Head and body cooling for the Dutch national field hockey goalies

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Joost Schootstra

Student
Joost Schootstra
4300572

Supervisory team
Chair: Prof. dr. ir. Jansen, K.M.B.
Mentor: Dr. Teunissen, L.P.J.
Contact at KNHB: D. Van der Laan

University
Delft University of technology
Industrial Design Engineering

Master Program
Integrated Product Design

Preface

This is the process report of 'Head and body cooling for the Dutch national field hockey goalies'. In here, the design process is shown to create cooling solutions that will help keep the Dutch national field hockey goalies in peak performance during the hot and humid conditions during the Summer Olympics of 2021.

Having played for many years as a field hockey goalie during my youth has been a great factor in choosing to work on this project. After starting the project I started playing again in a recreational team at RHC Rijswijk. This allowed me to empathize and connect with the target group, learning about the problems the goalies face during hot days. Next to that, it allowed me to test the prototypes first hand.

I want to thank Kaspar Jansen and Lennart Teunissen for supporting me throughout the duration of the project, Linda Plaude as well the employees at the digital fabrication lab and the model making and machine lab for helping me realize my prototypes, Inuteq for the guided tour in their workshop and Doris van der Laan for giving feedback on this project.

Enjoy Reading!

Joost Schootstra

Executive summary

Exercising in hot and humid environments can be very demanding for the human body. The next Summer Olympics (postponed to 2021 due to the COVID-19 outbreak) will be held In Tokyo. The average heat and humidity during this period is respectively 35°C and 70 to 80%.

This will put the athletes in risky situations due to the rise of the body temperature during the exercise.

Goalkeepers in field hockey are especially prone to the heat since they have to wear thick insulating protective gear to keep them safe. A rise in body temperature can deteriorate their responsiveness, raising the chance of letting opponent score.

The context of the goalkeeper has been analyzed for this specific weather situation. A set of cooling packs has been produced that can be placed under the trunk and spine area of the body protector, and under the sweatband inside the helmet.

Compromises had to be made to satisfy the comfortability, mobility, cooling duration, safety and ease of use. The mobility of the goalkeeper had to stay as high as possible, therefore only spots were chosen that were already covered by an existing piece of protective gear. Insulating material has been added to one side of the cooling packs so that the user can choose for higher or lower intensity cooling depending on their preference. The active cooling duration for each cooling pack is no longer than half a match in order to keep the packs as light as possible. The packs thus had to be easily replaceable since they have to be replaced during halftime. The compartments of the cooling packs shown in the design proposal on the next page had to be connected to the surrounding compartments, allowing the cooling liquid to flow away during impact, resulting in higher durability of the product. The holes that connected the compartments could not be too wide, since the liquid would flow down due to gravity, resulting in uneven distribution of the cooling liquid throughout the pack. To help resolve this last issue, a thickening agent has been added to keep the cooling liquid distributed evenly. All materials inside the cooling packs are non-poisonous in case the cooling pack would fail for any reason.

Multiple phase change materials have been tested. The final designs are filled with a mixture of ethanol, water, carboxymethyl cellulose (for an increased viscosity) and an edible blue coloring agent to give the perception of cooling.

The trunk and head packs are sealed using a heated aluminum mold. The back cooling pack is sealed using a laser engraver. The trunk and head cooling packs have been tested on impact under the protective gear according to European regulation and could be manufactured and used immediately. The Back cooling pack has not been tested on impact since there is no regulation to protect the back of the goalkeeper. Under normal use this pack would also not fail.

Design Proposal

Figure 1: Final prototypes

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1. Introduction

The next summer Olympics will be held in Tokyo, Japan. During these Olympic Games, the temperature and humidity will be relatively high (35°C and 70-80%). In order to prepare the Dutch athletes for these conditions, TU Delft collaborates with several universities, sports federations and companies in the 'Thermo Tokyo' project. In this project, we aim to develop and evaluate ways to limit performance loss and lower the amount of safety hazards associated with exercise in a hot and humid environment. TU Delft is specifically involved in developing cooling solutions.

There are various ways of cooling to limit performance loss during exercise in hot environments. Cooling can be applied before the exercise (pre-cooling), while exercising (per-cooling) or after the exercise (post-cooling). In sports-related literature, pre-cooling is widely studied, as this is a possible method to lower core and skin temperature before starting the exercise. Studies on per-cooling are however not as frequently conducted, as it is often difficult to cool during a competition due to practical and/or regulatory limitations. However, cooling during exercise could lower core and skin temperature and slow down the rise in temperature.

In field hockey, one of the athletes who is especially prone to the heat during competition is the goalkeeper. In contrary to field players, the goalie is not exchanged by a substitute every few minutes. Furthermore, the goalie is wearing a lot of (insulating) protective gear, limiting (evaporative) heat exchange with the environment. Next to that, evaporation is limited to a certain extent due to the humid climate in Tokyo.

2.1 Thermal regulation of the human body

The human body has an average internal temperature of 37°C. This internal temperature can increase to 38°C or decrease to 36°C due to circumstances such as the time of day, emotional state and physical activity (Epstein & Moran, 2006). The environment around the human body causes the body to cool down or heat up, but the internal thermal processes try to maintain a thermal balance. Figure 2 shows several methods of heat exchange of the body with the surrounding environment that can influence the heat balance. The amount of heat that must be transferred to maintain a healthy core body temperature depend on the metabolic heat produced by the body and the heat gained from the environment. To describe this (for a perfect heat balance), a heat balance equation is shown:

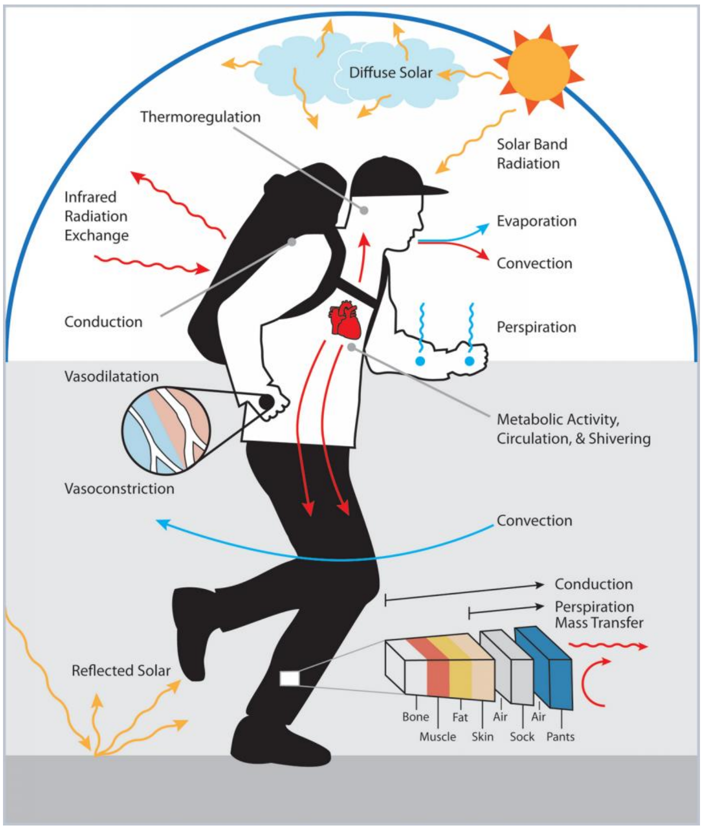


Figure 2: factors affecting thermoregulation on the human body

$(M–W_{ex}) \pm (R+K+C) = E_{req}$

$(M–W_{ex})$ = net metabolic heat production from total metabolic energy production (W/m^2),
M = metabolic rate,
W_{ex} = mechanical work;
$(R+K+C)$ = radiative, conductive and convective heat exchange (W/m2);
E = evaporative heat loss (W/m2).

In reality however, most of the time a positive or negative heat storage takes place, especially during exercise.

Metabolism defines the amount of energy that the human body produces through internal processes such as food digestion. An average human body produces about 17.5W of energy at rest, seated (Jetté, Sidney, & Blümchen, 1990). When physical activities are performed, the body requires extra energy. The metabolic rate increases with the intensity of the activity. Part of this energy is not transferred to kinetic movement, but to heat, which transports through the body through blood (Parsons, 2003). The metabolic heat production can be calculated with the following equation:

$H = M – W$

H = total metabolic heat production of the body (W/m^2);
M = metabolic rate (total energy produced (W/m^2));
W = external work performed by the body (W/m^2).

The surface area of the human body (BSA, m^2) can be estimated by the following formula when the height (H, m) and weight (W, kg) are known:
Women BSA = $0.000975482 \times W^{0.46} \times H^{1.08}$
Men BSA = $0.000579479 \times W^{0.38} \times H^{1.24}$ (Gehan, 1970)
An average Dutch male and female would be estimated to have a BSA of respectively 1.97 m^2 and 1.67m^2.

