, it would be the best solution."

illus. 102

2 Button

"The button is too small and difficult to operate."

illus. 103

3 Magnet

"Easy to operate, but the magnet might not be strong enough to hold it steady, also, the magnet could burn the skin in a fire."

illus. 104

5 Velcro-1

"Easy to operate, but the Velcro is non-elastic, negating the advantage of the elastic strap."

illus. 105

5 Velcro-2

"Easy to operate, but the Velcro is not breathable, which negates the advantage of the cotton breathable strap."

illus. 106

3 Velcro-3

"The weaving operation is not easy."

illus. 107

3 Snap-1

"The operation is somewhat complicated."

illus. 108

2 Snap-1

"Relatively easy to operate, but the metal snap can leave marks and cause discomfort to the skin."

Assembly and disassembly

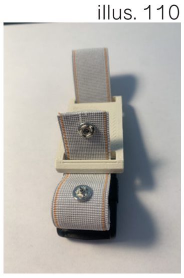
As the strap material is not yet determined, the product's requirement to be removed from the strap for separate cleaning is still considered. Visits to the fire department reveal that the disassembly and cleaning of fire products may be carried out either by the first user, the firefighter, or by a maintenance officer. Regardless of who performs this operation, there is a need for easy disassembly and assembly. Therefore, prototypes of different product and strap connection methods are created and tested with users. The test results are represented by a score from 1 to 5, and key user feedback is summarized as follows.

illus. 109

3 Velcro

"Punching holes is slightly troublesome."

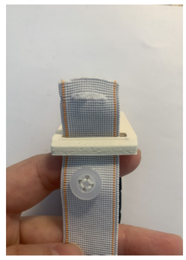
illus. 110



3 Snap

"Punching holes is slightly troublesome, and the thickness of the snap requires a larger hole in the product."

illus. 111



1 Button

"Both the button and the hole are very small, making it extremely difficult to operate."

illus. 112

5 Embed

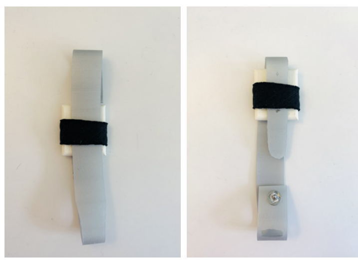
"Very easy to operate, this is the best solution."

illus. 113

4 Slide

"Relatively easy to operate."

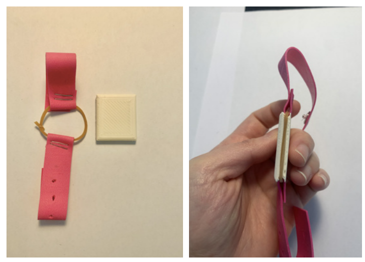
illus. 114



4 Pass through

"Relatively easy to operate."

illus. 115



5 Frame

"Very easy to operate, this is also a good solution."

Material and wet test

Research into the environment inside firefighting gear suggests that the product may face very humid conditions. Therefore, some potentially viable materials are tested at room temperature and under a small stream of warm water, simulating the potential environment the device might encounter (app.8). The primary aim of the test is to explore user perceptions of different materials in contact with the skin in the usage environment. The test results indicate that cotton provides the best comfort. Additionally, considering the concept requirement that users can wear the product for extended periods, taking into account both breathability and comfort, cotton remains the best material choice.

illus. 116

Canvas | Cotton | Nylon | Rubber | Elastic parachute

- Cotton is chosen as the material type for the strap.

Interaction test

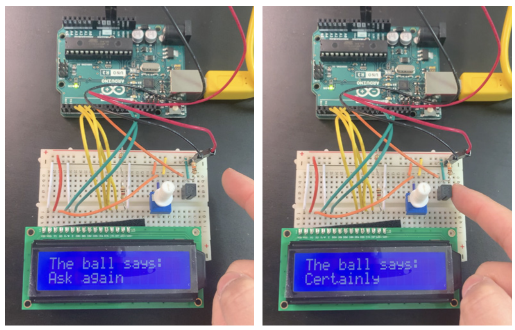
The concept involves some interactions, and there are concerns that the product's specific use cases could render some interactive functions ineffective. Tests related to manual dismissing and alarms are conducted.

Dismiss manually

Since the concept requires granting some autonomy to the user, there may be a need for manually turning off alarms. However, the firefighter's gear might hinder manual interaction. A prototype that includes a button is created, and firefighters are asked to try pressing the button while wearing their gear and protective gloves. The test results indicate that users can sense the product's location and tap it, but they cannot clearly perceive the button's location (illus.117). Therefore, the only solution is to turn off the alarm by tapping the product.

Here, a tilt sensor is used to test the tapping interaction method. As shown in the diagram, by tapping the sensor with a hand, changes in the displayed information are seen, confirming the possibility of interacting by tapping (illus.118). However, further research into the technology reveals that tilt sensors can only measure tilt angles when stationary, while gyroscopes can measure tilt angles during movement. MEMS sensors that include gyroscope functionality also have adjustable trip angle thresholds (Ericco, 2022). Therefore, MEMS sensors will be used for the interaction method of manually turning off alarms by the user.

illus. 117



illus. 118

illus. 119

Alarm test

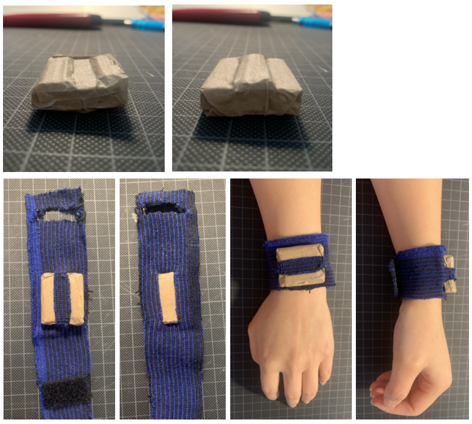
Research into the firefighting environment revealed that firefighting gear might have a muffling effect. Therefore, an alarm test is carried out. Placing a speaker producing 81 to 85 decibels of sound into the firefighter gear reduced the decibel level to between 63 and 68 (illus.119). This shows that the firefighting gear will have a significant impact on volume. Research shows that sound intensity doubles every 10 dB (Quisure, 2020). Earlier sections determined that fire scene alarms need to reach 95 decibels, but because the test speaker did not reach the level of 95 decibels, it is uncertain how much the firefighter gear would reduce a 95-decibel alarm. Therefore, future work needs to continue to test alarms that meet the decibel requirement to determine the required decibel level for alarms.

- Users can manually dismiss the alarm through MEMS sensors.
- The sound-muffling effect of fire suits has been proven.

Concept development

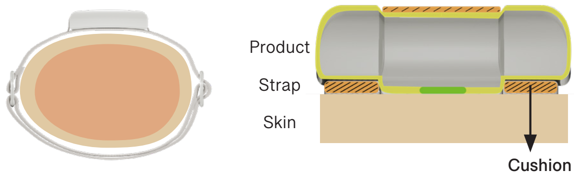
Comfort

Comfort, as a key design requirement, is further developed. Since biometric monitoring requires the sensor system to touch the skin and apply certain pressure to avoid sensor displacement, long-term wear of the product inevitably affects user comfort.



illus. 120

illus. 121

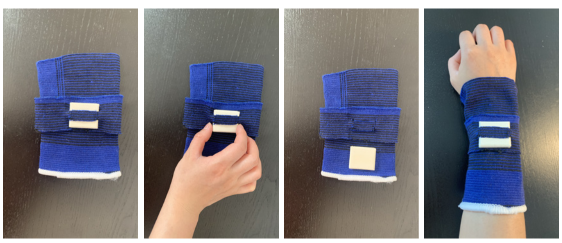


The solution is to design the shape of the product so that only the part of the product that need to come into contact with the skin have a protruding shape (illus.120). This way, other parts of the product can form a separation from the skin through the strap, acting as a cushion, ensuring maximum contact between the skin and comfortable fabric to enhance comfort (illus.121). This solution combines the idea of "Embed," which scored highest in user testing for assembly and disassembly.

Response to low compliance

The concept is further developed with the primary aim of finding a solution that integrates the product into the daily lives of firefighters, addressing some issues with firefighter low compliance. As a result, a concept involving variable identity and customizable appearance is created, which "deceives" the user about the product's identity and creates desirability by catering to different user preferences, thus persuading the user to use it and be willing to wear it for extended periods.

Based on the determined comfort enhancement and assembly solution, the product can adapt to strps of different widths, creating new identities for the product, such as wristbands, wrist guards, bracelets, etc., to meet diverse functional needs (illus.122). A detachable watch head and charger can also provide additional functionality through modular design (illus.124). In addition, customizable color combinations can align with the image of different fire stations or personal preferences (illus.123).



illus. 122

illus. 123

illus. 124

- The protruding shape of the part of the product that needs to come into contact with the skin, combined with the way the fabric creates a barrier between the product and the skin, can increase comfort.

- The routine of firefighters.

Concept Review

To evaluate the concept, user interviews are conducted (app.XX). Assessing the concept in conjunction with user feedback, the solution addressing firefighter low compliance seems more like a trick, designed for "sometimes", and it does not truly solve the problem. Although the product's identity is increased, it cannot always meet all users' functional needs. Moreover, this solution does not guarantee that users will tighten the strap, leading to potential loss of its functionality. Therefore, in order to propose a feasible solution that integrates the product into the firefighters' daily life, it is necessary to understand the routine of firefighters.

3.7 Firefighter routine

In order to integrate the product into the daily life of firefighters, their workflows, habits, and routines are studied. The aim is to gain a deeper understanding of firefighter's life to uncover opportunities and requirements for product development. The focus here is primarily on studying scenarios when firefighters are on duty. Below is a detailed introduction to the daily work of a firefighter on a 24-hour shift system. However, it is important to note that any of these activities can be interrupted by emergency service calls (Dmacc, n.d).

7 a.m. Shift Change

Arrive at the fire station to relieve the personnel from the previous shift. Check their gear, including personal protective equipment, in readiness for morning briefings.

Start-of-shift firefighters put on already-charged equipment.

End-of-shift firefighters take the equipment off to recharge.

8:30 a.m. Physical Fitness

Receive time for exercise (cardio, strength training) in the morning to maintain a healthy level of fitness.

Take a shower

Change into their station uniforms

May replace objects embedded by the product

10 a.m. Clean Up and Housework

Change into the station uniforms. Clean the fire station, fire apparatus, and equipment.

Always be equipped.

11 a.m. Food Shopping

Assigned cook for the day will take the fire apparatus to the market and shop for groceries in order to be readily available to respond to a call.