An average resting standing metabolic rate is around 65W/m^2 ,which would be 128 W for an average Dutch male (Parsons, 2003). This rate increases when physical activities are performed. A frequently used definition to measure the intensity of an activity is the Metabolic equivalent of task (MET), which translates to the amount of kilocalories burned per kg weight per hour. To calculate the energy use per minute, the following equation can be used:

Energy use per minute = (MET · 3.5 · Weight)/200

MET values for various sports are available online to use in this equation. For hockey the MET value would be 7.8 (Ainsworth, 2011). However, the MET value for a goalkeeper will be lower. With this equation, the energy consumption of a male hockey player would be 11 Kcal per minute, which translates to 800 W. Only a part of this energy is used to move the body, the latter is transferred to heat. The efficiency of the human body is about 25%, this would mean that 600 W out of the total 800 W is transferred to heat.

How do we lose the heat?
As seen in figure 2, the body will exchange the heat with the environment through conduction, evaporation, convection, radiation and respiration. In order to understand the working principles of these heat exchange methods, they will each be shortly discussed.

Conduction
Conduction is the transfer of heat through contact with solid materials. In figure 2 this is shown by the various layers the heat transfers through (bone, muscle, fat, skin, ai, sock, air, pants). Conduction can be calculated using the following equation:

$q = (k/x) \cdot A \cdot \Delta T$

q = heat flow (W);
k = thermal conductivity of a material (W/m^1K^1);
x = the distance between the two surfaces (m^2);
A = the cross sectional area of the surface (m^2);
ΔT = the temperature difference between the two surfaces (K).

Evaporation
During an exercise or in warm environments, the body needs to lose the extra heat to maintain thermal balance. The body can do this by increasing sweat production. The warm sweat can turn into vapor and transfer the heat to the surrounding environment.
Evaporative heat loss from the skin can be calculated with the following equation:

$Esk = (w(p_{sk,s} - p_a))/(R_{e,cl} + 1/(F_{cl}h_e))$

w = skin wetness (dimensionless);
$p_{sk,s}$ = water vapor pressure at skin, normally assumed to be that of saturated water vapor at t_{sk} (psi);
p_a = water vapor pressure in ambient air (psi);
$R_{e,cl}$ = evaporative heat transfer resistance of clothing layer (ft2·psi·h/Btu);
F_{cl}= clothing area factor, dimensionless.
h_e = evaporative heat transfer coefficient (Btu/h·ft2·psi).

Convection
Heat transfer through convection occurs when a liquid or gas flows along a surface with a different temperature. For example: airflow along skin. Convective heat transfer can be calculated with the following equation:

$q = hc \cdot A \cdot (Ts - Tf\,)$

Where heat flow *q* (W*)* is a function of the convective heat transfer coefficient *hc* (W/(m2•K)), the convective surface area *A* (m2) and the temperature difference between the surface temperature *Ts* (K) and the fluid temperature *Tf* (K).

Radiation
Radiation is the transfer of heat through electromagnetic waves such as sunrays. Radiation can be described by the following equation:

$q = \varepsilon \cdot \sigma \cdot A\ (T14 - T24)$

Heat flow *q* (W) is expressed as a function of *ε* (the emissivity between two bodies), σ (the Stefan-Boltzmann constant: 5.6703 10-8 (W/m2K4)), *A* is the area of the emitting body (m2), *T1* is the temperature (K) of the radiating surface and *T2* is the absorbing surface temperature (K).

Respiration
The air that we breathe in is heated inside our lungs. When we breathe out, the heated air leaves our body, resulting in heat loss. Heat loss through respiration is divided in sensible heat loss and latent heat loss (Djongyang 2010). They can be estimated using the following equations:

$C_{res} = 0{,}0014M(34 - T_a)$
$E_{res} = 0{,}0173M(5{,}87 - p_a)$

M = metabolic rate (W/m^2);
T_a = air temperature (°C);
p_a = ambient humidity (kPa).

Effects of a rising body temperature

The field hockey goalies wear a thick insulating layer of protection. Wearing this large amount of gear may increase the risk of heat strain since the thermoregulatory function is impeded. A research performed in 2008 measured the effects of heat exposure on thermoregulation and response time for field hockey goalies (Malan, 2010). Core temperatures, skin temperatures, body mass, fluid consumption and heart rate were administered from 5 participants during professional hockey games, as well as in 2 laboratory sessions. These sessions were held in a climate chamber set to cool (20C, 40%) and hot (35C, 40%). Inside the chamber, a hockey match was projected on the wall as seen from the goalies perspective. Prior to the match and after the match, response tests were taken (12 simulated penalty shots), measuring the movement of the goalies. With the core temperature increasing from 37.3 in the cold setting to 37,9 in the hot setting (figure 3), the average response time increased from 0.75±0.15 s to 0.87±0.15 s, which is 0.12s. A penalty flick can go as fast as 113 km/h. a ball that travels with 113km/h for 0.12 seconds travels 3.8m. The ball is flicked from the head of the circle, which is 14.63 meters from the goal. So, you can see that this fairly small increase in response time, can have big consequences in a game.

Figure 3: core temperature over time(Malan, 2010)

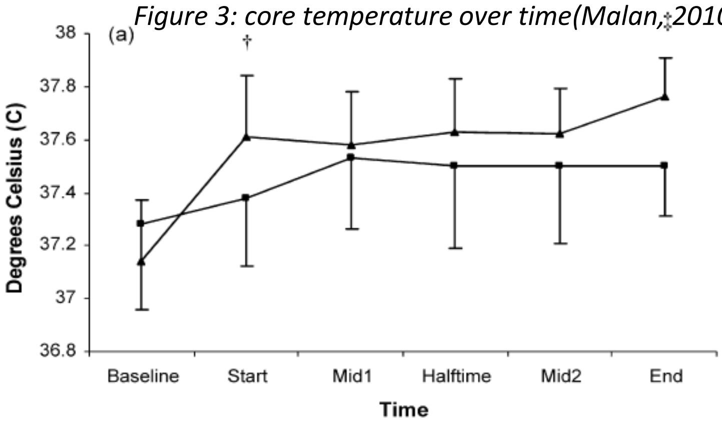


Figure 4 shows the median sweat rates of male athletes during a thirty minute exercise with a target heart rate of 150-160 bpm. As you can see, the sweat rate differs significantly per area. Taking this into account, we can create an opportunity to focus the product to be used in the areas where the heat exchange is high in order to maximize effectiveness.

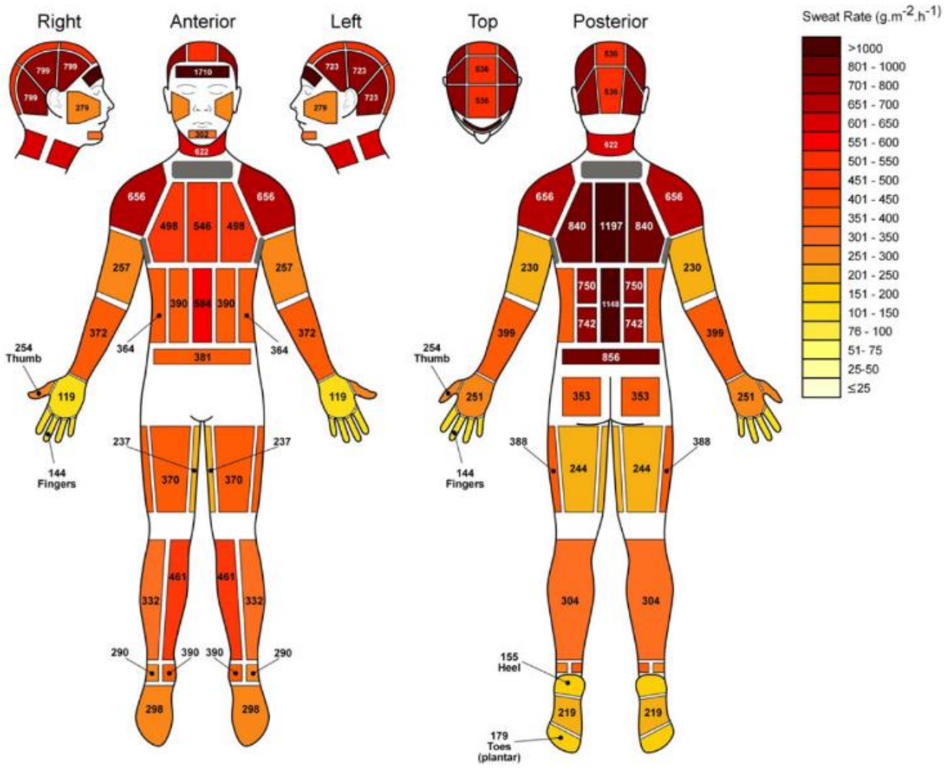


Figure 4: Absolute regional median sweat rates of male athletes at exercise intensity of 55% of VO2 max (Smith & Havenith, 2011)

2.2 Cooling Methods

In the previous chapter the various types of heat exchange have been discussed. There are already quite a lot of garments on the market that make use of these principles in order to cool down the body. Some of these product will be discussed in this chapter.

Convection:
Most products that use convection to cool down the body have built in fans that pump air alongside the body underneath the piece of clothing. When the air has a lower temperature than the body, heat transfer will take place from the body to the air. The heated air flows out through one of the openings of the garment and new colder air is pumped in to keep the heat transfer going. An example of this this kind of clothing is shown in figure 5. This is a Japanese brand called Tajima Seiryo which uses fans connected to a battery pack to let the air flow underneath your jacket or helmet.

Figure 5: Tajima Seiryo products

Conduction
Clothing pieces that make use of conduction usually consist of PCM materials such as the Inuteq PAC series shown in figure 6 the packs are filled with materials that have particular melting points. When the pcm pack is cooler than the body, and touches the body, heat exchange will take place through conduction. The overall temperature will stay the same while the pcm is melting until the pcm has completely melted. Pcms with higher melting points could thus provide a less intense and longer cooling effect and vice versa.

Figure 6: Inuteq PAC

Evaporation

Then there are garments that make use of evaporative heat transfer such as the dry®, H2O® and PVA® series of Inuteq as seen in figure 7. These product are activated by soaking them into water. Due to the evaporative cooling technologies they can cool down the body.

Figure 7: Inuteq evaporative technologies

Since the humidity will be so high during the Olympics and the protection is covering large parts of the body, it will be hard to keep the sweat away from the body through either evaporation or transport through garments.

2.3 Goalie gear

The hockey goalie wears quite a lot of gear to protect itself from the impacts of the hockey ball. To ensure the goalie is safe from harm, each gear piece has to comply with NEN-EN ISO 13546 :2002+A1:2007 (NEN, 2007). This standard describes the allowable shapes, ergonomic requirements, sizing and impact performance requirements. In figure 8, all protective equipment a goalie wears during a match is shown. In this project, the focus lies on cooling the head and torso.

Figure 8: Complete set of goalie gear

Since the focus lies on the head and torso, the gear that covers these parts are shown in further detail.

OBO CK Helmet (Carbon/Kevlar)

Figure 9: Carbon fiber helmet details

Materials
Outside: Carbon fiber + Kevlar. Also available in fiberglass (more durable but heavier)
Cage: High Carbon steel
Inside: Closed cell polyethylene foam or ethylene vinyl acetate foam (EVA)
Weight: 1kg

Blinders, chin/throat guards and spare removeable (Velcro lined inside the helmet where the forehead is placed) forehead sweat pads are commonly used accessories. The plastic helmet attachment for additional throat protection and throat guard are usually not used in combination. Instead of blinders, some people tape the top of the cage to block the sun.

Figure 10: throat guards, visor and sweat pads

There are several different outside layer materials available
- CK Carbon Fiber (best protection and lighter than fiber glass)
- FG Fiber Glass (equal protection, higher durability but heavier than carbon)
- PE Polyethylene (usually used for children and non-professional adults, cheaper and lower protection)
- PP Polypropylene (used for younger children, even cheaper and lower protection)
- ABS (used for the youngest hockey players, cheapest and lowest protection)

In the project, only the Fiber glass and Carbon fiber helmet will be used

OBO Body Armour

Figure 11: Body protector details

The OBO Robo body armour figure 11 consists of a layer of thick foam and a layer of hard plastic underneath the foam. Under the shoulders there are two straps used for connecting the elbow pads. Elbow pads also offer protection for sliding on the field (especially sand and semi-water fields, although most professional matches are played on water fields). Some goalies prefer not to use these elbow pads to increase mobility. Instead, they use sweatbands or sleeves (figure 12) to protect their elbows from scratching when sliding on the field. The sweatband shown in figure 12 is in this case not used for protection, but to soak up sweat that drips down from the arm in order to keep the hand protectors from slipping off.

Figure 12: sweat band and sleeves worn by goalkeeper

2.4 Tokyo

Figure 13: Oi hockey stadium

All field hockey matches will be held at the Oi hockey stadium (figure 13) in the south of Tokyo. As stated in the introduction, the temperature and humidity will both be high during the summer Olympics. In figure 14 you can see the average high temperature and the average low temperature in Tokyo during July and august. The area in between the two vertical red lines indicate the period of the 2021 summer Olympics. As you can see the peak temperature is at the final day of the Olympics (August 9th), with a high temperature of 33 degrees Celsius. The dotted lines indicate the perceived temperature.

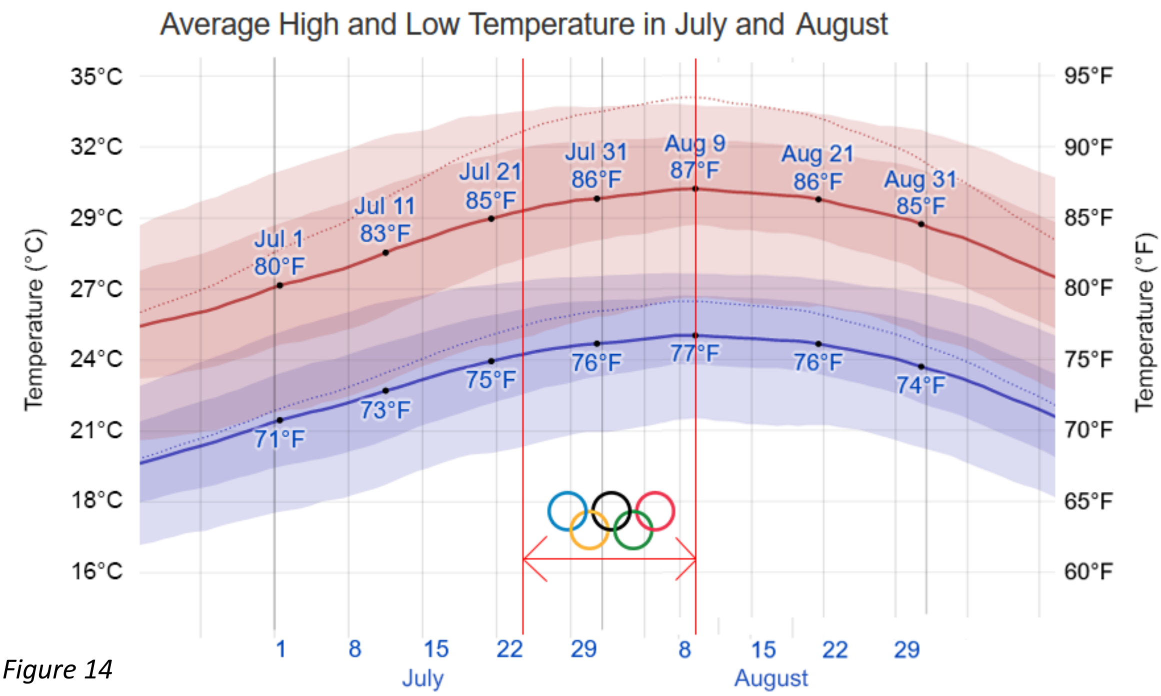


Figure 14

The perceived temperature in this period is significantly higher than the actual temperature. This is due to the fact that the humidity in this period is relatively high (on average about 77%). To measure the comfort levels of the humidity, we can use the dew-point, which is the temperature to which air must be cooled to become saturated with water vapor. The human body produces sweat which evaporates in the air to cool down. The rate in which the sweat can evaporate correlates with how saturated the air is and the amount of moisture the air can hold. When sweat is not able to evaporate, discomfort will occur

(Tanabe, 1994). The table below describes the chance and amount of discomfort due to humidity in Tokyo during July and august.