12 a.m. Noon Lunch

2 p.m. Daily Work

Conduct fire prevention inspections, give fire safety presentations, participate in a training drill.

6 p.m. Dinner

7 p.m. Work Duties/ Personal Time

Check their department e-mail and participate in online training. Watch television, or use time for personal development.

10 p.m. Sleep/Rest

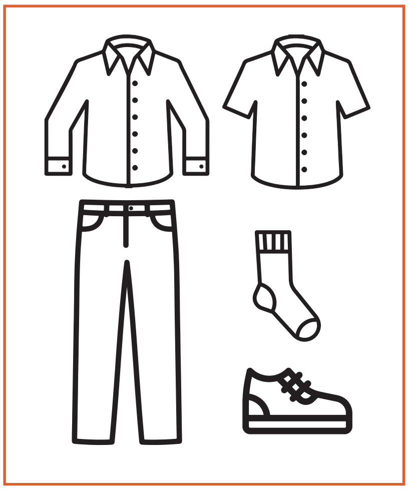
Try to get some sleep around 10 p.m.

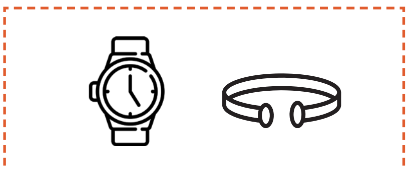
Sleep is not guaranteed.

6:30 a.m. Wake-Up Bell

Remove their bedding and prepare to brief the next shift’s firefighters.

illus. 125





illus. 126

Station wear

The station uniform of firefighters, which they wear while working at the station, is their formal attire and typically includes three basic parts: a shirt, trousers, and boots. You can choose a station-style t-shirt with either full-length or half-length sleeves as needed. The trousers are always long, complemented with a pair of boots and socks suitable for daily wear. Some firefighters also wear watches or bracelets while on duty.

The attire of firefighters, whether inside the station or in the field, serves two purposes: it acts as a symbol of honor and as protective clothing. They must always be prepared for possible emergencies, which largely involves having the right gear ready. The station uniform can be seen as an additional layer of Personal Protective Equipment (PPE), providing a minimum level of protection in the most extreme fire emergencies.

Therefore, when designing firefighter attire, protective factors must be considered, and it is best to follow the **NFPA 1975 standard**. This standard sets the minimum requirements for fire station uniforms to ensure they do not cause harm and stipulates requirements for flame resistance, heat resistance, odor resistance and insect resistance.

Sum up

Through regular study of firefighters, it is found that they may need to respond to emergencies at any time during their 24-hour shifts. Therefore, the product should function throughout their entire shift. In addition, it is noted that their shift patterns may result in them standing and moving continuously for 24 hours with minimal rest, causing severe mental and physical fatigue and increasing their risk of injury during tasks. This confirms again that the concept should be extended to their daily lives.

Furthermore, some new potential objects for product integration have been identified, providing opportunities to develop new solutions that blend the product into their everyday lives.

- **Firefighters must be ready to respond to emergencies at all times during their entire shift.**
- **The product needs to be able to operate continuously for 24 hours.**
- **The fabrics involved in the product must comply with the NFPA 1975 standard.**

3.8 Pivoting

As the concept is revisited, new product wear methods and locations are sought (app.9). The concept's context expands from the fire scene to firefighters' daily lives. This search is not limited to the personal protective equipment that firefighters wear at the fire scene, but rather their daily attire. The new concept is to integrate the product into the products that firefighters wear daily, enabling them to use the product effortlessly. It should be noted that the search for new wear locations is based on the results of previous strap tests, so any areas where muscles would contract and relax are not considered. Six new potentially feasible solutions are depicted in the following figure (illus.127).

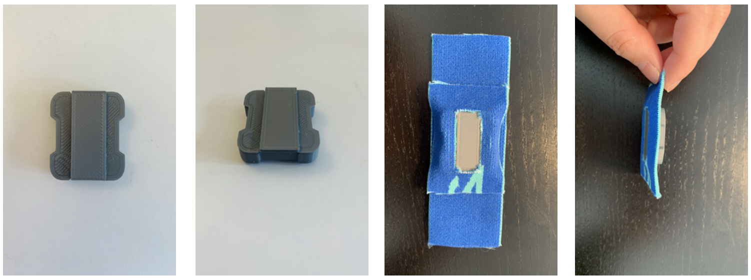
The search for new potential solutions is based on the following two types:

- **First level:** Objects that inherently have enough elasticity for the product to be directly embedded.
- **Second level:** Those that can indirectly apply pressure to the product by being subjected to pressure by other objects.

First level

Seconde level

illus. 127



illus. 128

illus.129

Prototype test

In the new prototype, the sensor box no longer attaches to the body with a strap, but embeds into identified new objects through a small pouch. The new prototype reflects the comfort-enhancing benefits of previous successful developments. Thus, the pouch has a hole that perfectly matches the protruding part of the sensor box, making the pouch a pad to increase comfort (illus.128).

It is important to note that the new potential solutions also do not consider the chest area, based on observations of the users, who hang their masks on their chests when not in use. This can cause any hard object on the chest to impact the chest, a hypothesis that has been confirmed during user testing with the prototypes (illus.129).

1 Forehead

illus.130

The prototype embeds at the forehead position of the hood. Although the hood is not part of the firefighter's daily wear, this solution is tested for future product development opportunities.

Feedback

Positive: " I did not expect it to be so comfortable, I cannot feel its existence at all. Embedding it in the forehead part of the hood is an excellent idea. The only problem is that firefighters do not always wear the hood. "

4 Wrist with cuffs

illus.131

Observation: The product embeds at the wrist of the shirt cuff, using the elastic cuff of the jacket for pressure. However, during testing, it is found that the cuff cannot provide sufficient pressure to prevent product displacement. After testing with the user wearing a close-fitting fire station uniform, it is found that the product can be slightly secured in place. However, when the user rotates his wrist, the product still moves.

2 Underpants

The product embeds into the top edge of the underwear, using the underwear's inherent elasticity to apply pressure to the product.

5 Abdomen with bet

The product embeds into the back of the shirt, using a tightened belt to apply pressure.

6 Lower back with belt

The product embeds in the abdominal area of the shirt, using a tightened belt for pressure.

When asking the user about these three locations, the user directly rejects the solutions.

Feedback

Negative: " Remember that the SCBA will cover and press on the back, any hard object on the back will cause discomfort or injury. Similarly, hard objects under the belt will cause discomfort, and we have not only belts on our pants but also belts equipped with SCBA, these belts may also cause product displacement. "

3 Sock

The product is embedded at the ankle of the sock, using the inherent elasticity of the sock to exert pressure on the product. Three prototypes with different embedding methods are made and received user feedback.

illus. 132

illus. 133

1. The product is embedded in a pocket on the inside of the sock.

Feedback
Positive: " It does not cause any damage to the embedded product, just a small pocket needs to be sewn inside the sock. "

Negative: " Although the product is small, a hard object in that location, if worn for a long time, can cause discomfort. "

2. The product is embedded in a pocket on the outside of the sock.

Feedback
" **Positive**

- This is the most comfortable solution, the sock forms a cushion between the product and the skin.
- The product is easier to remove and insert.
- It is easier to notice the product. "

Negative: " It requires redesigning the sock, and adding holes in specific locations, but it can be standardized like the fire station uniform. In this way, we have standardized socks. "

illus. 134

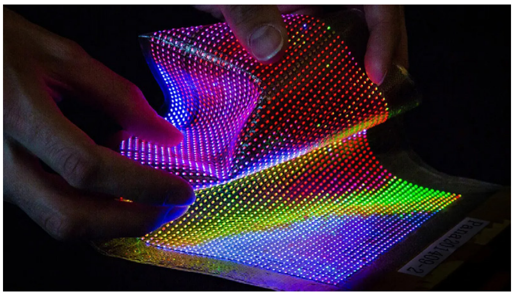
3. The product is embedded on the outside of the sock.

Feedback
Positive: " The product is easy to remove. "

Negative: " It feels unstable, and the product is prone to falling out. "

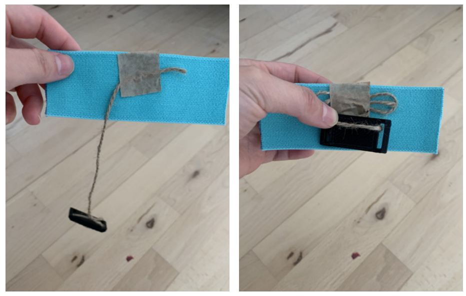
Concerns

Since the new concept no longer treats the product as an additional item, but integrates it into the firefighters' daily wear, a concern arises about "how can firefighters remember to remove the product from the embedded item for charging and cleaning?" Thus, two possible solutions are created and receive user feedback.



illus. 135

Solution 1
When the sensor detects that the user has removed the item where the product is embedded, it provides flashing lights and sound prompts.



illus. 136

Solution 2
When the user removes the item where the product is embedded, the product falls out and is attached to a string.

Feedback
" I think you do not need to worry about this issue at all. We have many pieces of equipment that are kept in pockets or hung on clothes. Before putting our clothes into the laundry bag, we always check all items and take them out. "

illus. 137

Sum up

Through prototype testing, it can be concluded that headgear and socks are viable solutions for integrating the product. Considering that headgear is not an item that firefighters always carry, or even always appear at the scene of a fire, this deviates from the value proposition of the concept, and hence, the sock solution is chosen. This solution differs from others that apply pressure to the product through external objects like belts, but instead uses the inherent elasticity of the socks to secure the product, allowing for long periods of wear without discomfort.