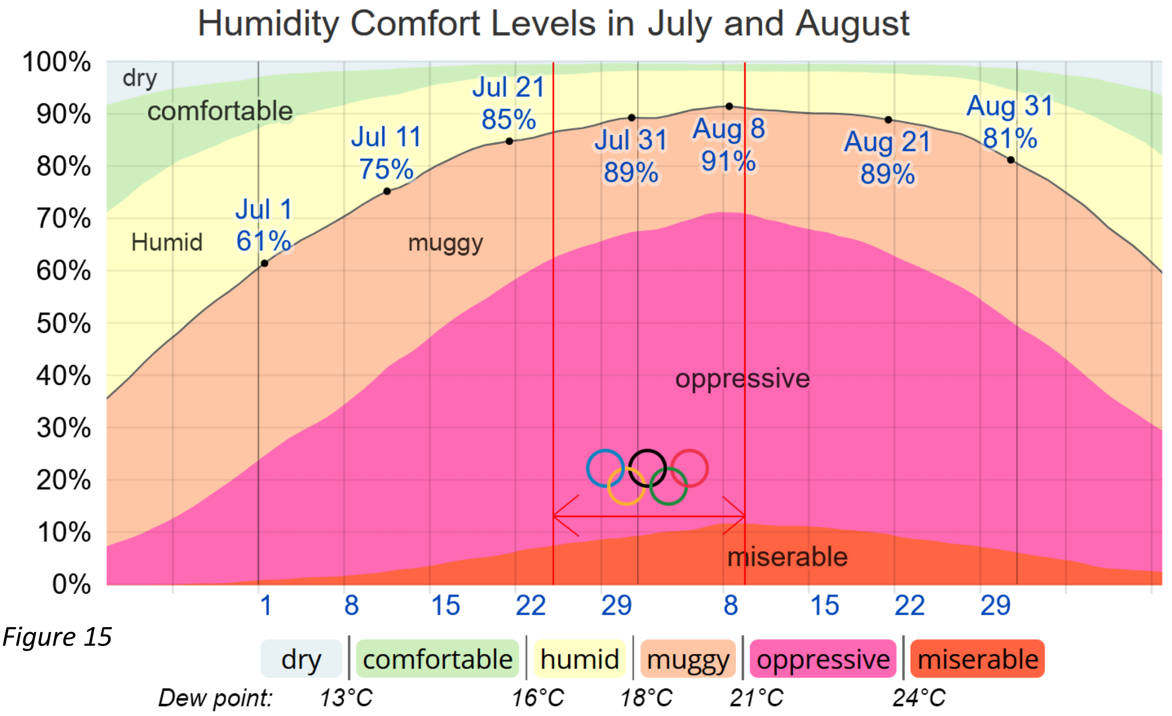


Figure 15

This means that the average time spent in the uncomfortable humidity levels during the summer Olympics ranges from 86 to 91%. As a comparison, the average time spent in these conditions in the Netherlands during this period is only 4%. For comparison see the tables below:

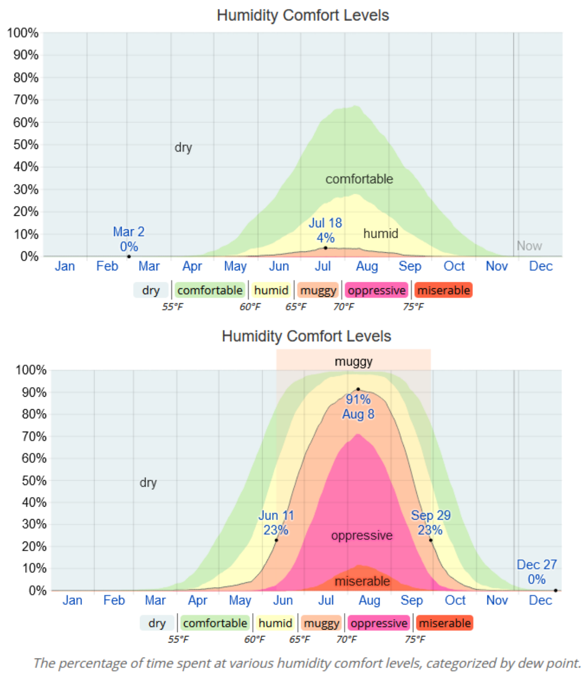
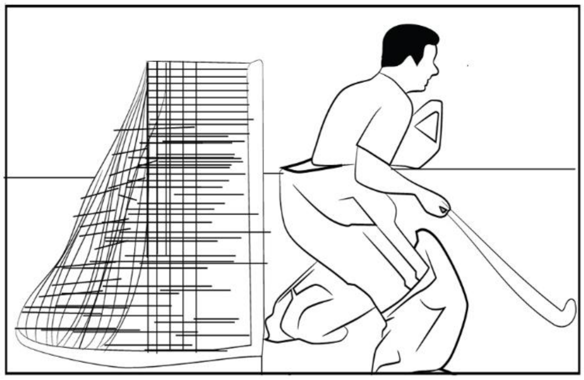


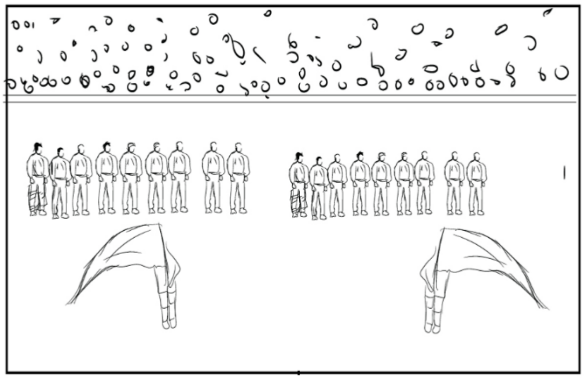
Figure 16

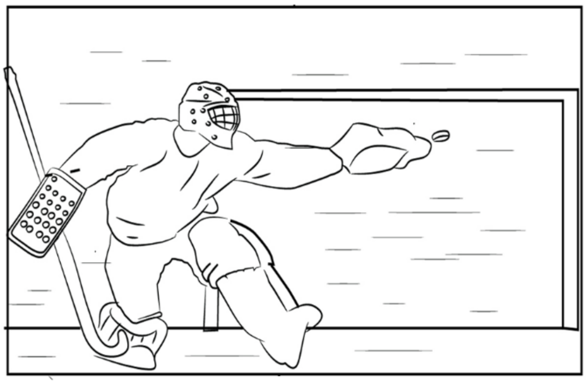
3.1 Storyboard



The goalkeeper puts on its protective gear

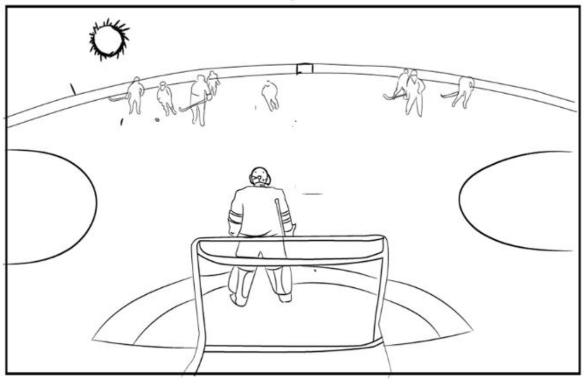
Before the match, the goalkeeper starts its warm-up. Exercises such as jogging, sidesteps, raising knees and stretching (sometimes this is done before changing into gear. After that, starting slow exercises with the ball (low hits, no helmet) and working its way up to hard hits and high





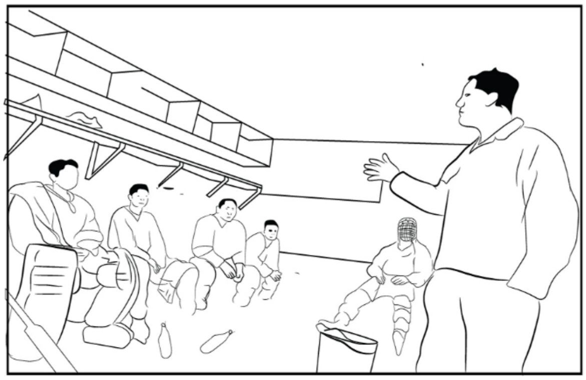
After the warming up, the teams retreat inside for a final talk, after which the teams line up and walk into the field. The national anthems play and the match is started.

Even though the goalkeeper is not constantly moving, it has to maintain focus at all times. The actions are mostly short explosive outbursts of energy, where response time is a critical factor. Due to the high temperature and humidity, the goalie can feel getting uncomfortable.



A quarter consists of 15 minutes of play time. However, time can be stopped when the ball is not in play. Usually this means a quarter can be around 20 minutes. After 20 minutes, there's a short break of **4** minutes on the field. The team gathers for a talk. Players can be switched out infinitely during a game. It is however not usual to switch out a goalie during play. In these harsh conditions it would be wise to switch out the goalie during the quarter-break.

During the second quarter, the first goalie has time to cool down by drinking cold beverages, putting on cold towels, changing garments etc. Around Oi stadium there is no protection against the sun. So, unless there are clouds, the goalie will be fully exposed to the sun during the match.



During half time, the teams retreat inside for about 10 minutes. Inside the airconditioned building they are able to cool down slightly before the next quarter starts. The third and final quarter both last approximately 20 minutes as well, depending on the amount of time stops due to penalties, injuries etc. in between is another short 2-minute break for a team talk.

Normally the duration of the break between q1-q2 and q3-q4 are only 2 minutes. For the olympic games in Tokyo, the duration is extended to 4 minutes due to the harsh climate. During the game, 16 people are allowed to be on the team, of which 11 are in the field (5 reserves). Players are allowed to be exchanged at all times (except during a corner penalty) as many times as you want (at the middle line). Keepers are allowed to be exchanged close to their goal. An extra 2 players are allowed to be reserved, but these players can not be exchanged during the match (only before/after a match). It is highly probable that 1 of these 2 extra players is an extra goalkeeper, which means the goalkeeper is not going to be exchanged during the entire match. This decision to keep only one keeper during a match is a critical factor in designing the cooling equipment.