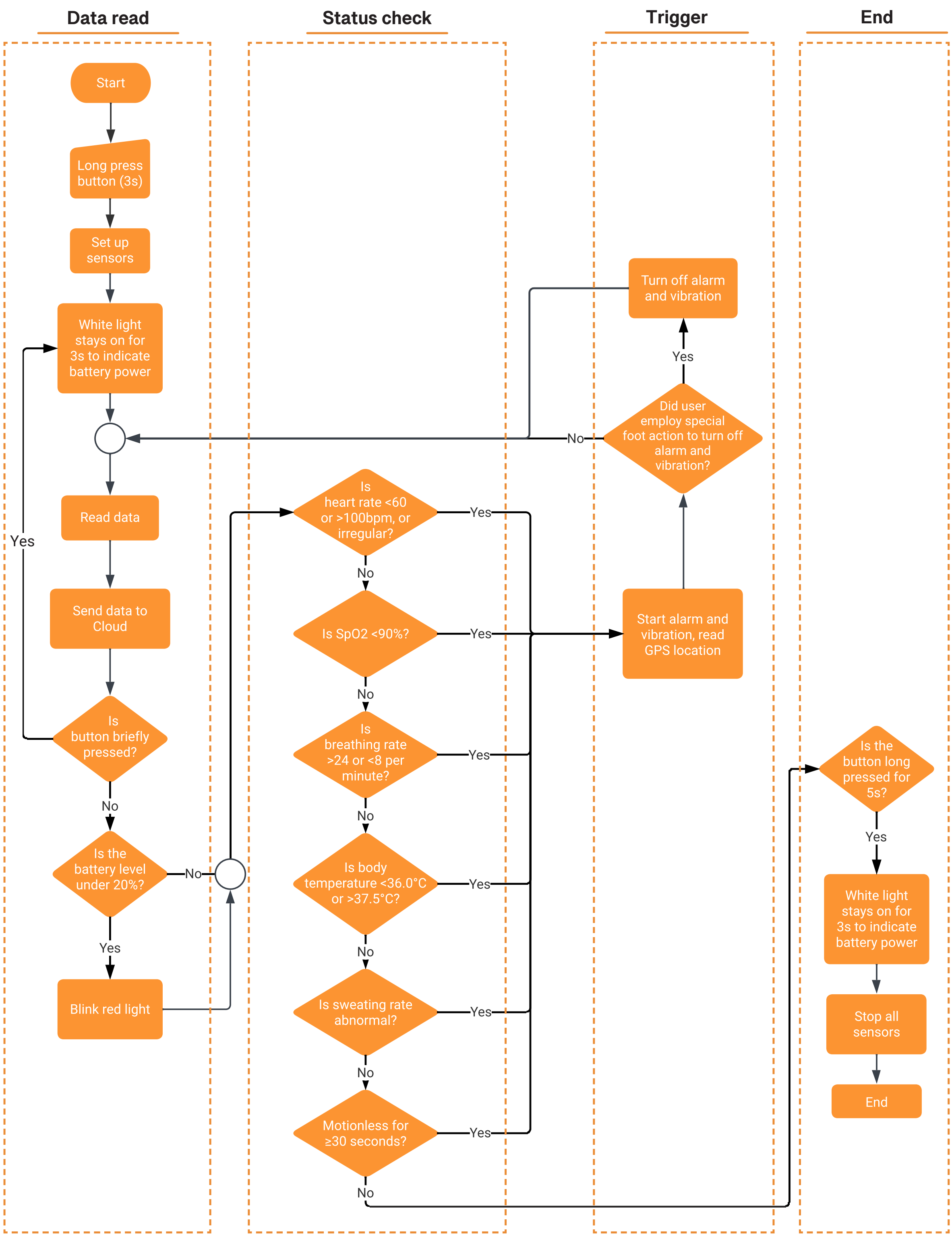
Regarding the three ways to integrate the product into socks, after evaluating user feedback, the second solution - integrating the product into an outer pocket of the sock - is chosen. This is because comfort is a very crucial factor in firefighter equipment design. However, the potential impact of firefighter boots on the product still needs to be researched, and the comfort performance of the product further enhanced.

- The solution of integrating the product into firefighting socks to blend it into the daily lives of firefighters is chosen.
- The method of embedding the product in an outer pocket of the sock is selected.

- The product construction should include a strap.
- The wrist is tentatively chosen as the monitoring location.
- Cotton is chosen as the material type for the strap.

3.9 Flowchart

A flowchart is created to help understand how the proposed concept responds to the monitored information. The abnormal vital signs in the flowchart are those of ordinary people in regular conditions. However, firefighters often show different values in action, requiring further study to correctly set up the product. The product needs a calibration period for optimal operation, aligning with the idea of daily use. The following diagram represents the concept's operation during emergencies, given the uncertainty of specific vital signs.



illus.138

DETAIL

This section delves into product details to perfect the construction of the concept, including the selection of materials, product architecture and manufacturing, as well as aesthetic design. Designs related to socks and charging bases within the product system are also presented. The phase concludes with an updated version of the design requirement list.

4.1 Pocket

This section represents the considerations of the pocket location, the material and the installation method. The purpose of development is not to affect the wearer's mobility, comfort and structural integrity of the sock.

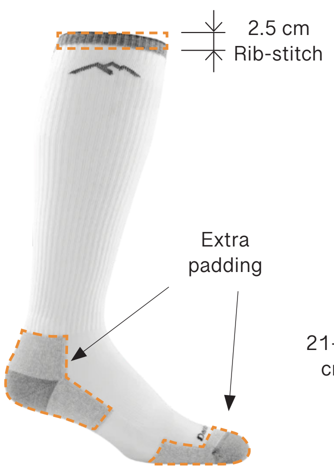
Firstly, to identify the optimal placement for comfort, the firefighter socks, being part of the product, are studied. The usage environment, firefighting boots, and station boots are also examined. The goal is to identify the potential impact for the user, including influences from other products like firefighting boots, and then minimize these effects to enhance comfort.

Firefighter socks

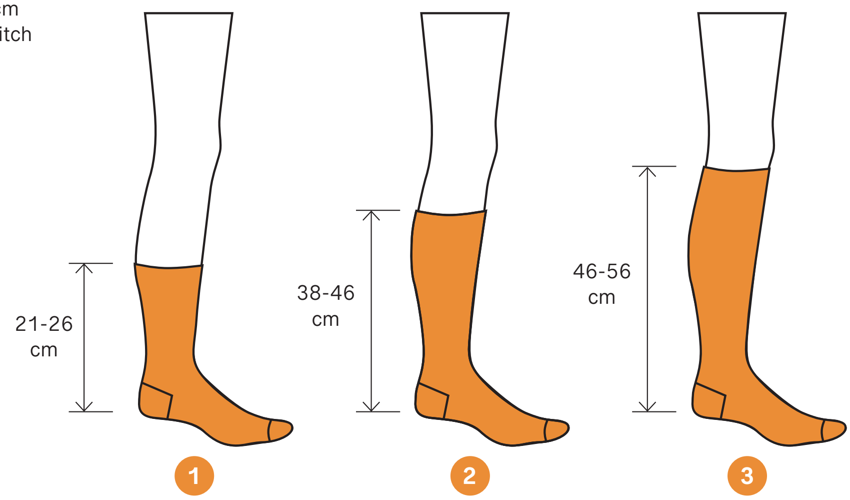
Firefighters work in extremely challenging environments and must be ready for various emergencies. They need specialized protective gear, including high-quality socks. These socks are designed to protect firefighters' feet from high temperatures and flames. They are made from flame-resistant and moisture-wicking materials that can withstand extreme temperatures, humidity, and irritant chemicals.

Firefighter socks are typically medium-weight socks about 1-2 millimeters thick, striking a balance between breathability and cushioning. High-quality socks, such as those made from Kevlar, Nomex, wool, or carbon fiber, can also provide arch support and additional padding in the heel and toe areas. This offers extra cushioning and protection for the feet, enhancing comfort and durability. In addition, it should be noted that some socks are rib-stitched about 2.5 cm from the top to ensure a snug fit around the calf, preventing them from slipping into the wearer's boots (Supplycache, 2023) (illus.139). This area is typically thickened, and products should not be placed here.

Below are three sock sizes a firefighter might wear, the first of which is rarely used by firefighters (illus.140).



illus. 139



illus. 140

1. Mid-calf length socks

These socks extend to the middle of the calf, providing coverage for the lower leg. They strike a balance between coverage and comfort, making them suitable for a variety of footwear options. However, to a firefighter, this may be considered slightly short to provide full coverage and prevent chafing or discomfort.

2. Over-the-Calf Lengt

These socks extend up the calf, usually ending just below the knee. This is the preferred length for most firefighters because they provide good coverage, ensuring the boot material does not directly contact the skin. This prevents injury from the protective boot material and ensures the sock does not slip down during physical activity.

3. Knee-High Length

These socks extend all the way to the knee, offering the maximum coverage and staying in place even during vigorous activity. Knee-high socks can also offer additional benefits like compression, which can help improve blood circulation and reduce swelling during long periods of standing or walking.

- Pockets should be positioned to avoid areas of rib stitching and extra padding.

Firefighter Boots

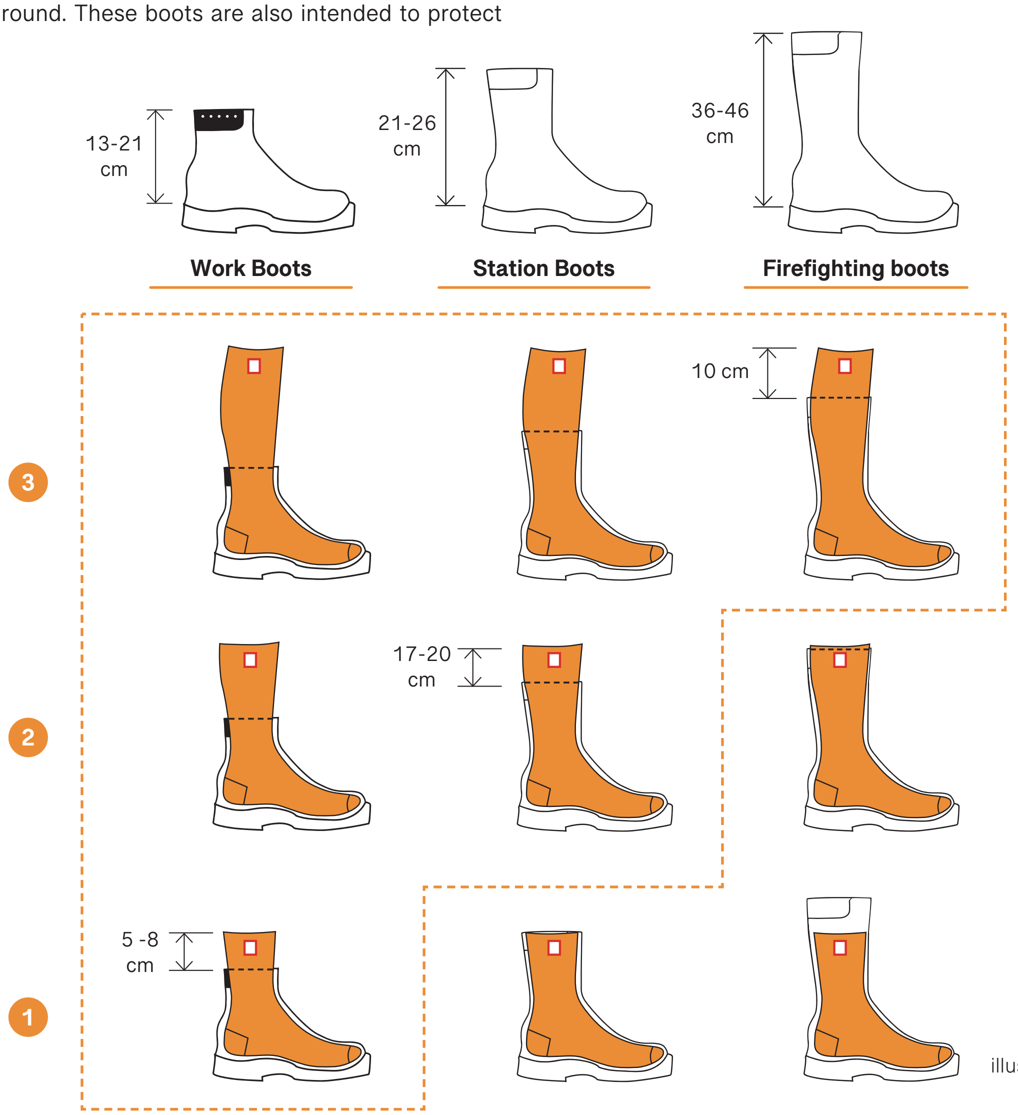
Station-Wear Boots

At the fire station, when not actively firefighting, firefighters typically wear shoes that are more comfortable and practical than firefighting boots. This can include work boots, sneakers, or station boots. Sneakers are usually low-cut, not extending above the ankle, and are thus considered to not come into contact with the product. Hence, the primary focus here is on the other two types of footwear. Work boots are usually the same height as the ankle or slightly higher, typically around 5 to 8 inches. Station boots, a common choice for many firefighters, are designed for quick and easy removal and replacement with turnout boots when a call comes in, typically measuring 8 to 10 inches in height. (Tariqul, 2022)

Fireground-Wear Boots

When responding to an alarm, firefighters must switch to firefighting boots designed for use on the fireground. These boots are also intended to protect their feet from high temperatures and flames. The interior environment of firefighting boots can be hot and humid, so the boot design includes breathable and moisture-wicking features to keep the feet dry and comfortable. The boots are also made from flame-resistant materials, providing extra cushioning and protection. (Haixusa, n.d.)

The following illustration shows the size proportions of the three types of boots and socks worn by firefighters (illus.141). From the size proportion chart, it can be observed that apart from the longest socks, the other two types may fall within the boots worn by firefighters. However, no matter which boots and socks the firefighter wears, if the product is placed as close as possible to the sock's opening, it can still avoid any contact with the boots as much as possible. This can serve as a specification for manufacturing requirements. In order for this solution to be implemented, the product needs to be positioned at least 5-8 cm from the top of the sock.

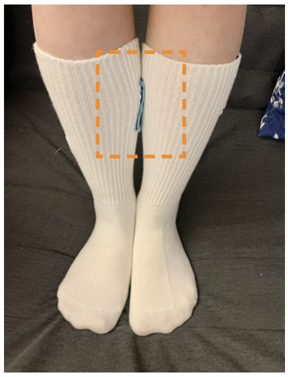


illus. 141

- The product needs to be placed at least 5-8 cm away from the top of the sock.

Placement position

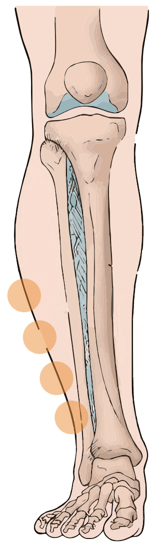
illus. 142



illus. 143

Firefighters often need to sit on their calves to perform various tasks (illus.142), which means that the front and back of the calf should not be chosen as the product's embedding location. According to prototype testing, the inner sides of both calves can press against each other, thus, embedding the product on the outer side of the calf is the best choice (illus.143).

illus. 144



illus. 145

The potential pressure that a shoe might exert on the product is simulated by manually pressing the product in four different locations, from the ankle to near the top of mid-calf length socks (illus.144). It is found that the discomfort is lower the higher the product is positioned, i.e., where there is more flesh (illus.145). Therefore, the product placement should avoid positions where the layer of flesh between the subcutaneous bone and epidermis is thin. This prototype test further confirms that the product should be embedded as close to the top of the sock as possible.

Additionally, from the cross-sectional view of firefighting boots, it can be seen that the part above the ankle is filled with a layer of perforated foam. Also, the circumference of the boot becomes larger towards the opening, which means there is more space available (illus.146) .

Generally, the calf circumference of firefighter boots ranges from about 15 inches to over 20 inches (38 to 51 centimeters). For safety and to prevent chafing, they should fit snugly, but they should not be so tight as to cause discomfort or restrict blood circulation. There should be enough space to comfortably accommodate the firefighter's calf, even when wearing thick socks or trousers underneath. (Haixusa, n.d.)

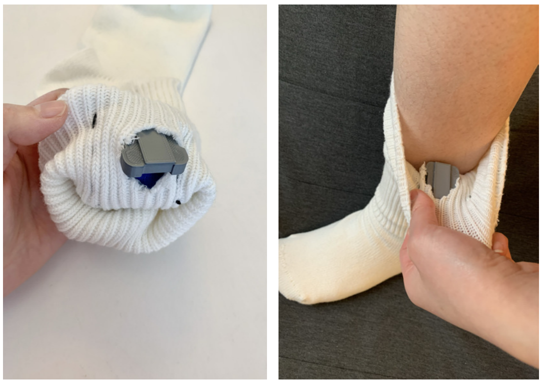
Open Pore Foam

Thermal barrier, aids in transporting moisture to the outside and increasing comfort.

illus. 146

- The pocket should be placed on the outer side of the sock.

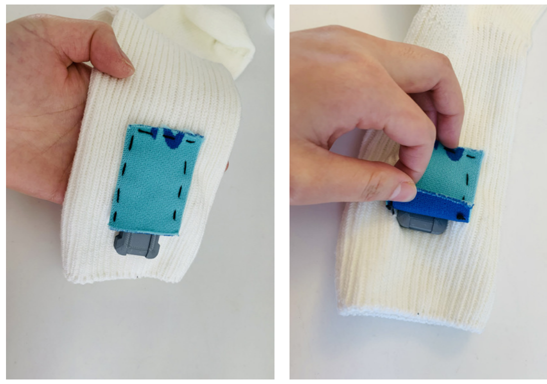
Pocket construction



illus. 147

Reinforcing the sock hole
To ensure the hole of the sock maintains its shape and size, thus keeping the product in place without slipping through the hole. A solution has been chosen that reinforces the opening through buttonhole stitching at the edge of the sock opening. This stitching technique forms a tight edge, preserves the opening shape, prevents wear, and enhances the hole's durability. (illus.147; 149; 150)

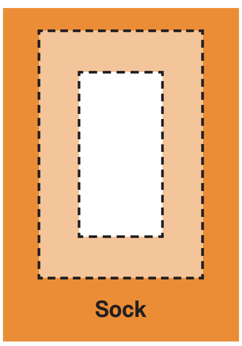
However, further experiments and tests are still needed to determine the width of the seam, and to find an optimal balance between comfort and the stability of the sock opening.



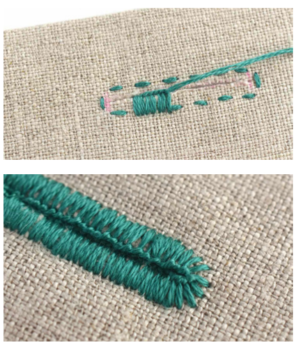
illus. 148

Pocket closure system
To prevent the product from falling out, the opening of the small bag needs a closure system. More importantly, this closure system also ensures that the integrity of the sock is not damaged when the product is not in use. Considering that zippers, which are hard metal, may increase discomfort, Hook and loop is chosen. In the pocket construction, it will exceed the width of the bag opening where the product is placed, thereby ensuring structural integrity. (illus.148)

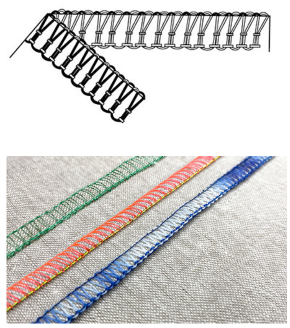
Overlock stitching is chosen as the method for attaching the pocket to the sock. It is commonly used at the edges of fabrics in garment construction, where the thread wraps around the edge of the fabric to prevent wear and secure the pocket firmly to the sock. (illus.151-152)



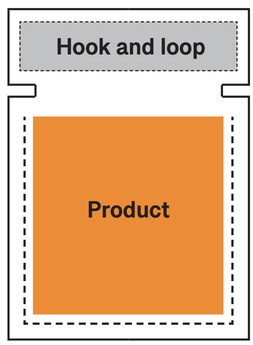
illus. 149



illus. 150



illus. 151



illus. 152

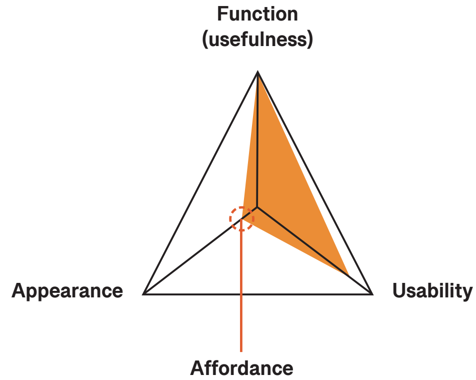
illus.153:FR Blending Knitting Fabric

illus. 154

Pocket material
The material for the small bag needs to be heat-resistant while also possessing sufficient elasticity to conform to the surface of the sock when no product is inserted. Therefore, Nomex and Spandex blend knitted fabric is chosen. It combines the flame-resistant properties of Nomex and the elasticity of Spandex. This material is also used for elastic close-fitting firefighter station uniforms, so it complies with NFPA 1975 standards (illus. 153). Moreover, to maintain the fire-resistant characteristic during bag sewing, all threads used are made from Nomex fire-resistant threads (illus. 154). (Haihuei, 2022)

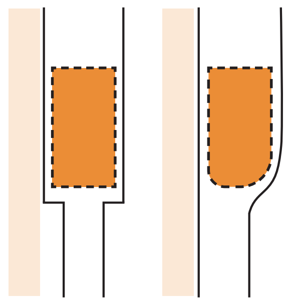
4.2 Aesthetics

Regarding the product's appearance, several interviews with different users throughout the project development reveal that they don't have particular aesthetic requirements. They value the product's functionality and usability more. Therefore, in developing the product's appearance, the focus is on functionality as the basis and usability as the goal, while also considering the requirement of affordance to enhance user experience.