3.2 Testing PCM

Figure 17: Climate chamber

In order to find a PCM that is best suitable for the context of the goalie, tests have been conducted in a climate chamber to find the heat capacity and conduction rate. The climate chamber was set to 35 °C with a relative humidity of 80%. A heating box was placed inside that kept the plate at 34°C (with a maximum power of 40W). The temperature of the heat plate is set a bit lower than the climate chamber to avoid powering the heat plate before placing the cooling pack samples (this is adjusted to 35°C in the new tests). The PCM packs (12 by 14cm tpu bags filled with about 250 grams of PCM cooled at -21°C) were insulated with a foam cover to simulate the body protector. The Computer showed the power output of the heat plate during testing. The setup can be seen in figure 17. The results of the initial tests are shown in the graph below. The initial test were conducted with materials that have a melting point above 0 degrees Celsius (except the H20 packs). During the phase change from solid to liquid, the temperature stays relatively stable. The higher the line, the more power the heat plate had to use to keep the plate at 34 °C, which relates to a higher intensity of cooling.

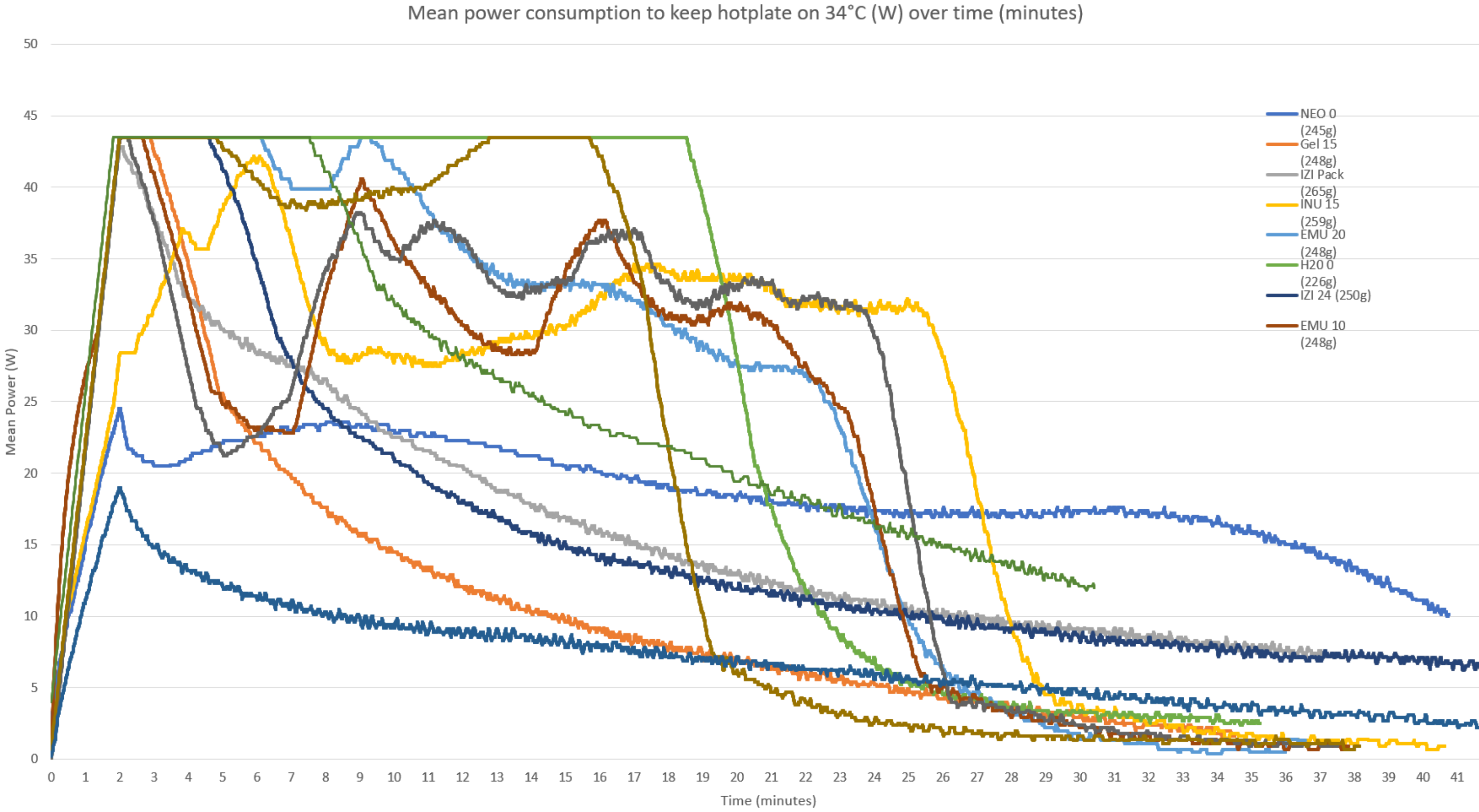


Figure 18

Since the heat plate is capped at 40W, you will see a horizontal line when the heat plate operates at full power. With the PCM materials with a higher melting temperature, the heat plate does not have to run at full capacity in order to keep the temperature at 34 degrees Celsius, resulting in less intense cooling that is stable over a longer period of time.

The same applies to the water pack that has a neoprene layer on the outside. This insulating layer results in low intensity cooling that can cool over longer periods of time.

Since these materials change phase from solid to liquid, they will be solid when the goalkeeper would start using them which could negatively impact the safety and comfort of the protective gear (especially in the helmet). Therefore the same test was run again with materials that have a melting point below 0 degrees Celsius. These materials are often used for injuries since they are easily malleable when they are taken out of the freezer (if the melting point is lower than the temperature of the freezer) and can thus take the shape of the body part that is injured.

The first material that was tested was a hot/cold kompres from Heltiq shown in figure 19. The material was removed from the pack and placed in a testing pack that is the same size as the previously tested materials. Next to the compres, various solutions have been in the following proportions:
Salt:water, 1:12, 2:12, 3:12(SAT).
Antifreeze:Water, 1:4, 2:4. 3:4.
Spiritus (85%):Water, 1:4, 2:4. 3:4.

When the packs were taken out of the freezer first, the initial malleability was tested. Varying from Solid to Slushie to liquid (the packs were colored with food coloring to keep them apart:

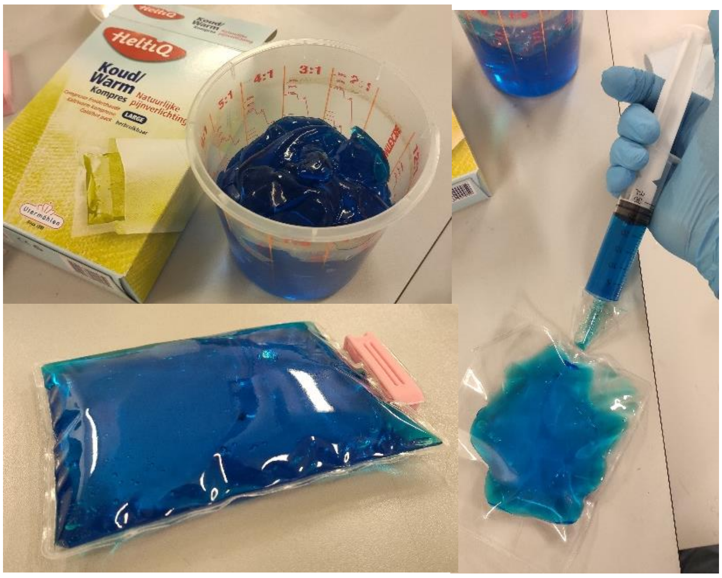


Figure 19: Heltiq kompres

Salt:
Red cloudy (3:12, saturated: 26%) – Slushie-like, malleable
Yellow cloudy (2:12, 16,6%) – Solid, not malleable
Green cloudy (1:12, 8,3%) – Solid, not malleable

Antifreeze
Pink clear (1:4, 20%) – Slushie-like, moderately malleable
Red clear(2:4, 33%) – mostly liquid, few small slushie chunks
Purple clear (3:4, 43%) - liquid

Alcohol (85%)
Light blue (1:4, 20%) – Slushie-like, very well malleable
Average blue (2:4, 33%) – liquid

Dark blue (3:4, 43%) – liquid
Hot/cold pack from Heltiq - thick jelly substance, malleable.

After a second freeze of the red salt pack, hard chunks formed inside making it hard to form. The results of these materials on the heat plate are shown below:

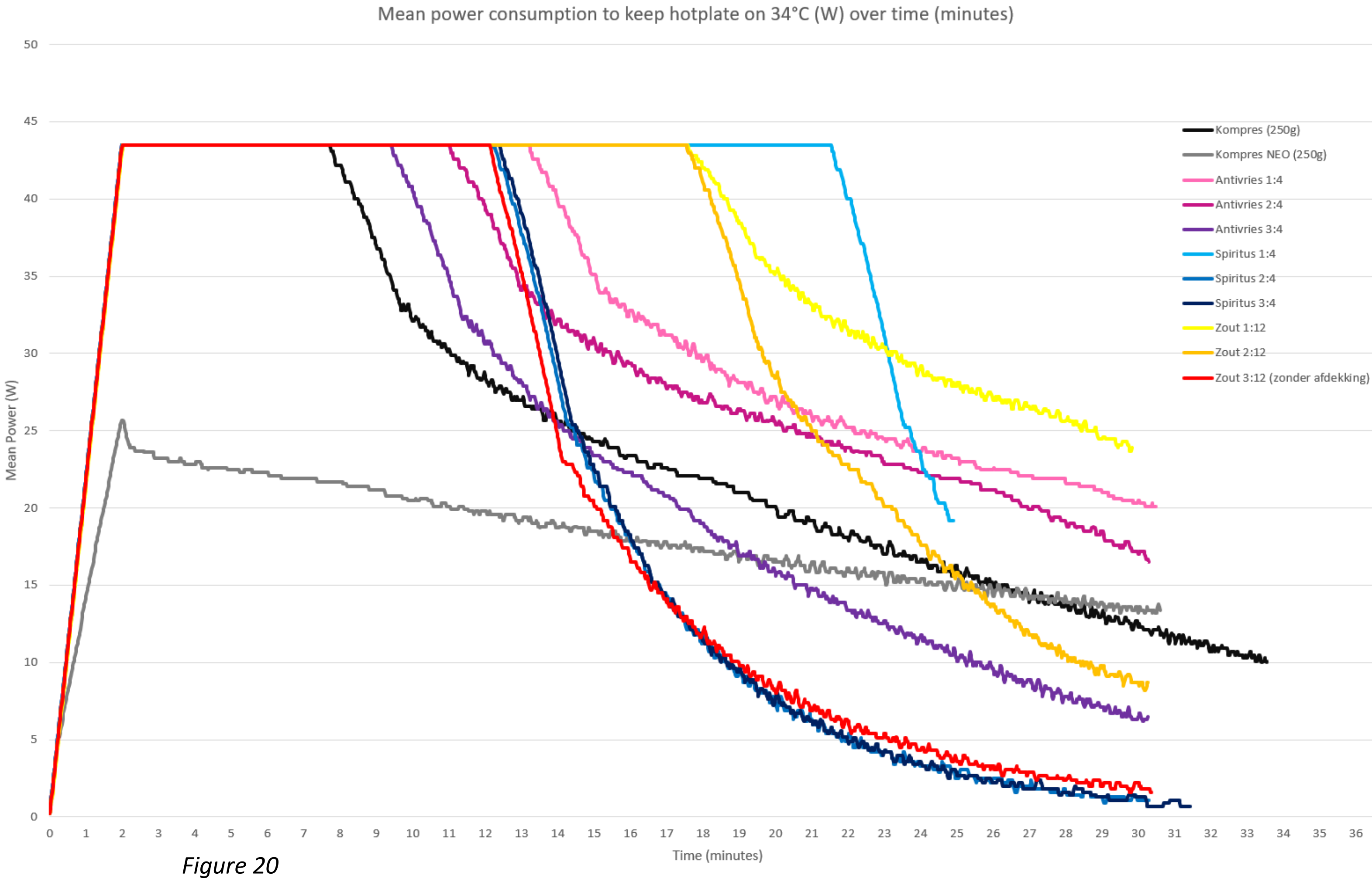


Figure 20

The results here show that the hot/cold pack from Heltiq has the least intense cooling of all solutions tested, but that it can cool over a longer period of time. One of the reasons that this might occur is that in liquid form at room temperature, the material has a high viscosity. Which could make it harder for the material to heat up evenly (this will be tested later). the next thing that needs to be tested is if the materials such as the 1:4 alcohol solution could behave the same way when introducing a thickening agent. Furthermore, could this have a positive/negative effect on the protective capabilities of the body armour?

Appendix C shows the results of the initially tested materials separately including the temperature of the heat bed and the temperature of the top area of the cooling pack.

3.3 Cooling areas

Since the Body protector and helm are padded with thick (insulating) foam, it is hard for the heat to escape. An advantage when placing PCM packs under the protective gear, is that the environment has a lesser effect on the heat exchange with the cooling packs. Thus there will only be heat exchange between the body and the cooling packs, making it more efficient compared to areas without protective cover. A disadvantage of placing the cooling packs behind the protective gear is that it could negatively influence the protective capabilities of the overlaying gear. The body protector is secured in place with 2 elastic bands with Velcro attached running along the spine area. This gives the opportunity to place cooling packs along the spine area as well.

The cooling packs could still be placed on areas that are not covered by protective gear. In these areas it should be taken into account that there will be heat exchange between the cooling packs and the environment. Accordingly measures could be taken to limit this unwanted heat exchange by for example placing an insulating layer on the outside

Another thing to take into consideration is the freedom of movement of the goalie. With the design, the movement of the goalie should not be impaired by the cooling product, not by means of adding too much weight as well as stiffness of the cooling product.

Since the duration of the break between q1-q2 and q3-q4 is only 4 minutes, ease of use should be taken into account. The goalkeepers from the female national team indicated that they rather have a lightweight solution that doesn't work as long than a heavy solution that could work for a longer period of time. Therefore I wish to design a cooling pack that is optimized to work the least amount of time (at least one quarter) and could thus be as light as possible. But in this case, the cooling packs should be able to be replaced within the 4 minutes of breaktime. Questions that arise here are: how can the cooling packs be easily accessible under the body protector? How should the cooling packs be attached? On what areas does the goalie need assistance to replace the packs?

4.1 Trunk Cooling packs

Figure 21

The initial designs of the trunk cooling pack only consists of 2 layers of plastic that is welded together using a laser engraver. The honeycomb structure ensures that the cooling pack can stay relatively flexible. Figure 21 shows the area of the inside of the body protector that is easily accessible from the openings under the chest area. This is why I chose to make the first prototype fit this area. In order to be able to secure the cooling packs and remove the packs easily, a pouch has been sewn in the body protector including 2 lines of Velcro on the top part of the pouch as well as the top part of the cooling pack as shown in figure 22. Hexagonal compartments in the cooling pack are connected so that the fluid can flow from compartment to compartment. The channels are made narrow so that the fluid can only flow when a slight overpressure is applied to the neighboring compartment. The packs were filled with water using a syringe and needle and sealed off using an iron.

Figure 23

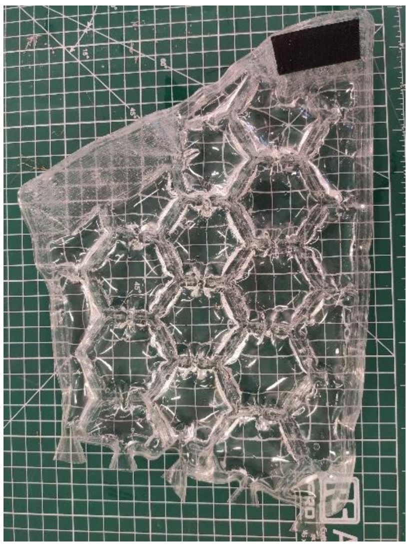


Figure 22

The cooling packs were tested during a hockey training on a 'hot' summer day (24°C). the packs each contained 210 ml of ice at the start of the training. They were placed after the warming up. The intensity of the cooling in the beginning was high, which resulted in an uncomfortable feeling. After ten to fifteen minutes, the uncomfortable feeling was gone and the packs kept cooling the body less intensely. The first pack was removed after 46 minutes. At this point, small chunks of ice were still visible in the compartments. After 80 minutes the second pack was removed. This pack had fully warmed up to the surrounding temperature.

To counter the uncomfortable feeling at the start, a layer of neoprene has been added on the cooling pack. This would insulate the cooling pack resulting in a less intense cooling (as seen in the results of the heat plate test).

Both packs can be replaced in under a minute, which would allow the goalkeeper to replace them during the 4 minute breaks.

Figure 25 shows a frame from video of the training when I was testing the icepacks

Figure 24

Figure 25

4.2 Head Cooling pack

The initial design for the head cooling pack was made using the same principle of the core cooling pack, with a different compartment shape to accommodate the shape of the head. At first, a design was made that would cover the top and back part of the head as seen in figure 26. The design on the left was not flexible enough to form around the head (when

Figure 26

frozen solid). The second design was made out of small triangular compartments that could be formed around the head more easily. When the pack was taken out of the freezer and lined up inside the helmet, you could instantly feel that it was not comfortable to have the solid bubbles pressing on the head. A more user friendly method of placing the pack had to be found. Since the helmet has a line of Velcro lined up in front of the forehead area to place the sweatband. A third iteration was made to make use of this. Next to that, the pack was filled with the 1:4 alcohol:water solution in order to make the pack malleable and maximize the contact area with the forehead. (additionally a second core cooling pack was made to test the 1:4 alcohol solution there as well. (the blue color originated from the coloring agent in the denatured alcohol.