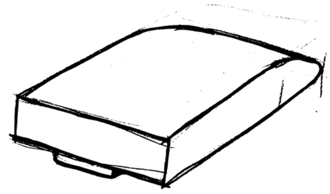


1

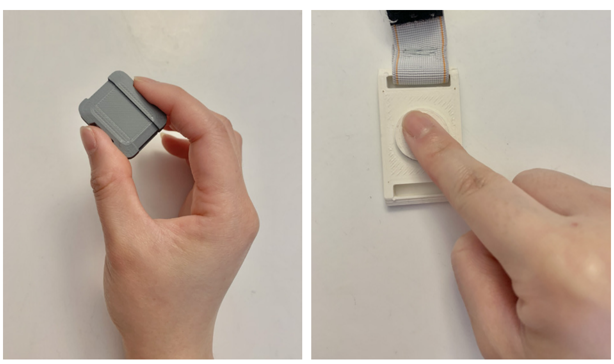
illus. 155

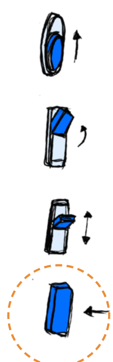


As the product's use involves sliding it into a sock, a prototype with both straight edges and rounded edges is used to simulate this scenario. The results indicate that straight edges hinder the product's insertion into the sock, whereas rounded edges do not. Considering the product will be inserted into a pocket, the fabric on the outside also needs to be taken into account. Therefore, two lower edges of the product must be rounded.

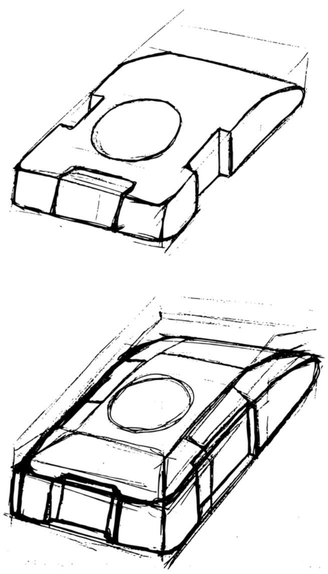


2



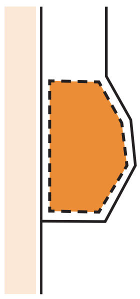


illus. 156

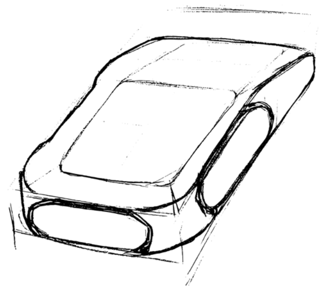


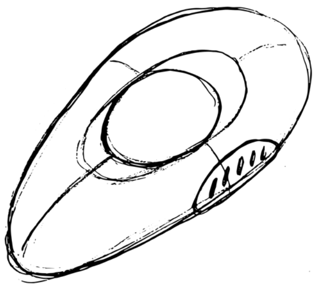
The product's shape should also consider the scenarios in which users grasp it and its on-off button. Preliminary product assembly indicates that the product will be relatively flat in shape. Considering the product's sides might be where users grip it, the product's button is chosen to be placed on the front. This potentially increases the interaction area between the user and the product, enhancing user experience and the product's affordance. As for the button mechanism, considering the product's small size, a press-and-release mechanism is chosen.

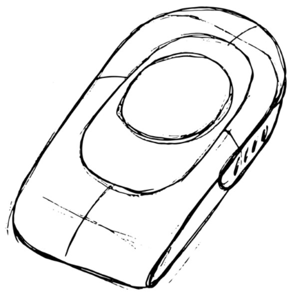
3



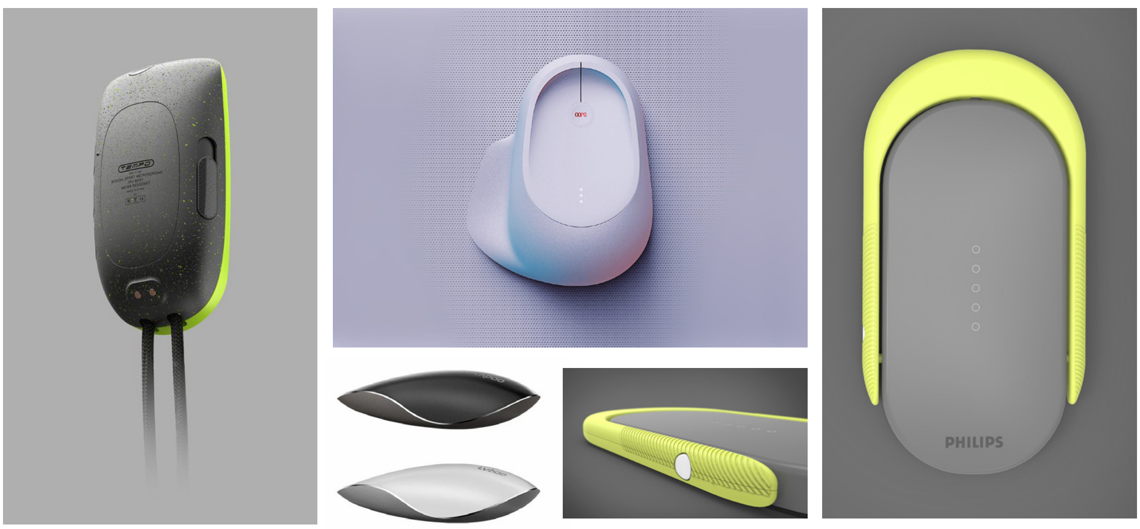
Considering the product will be placed inside a fabric pocket, the product's outer edges should avoid a rugged appearance that might cause fabric wear. Additionally, a rugged appearance could potentially cause discomfort due to friction between the product and shoes. Therefore, a sleek-looking product styleboard is created to help navigate the development of the product's appearance.







Styleboard - Form



illus. 157

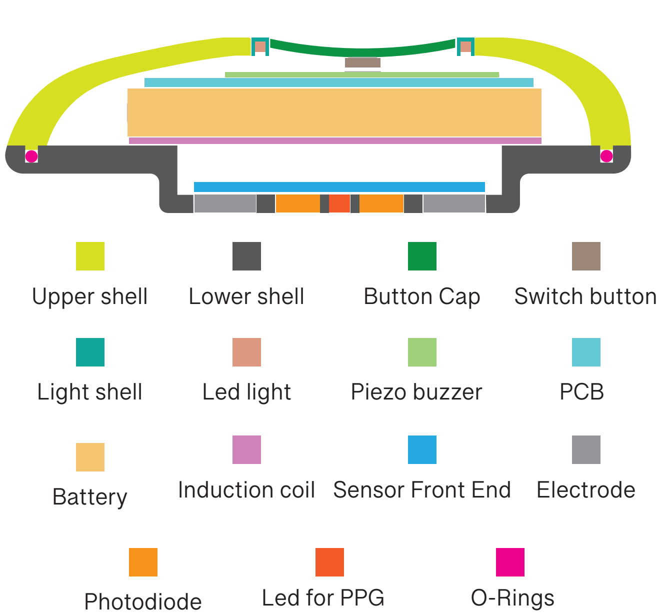
Styleboard - Color

illus. 158

4.3 Product architecture

Construction

Since the product's shape and style are determined, before further developing its appearance, the specific components needed for the product are studied to solidify the concept and establish the product's construction. Among these, key parts such as the sensor frontend and other technical components that need to come in contact with the skin, are positioned prominently at the bottom of the product. This way, the rest of the product can be separated from the skin by a layer of sock to increase comfort. Apart from the components already introduced, other components are presented as follows.



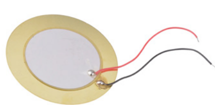
illus. 159


illus. 160

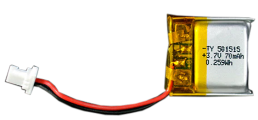
Switch Button
Given the small size of the product, the mechanism of Tactile Switches is chosen to provide the best user experience. The recessed button cap is designed to prevent accidental triggering due to possible contact with shoes.


illus. 161

LED Light
Since the product is a power-consuming device, it is essential for users to understand the battery status. A mini LED light strip is embedded at the top of the product, allowing users to visually grasp the power consumption situation.


illus. 162

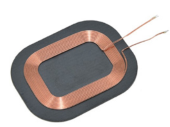
Piezo Buzzer
The piezo buzzer is a compact, efficient, and low-power audio device. It's commonly used in alarm systems due to its precise frequency control, enabling stable, clear warning sounds.


illus. 163

Battery
As a daily wearable device, the product needs to store power. A Li-Po battery is chosen since it is a rechargeable battery with high energy density, low self-discharge rate, and stable performance. The battery is the largest component, consisting of three 3.7V cells connected in series to power the piezo buzzer, usually at 9V for a louder sound. With a 150mAh capacity, the product can run for at least 24 hours, including two hours of alarm, without GPS and Leds (app.10).

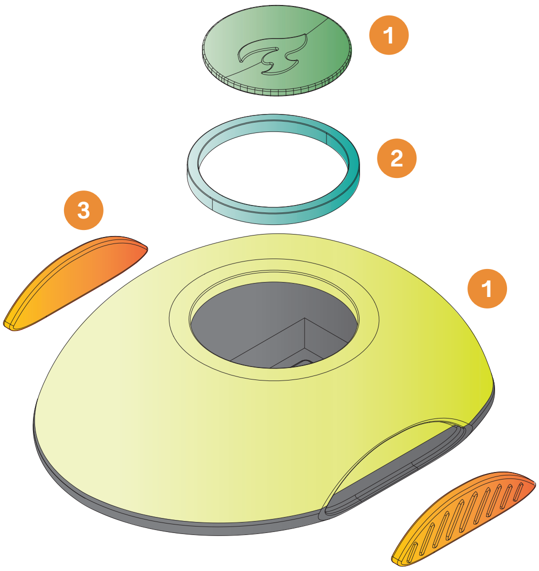
Since the buzzer still needs to be tested in real-use scenarios to determine the appropriate decibel level and operation status under extreme conditions, power consumption needs to be recalculated.