4.3 Back Cooling pack

During this project, the Dutch women's national hockey team had already been testing some ways to cool the body in the Tokyo climate. One of these ways was to place cooling packs (which had a similar shape of the ones tested in the climate chamber) in pouches sewed into their clothing. The feedback received from these tests (acquired from Doris van der Laan, Exercise physiologist at the Dutch women's national hockey team) indicated that the goalies also prefer a cooling solution to cool their back (spine area), which is one of the areas on the human body that produces the most amount of sweat as seen in figure 4.

Since the mobility of the goalkeeper needs to stay as high as possible, and the added weight as low as possible, it would be good to incorporate a flexible cooling pack in the protective gear that already has an insulating layer. The body protector is held in place by 4 elastic straps that wrap from the back around the sides of the body to the front, and are secured with Velcro fasteners. These elastic straps are attached to a thick pad that covers a part of the spine as seen in figure 27

Figure 27

This would be an ideal spot to place a cooling pack since the back pad has an existing insulating layer of foam attached. In order to place a cooling pack in this area, a mesh fabric insert has been added to secure the cooling pack as shown in figure 28 (the handle of a hockey stick was placed inside to better indicate the mesh pad).

Figure 28

Figure 29

4.4 Safety testing

The protective gear that the goalies wears during a match have to be certified. Before the protective gear can receive a certification, they have to comply with ISO 13546+A1 (NEN, 2007), which describes the requirements and test methods for all protective field hockey goalie gear, with the exception of helmets. This is a harmonized standard derived from EU regulation 2016/425, which covers all personal protective equipment. In order to make sure the cooling packs do not fail during a match, they will be tested in a similar way as the protective gear.

The test is described in the following citation from the norm:

'Field hockey protective equipment shall be impact-tested with a falling mass in a vertical guidance system that allows the terminal velocity of the falling mass to be measured and to be within ± 2 % of the required velocity. For equipment with the exception of hip protectors the total mass shall be (2 500 ± 100) g including a hockey ball shaped hemispherical steel striker (72 ± 2) mm in diameter. Hip protectors shall be impacted with a flat face impactor (80 ± 1) mm in diameter on a falling mass of (5 000 ± 100) g.

The drop heights of the masses above the top surface of the protective equipment being tested shall be adjusted so that the impact velocities provide impact energies as specified in 4.6, Table 17 (figure 30 in this case), *with a tolerance of ± 5 %.* (full table available in appendix D)

The different anvils and the guard ring system specified below (not specified in this report)*) are designed to represent the profiles of body parts and, in part, their responses to impact. Each anvil shall be mounted directly onto a stiff load cell or force transducer, such as a piezo-electric load cell. The frequency response of the load transducer shall be at least 10 kHz. The anvil and load cell shall be bolted or clamped to a concrete or similar massive base of at least 1 000 kg. The anvils shall be made of steel and the mass above the load cell shall be (10 ± 1,5) kg.*

The recording system shall show a continuous force with time, or shall have a peak force detection capability. Sampling systems shall have a minimum rate of 10 kHz. The complete system shall be able to measure forces up to 50 kN with an accuracy of 0,1 kN between 1 kN and 10 kN.'

Item of equipment and zone of protection		Maximum transmitted force kN	Impact energies to be used to test different performance levels of equipment Joule				
			Level 1	Level 2	Level 3	Level 4	Level 5
Shin protectors:	Zone 1, ankle area	3	A1 1	1	1	1	1 A1
	Zone 2, outer area	5	A1 5	5	5	5	5 A1
	Zone 3, central area	5	A1 5	5	5	5	5 A1
Leg protectors:	Zone 1, lateral aspect	5	3	6	9	12	15
	Zone 2, outer shin area	5	8	15	20	25	30
	Zone 3, inner shin area	5	15	30	40	50	60
	Zone 2, outer knee area	6	8	15	20	25	30
	Zone 3, inner knee area	6	15	30	40	50	60
Kickers:	Zone 1, outer area	3	10	10	10	14	20
	Zone 2, toe area	3	10	10	15	21	30
	Zone 2, lateral surface	3	10	10	15	21	30
	Zone 3, medial surface	3	10	15	25	35	50
Abdominal protectors		4	8	11	14	17	20
Thigh protectors		4	8	11	14	17	20
Hip protectors		4	7,5	15	25	30	35
Chest protectors:	Zone 2, outer area	4	-	5	10	15	20
	Zone 3, heart area	4	5	20	30	40	50
Breast protector with a chest protector of the same or a higher performance level		2	5	20	30	40	50
Shoulder protectors:	Zone 1	6	3	6	9	12	15
	Zone 2	6	8	11	14	17	20
Upper arm protectors		5	8	11	14	17	20
Elbow protectors		4	3	6	9	12	15
Forearm protectors:	Zone 1	4	3	6	9	12	15
	Zone 2	4	8	11	14	17	20
Goal-keepers gloves:	Zone 1 left hand	3	5	5	6	8	10
	Zone 1, right hand	3	5	6	8	10	12
	Zone 2, left hand	3	5	7,5	10	12	15
	Zone 2, right hand	3	5	7,5	10	12	15
	Zone 3, left hand	3	7,5	10	12	15	20
	Zone 3, right hand	3	15	20	30	35	35
	Zone 3, digit ends	2	15	20	20	25	25
Soft genital protectors		3	5	10	15	20	25

Figure 30

As seen in figure 30, the helmet is not taken into account in ISO 13546+A1. In order to find out how the helmets are tested, the manufacturer of a widely used goalie helmet has been contacted (OBO New Zealand) Appendix E. They follow an American standard to test their helmets for impact (NOCSAE DOC (ND) 061-14) (NOCSAE, 2016). In these tests, five helmets are mounted on five separate NOCSAE head forms. Each helmet will be impacted once on a different location with a hockey ball travelling at 26.8m/s (96.5km/h)(using a hockey ball launcher, figure 31). The impact location and ball travel direction is NOCSAE DOC (ND) 061-14 indicated with the metal pin shown in figure 32 (the image was taken from the norm, however, the right image is the same as the left image. I think this is a mistake made in the norm). NOCSAE DOC (ND) 061-14 (NOCSAE, 2016)

Figure 31

FRONT FRONT BOSS SIDE

Rear Boss *Figure 32* Rear

The helmet passes the test when no structural changes take place (visual deformation of the material)

Using these descriptions, a setup has been made to test the cooling packs for impact. However, a few simplifications have been made:

- The main tests will be performed according to the ISO standard (drop tower), the impact energy on the helmet shall be derived from the American standard to be used in this test.
- The striker used in this setup is hemispherical with a diameter of 5,4cm, where an official hockey ball has a diameter of 7.2cm.
- The anvil used in this setup is a steel cylinder with a diameter of 9cm, and is thus not formed in the shape of a specific body part.

- The load cell used in this setup has a programmed frequency of 8kHz. Going as high as 10khz would result in less accurate readings.

The full setup, including the placement of a cooling pack sample is visualized in figure 33