Wireless Charging Coils
To avoid corrosion risks from a humid environment, the product uses wireless inductive charging. This method employs electromagnetic induction, generating a magnetic field when current passes through a charging station or pad, thus inducing a current in nearby devices. The Qi standard, set by the Wireless Charging Alliance, supports a 4 cm charging distance and delivers 5-15 watts for small devices.


illus. 164

Material

The choice of materials for the product is based on the ability to withstand the harsh firefighting environments and usage conditions that firefighters may face. According to requirements collected from summaries of fire scene environments, the material of the equipment should be able to withstand high temperatures of 260 degrees Celsius for at least 5 minutes and safely come into contact with skin at 60 degrees Celsius.



illus. 165

illus. 166

1. Celazole® T-Series

The product's casing and buttons are made from Celazole® T-Series, the primary material for the product, used mainly to protect the device to withstand the fire scene environment and allow safe use by users.

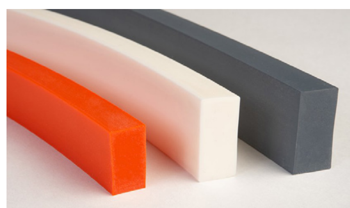
This material is a moldable, injectable composite formed by blending PBI (Polybenzimidazole) and PEEK (Polyether ether ketone) polymers. PBI is a high-temperature polymer, capable of withstanding temperatures up to 537°C, widely used in various firefighting applications. Its heat resistance, abrasion resistance, strength, and mechanical property retention are the highest among all thermoplastic plastics on earth. PEEK adds to the composite's overall mechanical strength, chemical resistance, and thermal stability, enhancing its injection molding and extrusion handling. (Polymics, 2023)

illus. 167

2. NEXTREMA® glass-ceramic

As for the LED light strip casing, apart from being able to face extreme environments, it also needs certain transparency. Therefore, NEXTREMA® heat-resistant glass-ceramic is selected.

This is a sturdy insulating material with excellent temperature resistance, capable of withstanding up to 950°C, as well as being resistant to acids, alkalis, and corrosion. Its linear thermal expansion coefficient is almost zero, maintaining stability even under extreme temperature differences (Schott, n.d.).



illus. 168

3. Silicone rubber

The grips on both sides of the product provide anti-slip properties and are easy for users to hold. Silicone rubber is chosen for this part. It is a material with excellent resistance to high temperatures, ultraviolet rays, ozone, and fire. Its thermal stability is outstanding, maintaining its utility within a temperature range of -55 to 300°C. In addition, silicone rubber has excellent water resistance and low chemical reactivity, and it does not promote the growth of fungi, microbes, and bacteria. (SpecialChem, 2023)

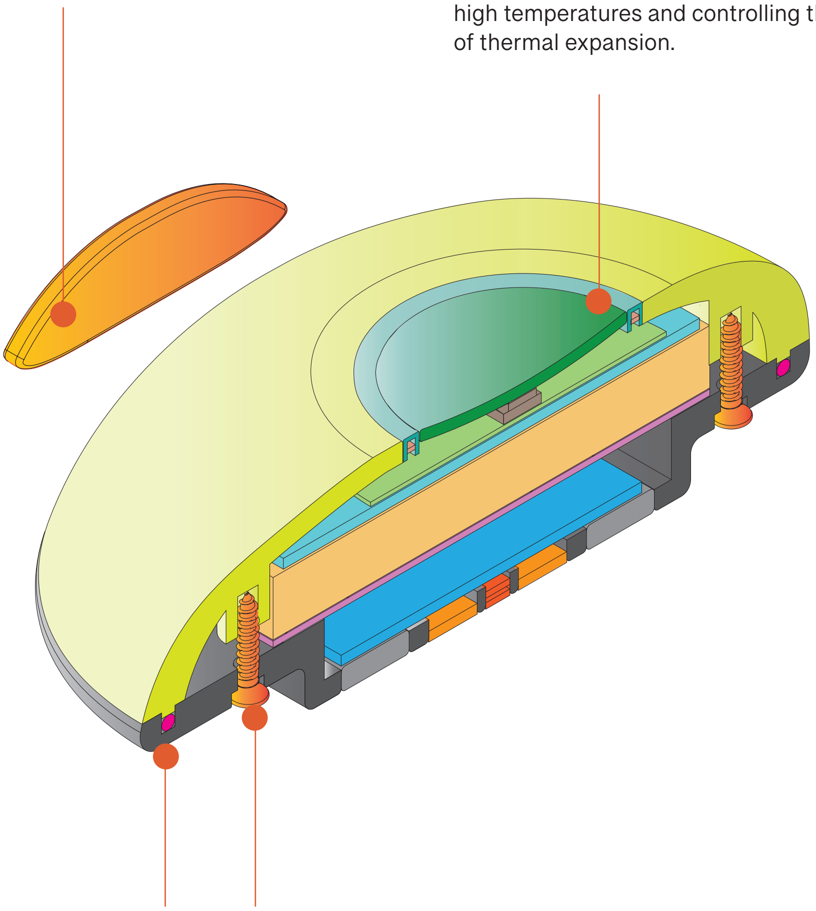
Production & Assembly

Given the potential for extremely wet and complex environments in which the product will be used, to ensure that it works in such environments and can be used safely by users, the device should comply with IP protection standards. IP68 is the highest International Protection (IP) standard, describing how equipment resists the intrusion of liquids and solids. "6" signifies that the device can prevent the entry of dust. "8" indicates that the device can be submerged in water for a prolonged period without damage. An IP68-rated device can be submerged in water up to 1 meter deep for 30 minutes (Smith, 2022). The following is the assembly scheme developed for the product considering IP protection, which is still under testing.

Overmolding

The grips on both sides of the product are made using overmolding. The process involves placing plastic parts in a mold and injecting silicone rubber, with the heat generated during the molding process causing the silicone to adhere to the plastic (Miwo, 2023).

The buttons, LED light housing, and the product's upper casing are also assembled together using overmolding, which directly molds silicone rubber onto these parts, forming a single entity to protect the product from the effects of dust and liquids. However, there are technical challenges to be addressed during the manufacturing process, such as dealing with high temperatures and controlling the coefficient of thermal expansion.



illus. 169

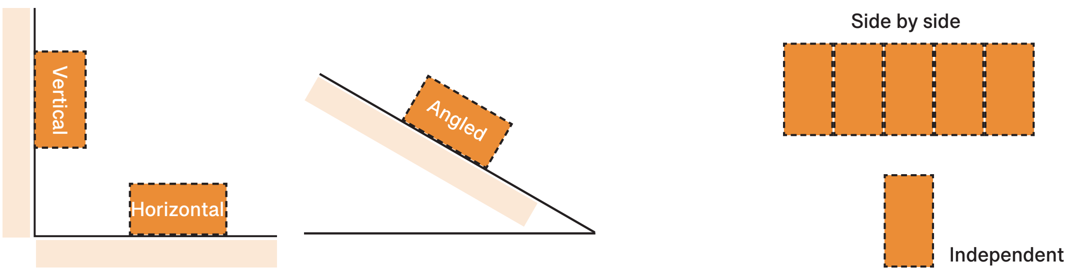
Screws and Silicon O-rings

The upper and lower casings of the product are assembled together using four screws inserted from the bottom casing. This flexible installation method allows for component replacement, making the product more sustainable without affecting its appearance. Furthermore, there is an O-ring gasket in the groove where they are assembled together. This is the most common, very useful, and least expensive method to make the device waterproof and dustproof. The primary mechanism is that the rubber is elastic and covers the two connecting components, preventing any liquid or dust from entering between the component and the seal (O-rings, n.d.).

4.4 Charger

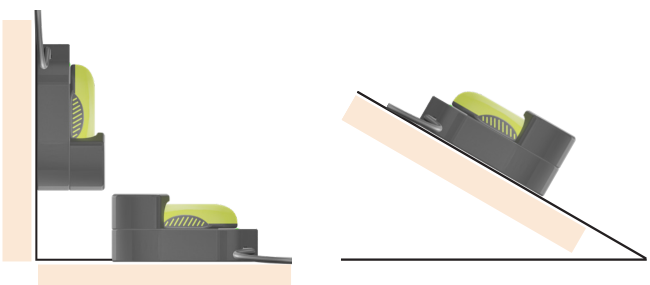
With the determination of the product's charging method, the product's charging stand, which is part of the product system, has been developed. Based on the product's shape and inductive charging method, the charging stand also needs to match the equipment system of the fire station.

illus. XX

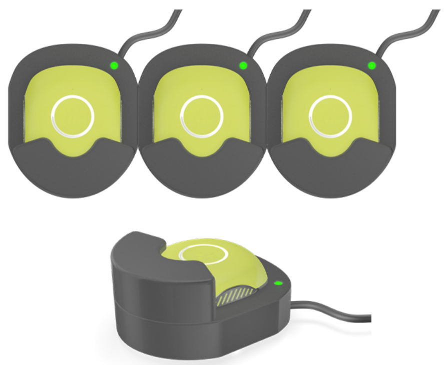


Observations of firefighters' electronic devices show that equipment can be installed on planes of different angles, including horizontal, vertical, and angled surfaces. Therefore, the product's charging dock must be able to keep the product stable on these surfaces.

In addition, the charging dock for electronic devices needs to be able to function independently, and multiple docks should be able to be placed side by side to meet the different needs of usage scenarios.



illus. 170



illus. 171

illus. 172

Charging stand

The appearance of the charging stand remains consistent with the product's style, and its color is align with other chargers in fire station. The lower part is a slot providing product support and keeping it in place, even on vertical or angled surfaces. The charging dock can operate independently or be placed side by side. Furthermore, an LED indicator light is positioned above the power cord on the upper right as a successful power supply reminder.

The construction of the charging dock is simple, mainly including an inductive coil for powering the product and a microcontroller board used for power management and LED light control. ABS is chosen as its main material, because this material has good mechanical strength and wear resistance, while also being able to withstand certain temperature changes.

Table of requirements 2.0

Through the creation and testing of the Minimum Viable Product (MVP), key features have been concretized, leading to further updates in design requirements. In addition, two new product features have been extended from the information convey function, namely location and distress signal.

Fundamentals	Requirement 1.0		Requirement 2.0	
Time	Not increase the turnout time.	P20	Integrate product into fire socks.	P71
Portability	Be portable by firefighters.	P18	Embed the product in an outer pocket of the sock.	P71
	Be worn in a removable way.	P47		

Fundamentals	Requirement 1.0		Requirement 2.0	
Comfort	Be comfortable.	P19	The product's contact area with the skin protrudes, and fabric acts as a barrier between the product and the skin.	P65
	Not impact the mobility of firefighters.	P19	Pockets should be positioned to avoid areas of rib stitching and extra padding.	P74
			The product should be placed at least 5-8 cm away from the top of the sock.	P75
			The pocket should be placed on the outer side of the sock.	P75
			The appearance of the product should avoid corners and sharp edges.	P79
	Not add much weight to the firefighter.	P19	The choice of concept technology is suitable for small wearable devices.	P42

Fundamentals	Requirement 1.0		Requirement 2.0	
Standard	Not affect the integrity of the protection of existing firefighter protective equipment.	P16	Pockets need to have a hook and loop closure system.	P77
			Reinforce the opening through buttonhole stitching at the edge of the sock opening.	P77
	Be compliant with Personal Protective Equipment standards.	P18	**NFPA 1982 for PASS devices. P55**	
	Be durable enough to withstand the abrasion on the fireground.	P35	Retain function at a skin temperature of 60 °C.	P57
			The material can withstand a high temperature of 260 degrees Celsius for at least 5 minutes.	P57
			The alarm should be able to reach 95 dBA.	P57
			Celazole® T-Series, NEXTREMA® glass-ceramic and Silicone rubber are materials of the product.	P81
			NFPA 1975 standard for fabric. P65	
			Nomex and Spandex blend knitted fabric is the material of pockets.	P77
			Nomex fire-resistant thread is used for sewing.	P77
			IP68 protection standard	
			Components with gaps are assembled by overmolding.	P82
			An O-ring gasket is in the assembled groove of the product housing.	P82

Fundamentals	Requirement 1.0		Requirement 2.0	
Maintenance	Be maintainable.	P35	A switch button is present.	P80
	Be worn in a removable way.	P47	The housings are assembled together by screws.	P82
			The product system includes a charging base.	P83

Key functionalities	Requirement 1.0		Requirement 2.0	
Data collection	Have heart rate, oxygen saturation and respiration monitoring via reflective PPG technology.	P42	Photodetector *2	P59
			Sensor front end with green LEDs	P59
	Allow the sensor system to come into contact with the skin.	P42	Measurements using the PPG technique require securing the device to the skin and avoiding displacement.	P59
	Have sweat monitoring via EDA technology.	P44	Bioimpedance senso *1	P44
			Stainless steel dry electrode *2	P44
	Have skin temperature monitoring via themistor technology.	P44	Thermistor *1	P44
	Have movement monitoring via MEMS sensor	P45	MEMS sensor *1	P45
Work automatically	Not require firefighters to be distracted to operate it while on duty.	P17	Be able to operate continuously for 24 hours.	P67
	Be able to work automatically.	P31	150mAh Li-Po battery *1	P45
	Enable long-term monitoring of firefighters' vital signs.	P37		
Information convey	Provide real-time monitoring.	P41	The information is transmitted to the cloud, and the commander and workshop personnel can access the information.	P55
	Reduce dependence on their radio system.	P18	Information is conveyed to commanders via Wireless Sensor Networks (WSNs).	P55
	Not impact their current radio system.	P23	Firefighter location information needs to be communicated. (Location)	P55
			GPS *1 and barometer *1	
	Be able to convey monitored information to firefighter teammates and commanders.	P33	Information is conveyed within the team through alarms. (SOS Distress signal)	P55
			Piezo buzzer *1	P80
Dismiss manually	Be able to let firefighters know their physical condition.	P37	The information can be communicated to the firefighters themselves via vibrations.	P55
			Haptic Driver *1	
	Give firefighters some autonomy in decision-making.	P18	Can manually dismiss the alarm through MEMS sensors.	P64

illus.174

IMPLEMENT

This chapter presents how the product is introduced to the market, including the creation of a business plan and operational value chain. The cost and pricing of the product system, as well as opportunities for scaling, are also described.

5.1 Business strategy

In order to introduce the product to the market, a detailed business plan is being developed to make the market strategy clearer and more precise.

1. R&D (research and development)

The development of the project is attributed to the close collaboration with NOBR, gaining firsthand insights from the primary users - firefighters and secondary users - incident commanders, and facilitating the establishment and growth of the project through iterative testing of the MVP. Since the project is still in the concept validation stage, functional prototypes need to be created and tested in real environments, followed by continuous optimization. This requires continued collaboration with NOBR.

2. Certification

Prior to the product's market entry, professional testing is conducted to ensure it meets corresponding standards, thereby guaranteeing product quality. This requires referencing NFPA 1982 standards for fire tolerance and alarm-related requirements of PASS devices.

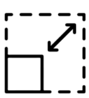
3. Collaboration

Collaborating with Dräger and receiving investment from them, Dräger will become a key partner for the startup, serving as the main sales platform in the B2B sales model when the product enters the market. Additionally, coupling the product with their mature, fire scene compatible wireless data transmission physical gateway will yield additional economic benefits for them. This strategy also helps shorten the development and launch time for the product system.

Dräger is a global leader in medical and safety technology, revered in firefighting equipment. They commit to delivering "innovative technology with comprehensive support" for human life. This aligns with the startup's philosophy, helping to establish brand image and introduce the product to their vast existing customer base.

4. Production and launch

Cooperation with material and service suppliers enables mass production and market launch of the product. The marketing strategy involves simultaneously opening B2B and B2C sales channels, which helps expand distribution channels and market coverage. Customers can obtain the product through the Dräger platform or directly purchase from the company's official website.



6. Scaling up

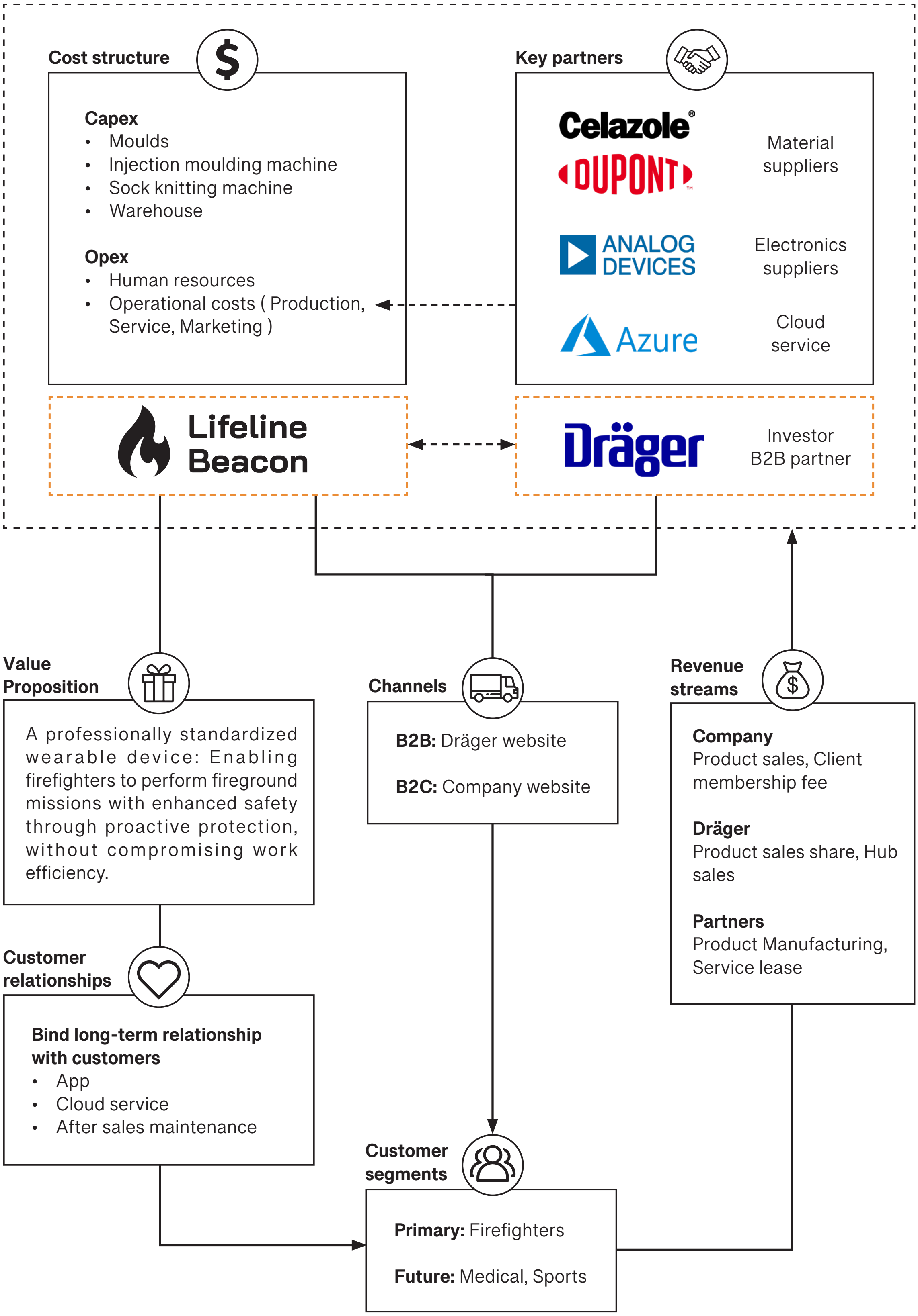
Upon achieving financial balance, the company invests in the development of the next-generation products, thereby expanding the market to other target groups.

5. Break-even

After a certain number of products are sold, the company reaches the break-even point, generating returns for the company and investors.

Operational value chain

A business model canvas has been created here to visualize the key elements involved in business operations and how they interconnect in the value chain. It helps foster a shared understanding of the business model among stakeholders, facilitating their adjustment of activities, discussions, and decision-making.



5.2 Estimates and Pricing

Cost

To estimate the economic benefits that this project can bring, the cost is calculated first, including variable costs of product manufacturing, wages, service leasing, and fixed costs of investment (app.11).

The manufacturing cost of the product includes material costs, manufacturing costs, 25% overhead, and packaging and transportation costs. It decreases when the manufacturing volume exceeds 10,000 units. The cost calculation is based on the sale of the product as a set, including a main product, a charging base, and two pairs of socks. (illus.175)

Product	Cost > 10000 pcs	Cost small amount	
Main product	59.26	77.50	$ per unit
Sock	8.31	12.31	$ per unit
Charging station	8.70	8.70	$ per unit
1 set: 1 product + 1 charger station + 2 pairs of socks			
Total	**84.58**	**110.82**	$ per unit

illus. 175

Wages	Cost	
Wages (Denmark)	58,000	$ per year
Employees	2	persons
Total	116,000	$ per year

Service	Cost	
Cloud service	10,000	$ per year
Software maintainan	6,000	$ per year
Marketing	5,000	$ per year
Total	21,000	$ per year
Total	**137,000**	$ per year

illus. 176

To run the company, it is estimated that two employees will be needed in the initial startup, responsible for manufacturing and sales management, as well as after-sales service. In addition, due to the sensitive information involved in the data collected by the product (personal health data), to ensure the security, privacy, and availability of user data, the startup needs to purchase cloud services to provide data management and security protection capabilities. At the same time, because the product system comes with app services, the maintenance cost of the App and software is also considered. 15% of the annual software development cost is used for software maintenance (Chomko, 2012).

Regarding investment costs, after cost-conscious consideration, the company only invests in molds and manufacturing machines for the main materials of the product, while the manufacturing of components made up of other materials will be outsourced. In addition, the company needs to spend about 40,000 dollars to develop software adapted to the product (SPD load, n.d.) (illus.177). The investment here will be provided by the partner, Dräger.

Initial investment	Cost	
Mould for product upper shell	2,000	$
Mould for product lower shell	2,000	$
Mould for charging station_P1	2,000	$
Mould for charging station_P2	2,000	$
Mould for charging station_P3	2,000	$
Injection moulding machine	30,000	$
Sock knitting machine	3,400	$
Software development	40,000	$
Total	83,400	$

illus. 177

Pricing

To establish a reasonable price, factors such as costs and competitors' pricing are taken into account. After conducting a comparative analysis of competitors, the final price for each product set is set at $315 to ensure strong market competitiveness. (illus.178)

It is important to note that the pricing strategies differ between B2B and B2C sales, allowing partners to benefit. Additionally, as the company's business model focuses on building long-term relationships with customers, a yearly membership fee of $240 will be charged to each customer in exchange for various services. To estimate revenue, it is assumed that each customer will purchase a one-year membership. (illus.179)

illus. 178

Source of income	Retail	Partner	
Selling price	**315**	**220**	$ per set
Membership fee	240	240	$ per year
Total	**555**	**460**	$ per set

illus. 179

Break-even

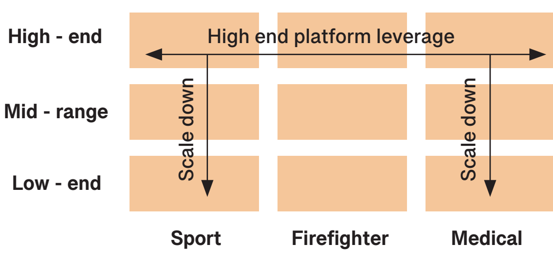
	Time		Sales units	Profit Company	Profit Investor
B2C	Year	0	0	-$400,000	
	Year	1	2,000	$751,360	
	Year	2	5,000	$1,683,900	
	Year	3	8,000	$3,184,440	
	Year	4	10,000	$4,314,200	
	Year	5	10,000	$4,314,200	
B2B	Year	0	0	$0	-€ 83,400
	Year	1	500	$174,590	€ 47,500
	Year	2	1,000	$349,180	€ 95,000
	Year	3	1,500	$523,770	€ 142,500
	Year	4	2,000	$750,840	€ 190,000
	Year	5	2,000	$750,840	€ 190,000

illus. 180

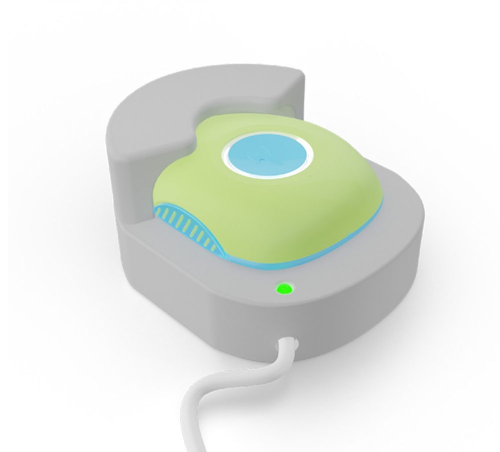
From product development, obtaining certification to signing a cooperation contract with investor Dräger, it is estimated to take a year in total, with research and development costs amounting to $400,000. The product is expected to be launched in the second year. To estimate product sales, the number of potential customers is surveyed. Available data indicates that there are a total of 1,063,400 active, volunteer, and paid firefighters in the United States (FEMA, 2023), and approximately 365,000 individuals employed as professional firefighters in the European Union (Eurostat, 2022). Therefore, it is realistic to estimate sales of 2,000 units in the first year after market launch, and sales are expected to increase annually as marketing efforts continue. (illus.180)

To forecast revenue, the company's and investors' cash flows are calculated (app.XX). The revenue projections for the company and investors over the next five years are explained in the table below. In addition to generating revenue through the B2C model, the company can also gain sales shares through the B2B model. As shown in the table, the company can achieve a break-even point in the second year, while investors will reach a break-even point in the third year. According to the business plan, once the break-even point is reached in the first year following market launch, the company will allocate new development funds for market expansion. This will involve hiring four employees to manage additional production and distribution lines, as well as marketing, and the corresponding service leasing expenses will double as the customer base expands. Despite the increased costs, the company will be able to recoup the investment and generate profits in that year.

Scaling



illus. 181



In addition to the current market segments, there is great potential to expand the market to different user segments such as sports and healthcare, as they all have a need for vital signs monitoring. While the initial user group for the project is firefighters, who have the highest demands for product quality and performance, there is an opportunity for the product to expand into the mid-range or low-end market segments (Meyer, 1997) when targeting other customer segments. Furthermore, due to its flexible installation method, the product has significant room for customization of monitoring functions according to the specific needs of different customer groups. Additionally, the product can easily be embedded in objects beyond socks, allowing for potential future development of the company's product line to extend to other wearable devices compatible with the product. (illus.181)


LAC
SPERIAN

EPILOGUE

This chapter is the end point of the introduction to the project process, stating an evaluation about the project, and reflections on the product and the process as a whole.

illus. 182

Conclusion

Fireline Beacon is an innovative safety device designed for the firefighting market, born out of identified market opportunities. However, introducing a new product into the firefighting market faces challenges such as low compliance, discomfort, and mobility impact, all of which are identified through in-depth analysis of firefighting equipment and user interviews. These issues threaten firefighter task efficiency and safety, driving the project's development. Time is a key factor for firefighters; they have no extra time to wear additional devices. Therefore, product development focuses on resolving these issues, ultimately integrating the product into firefighter socks to minimize the impact of usage. The product's uniqueness requires it to meet high standards, dictated by research into fire scene environments and product usage environments, guiding material selection and product construction.

Considering the product's market positioning aims to enhance firefighter safety, product development expands to encompass key individuals in the entire scene, not just firefighters. Regarding how the product operates in a team and system, a key point is how information is transmitted, facing certain constraints and challenges. The product also needs to minimize reliance on and impact on the current radio system. Research into the causes, symptoms, and timelines of firefighter casualties reveals design opportunities to improve safety by monitoring vital signs and activity levels. The product's monitoring data needs to be transmitted to companions on the fire scene and commanders outside, with the low visibility on the fire scene making alarms the best mode of information transmission. Wireless sensor networks are chosen to monitor firefighter vital signs, promoting timely rescue and dynamic personnel deployment. To improve firefighter safety and autonomy, the product's vibration function can also enhance firefighter awareness in non-emergency situations, helping to prevent injury situations from worsening.

Reflection

Product

The development of the concept is based on iterative prototype building, testing, and learning. Thus, many key features have been confirmed throughout the process.

Standard Testing
Given the unique work environment of firefighters, their equipment has stringent requirements and various standards. Based on research into fire conditions and product use environments, essential standards that product development needs to meet are identified. These standards guide the selection of materials and the foundation of product construction. However, due to complex standards for firefighting equipment, time constraints, and the difficulty of testing in real environments, some assumptions are still based on the working principles found through desktop research. Therefore, to fully verify the concept, these standard tests must be carried out.

Embedded Objects
The firefighting sock scheme is a comprehensive consideration of product monitoring technology requirements and a result of evaluating all possible wearable options for firefighters. Attempts to increase the comfort of firefighters using it and minimize the impact of mobility are made through proposing various solutions. However, the addition of an extra device still impacts firefighters. Although socks are something a firefighter is likely to wear for a long period, and the inherent elasticity of socks provides advantages for the monitoring function of the product, the acceptance of this scheme by the entire firefighting community remains questionable. As the target audience for the project includes all firefighters, this implies diverse user preferences, which creates a dilemma for defining the position of the device. Therefore, the embedded object still needs further evaluation.

Monitoring Technology
The product involves different monitoring contents, leading to various monitoring technologies. Due to time and technology accessibility constraints, only one technology was experimented with and confirmed during the development process. As the components involved in these technologies will directly affect the construction and appearance of the product, there is a need to clearly understand the specific requirements of all the involved technologies and their components before further developing the product. For example, the number of LEDs and photodetectors required for PPG technology to ensure optimal measurement results, and the volume of the electrodes and the required skin contact area for EDA technology.

Manufacturing Method
The product must comply with international protection (IP) standards, which dictate its assembly and manufacturing processes based on its intended environment. Accordingly, silicone O-ring and over-molding techniques are proposed. However, a potential problem arises when combining the disparate properties of two materials that can be used in a fire environment: Celazole® T-Series and NEXTREMA® glass-ceramic. Their differing thermal properties could cause structural problems during molding due to varied expansion coefficients. Further research is needed to ascertain whether careful temperature control can address this concern; otherwise, an alternative solution will be necessary.

Process

As my graduation project, this endeavor differs from my past semester projects in numerous ways, particularly regarding project duration and the breadth of milestone setting. This new environment, coupled with unfamiliarity with the project's subject matter, led me initially to an insufficiently agile state where I spent a lot of time delving into the project's background and exploring the problem. However, such an approach carries significant risks of "doing the wrong thing," leading to wastage of time and resources.

Recognizing this issue, I engaged in deep reflection on my project management strategy. I started employing lean and agile thinking to optimize project progress, getting the project back on track. By integrating design thinking with the Lean Startup mindset, I implemented a new strategy: continually verifying assumptions to reduce uncertainty and better manage risk. This novel method not only boosted the project's efficiency but also provided a strong impetus for its further development.

Moreover, I realized the critical role of more systematic and structured project management for long-term, broad-ranging projects. To adapt to this context, I incorporated more feedback loops and regular check-ins in the planning and implementation process. This approach enables the early detection of potential problems and timely adjustments, thereby more effectively leveraging my resources and avoiding unnecessary or incorrect tasks.

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Illustration

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