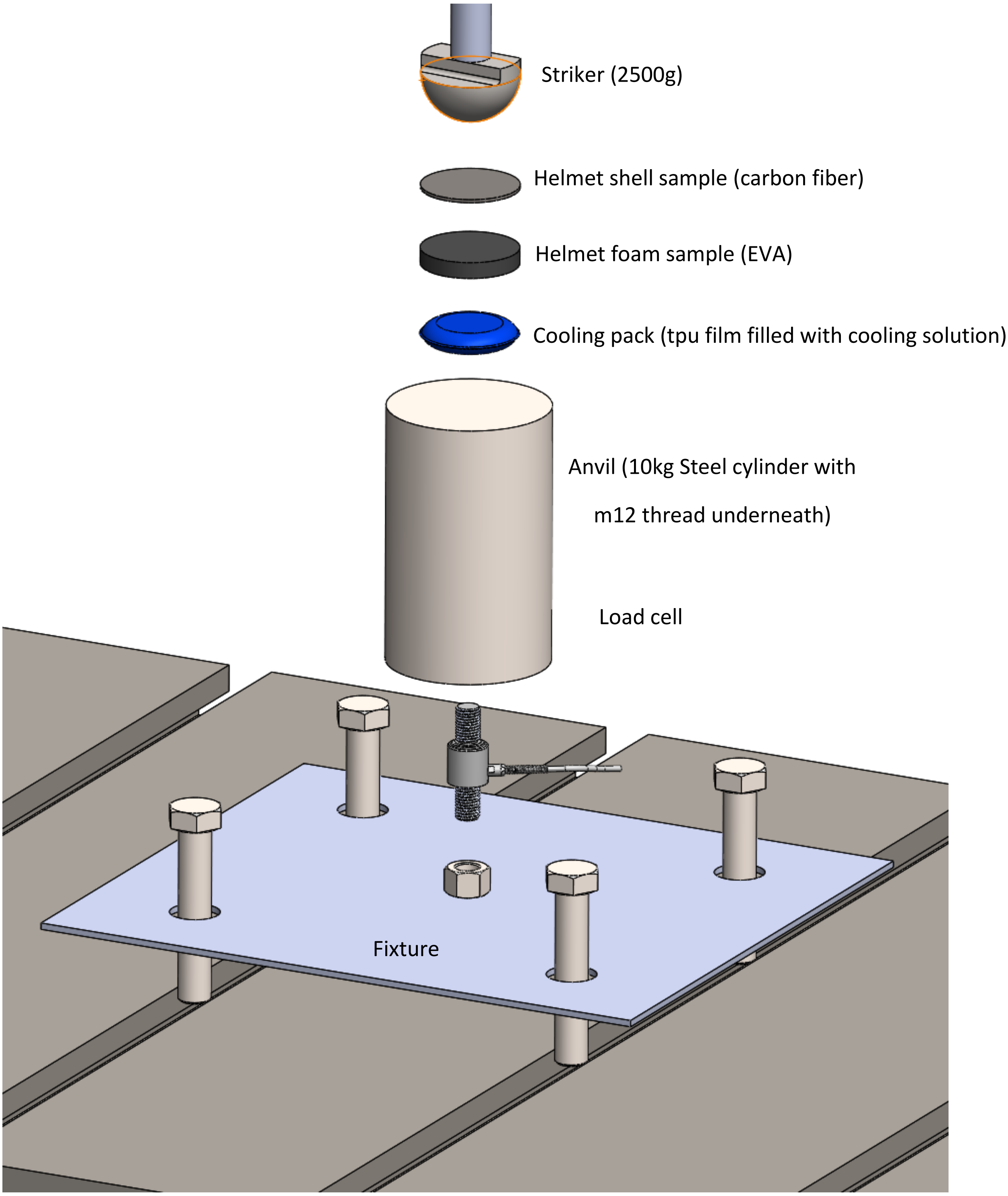
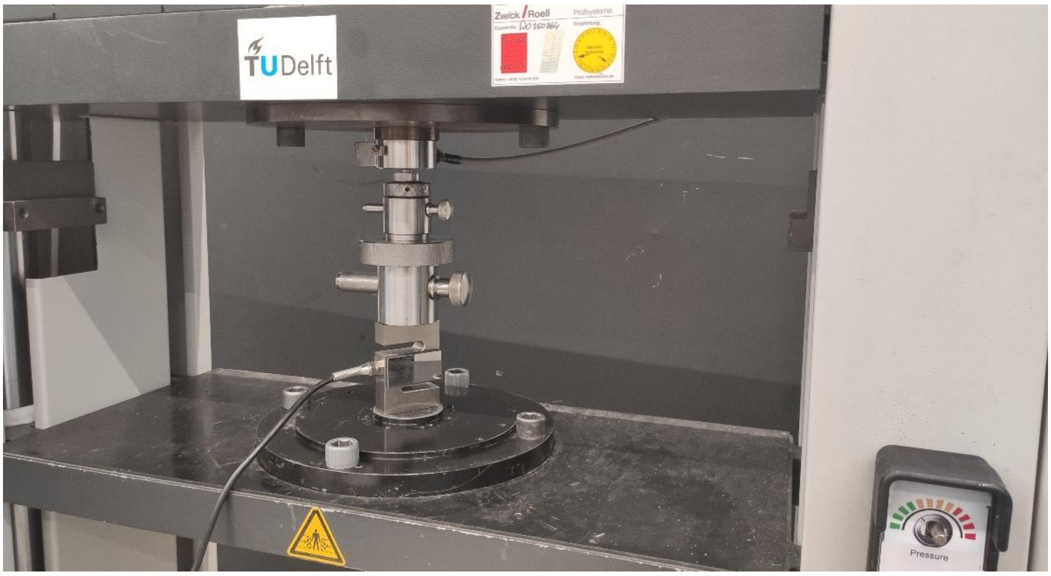


Figure 33

In order to secure the setup, a threaded rod was placed in the middle of a steel plate, that could be bolted down to a welding table. The load cell has threaded holes on the top and bottom part. The bottom was mounted on the steel plate and the top was mounted to the 10kg cylinder with a threaded rod attached to its bottom. A box was made to put around the cylinder to be able to place a plastic bag around the cylinder to catch possible leaking cooling fluids. At last, another box made out of clear PETG sheet and 3d printed parts was placed on top of the wooden box to be able to see and film the impact without splashing the liquid around when a cooling pack would fail (during the first tests a Tupperware box was used). Before the tests started, the load cell had been calibrated using a press.



The ISO standard requires a value under the maximum transmitted force in order to make the gear pass the test. In the American norm, the helmet passes the test when no irreversible deformation takes place. In order to derive the impact energy used to deform the helmet, the impact tower was first used solely on the helmet sample (without the cooling pack underneath). The helmet consists of a circle shaped piece of shell taken from the side of the helmet with a piece of protective EVA foam glued underneath (the same type of foam that the helmet is lined with). The striker was dropped from 70cm with increments of 10cm until the helmet showed a (significant amount of) deformation as shown in figure 34. The height at which the striker was dropped to create a dent like this was 160cm.

Figure 34

The impact energy is calculated using the following formula:

$KE = ½ \cdot m \cdot v^2$

KE = Kinetic Energy. After the striker hit the sample, all kinetic energy is transferred to the sample. This energy is the is the impact energy.
m = mass of the striker, which is 2,5kg.
v = velocity of the striker just before impact

Since there was no room to fit the sensor that measures the speed of the striker in my setup, the striker was first dropped without using the setup and only using the velocity sensor. The striker was dropped from various heights multiple times to see what the velocities were at those heights. With a couple of these measurements, a graph was made to know the velocities at certain heights the striker was dropped from.

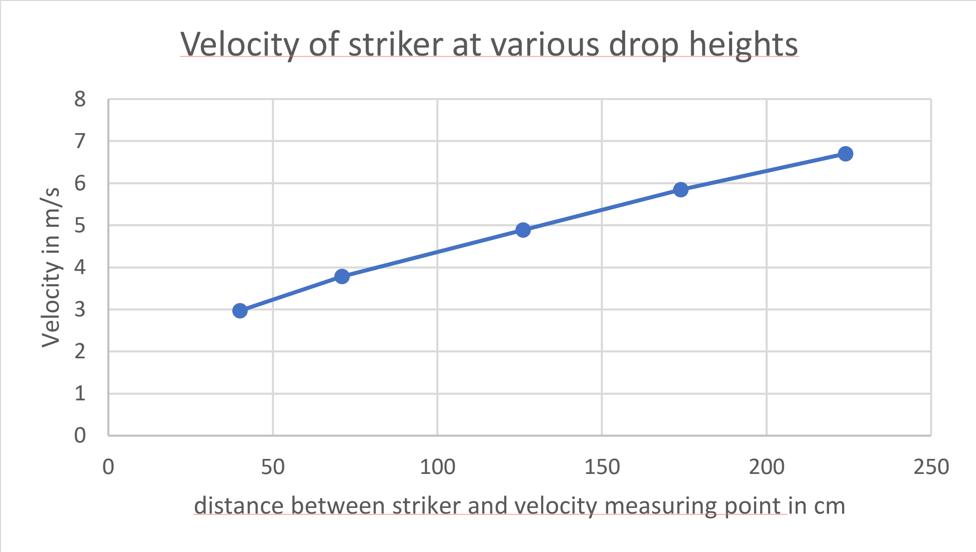


Figure 35

The velocity of the striker was measured from 5 heights 5 times each. Then, out of the 5 values, 2 values that were the farthest off the other values were discarded. Out of the remaining three values, the average was taken and used to make the graph in figure (35)

Now, the impact energy on the helmet can be measured by filling in the formula:

$KE = ½ \cdot 2{,}5 \cdot 5{,}6^2$
$KE = 39{,}2$ *Joule*

However, in this setup, the helmet sample is placed on a steel cylinder that does not move on impact. In the American norm, the head form moves on impact. A greater movement on impact lowers the impact force. This method of calculating the 'impact energies to be used to test performance level 5 helmets' will thus result in a worse case scenario compared to the American norm. Another thing is that the helmet might be over-dimensioned, for example: the helmet might be able to withstand the impact of a ball travelling a lot faster than the indicated 96,5 km/h.

All in all, this value gives an indication of the magnitude of the impact energy to be used in the following tests. Furthermore, the values in the table of figure 30 help verify this indication of magnitude as well.

Testing the cooling pack samples
For the first tests, small round cooling pack samples were made to fit inside the setup. The sample packs were filled with various fluids that had been tested in the climate chamber: all antifreeze and alcohol mixtures and one filled solely with water. Next to these packs, 3 packs were tested that had a thickening agent mixed in. An alcohol(85%):water solution with ratio 1:4 was added to superabsorbent polymer balls, which turned the liquid into a hydrogel. After fully absorbing the liquid, the balls were blended to create a gooey gel-like substance. This substance was mixed in with the earlier mentioned 1:4 alcohol:water solution in three different ratios which in turn created 3 different thickness levels of the gel namely: 100% gel, 66% gel and 33% gel. All packs are shown in figure 36

in this figure, the packs were sealed with clips. Before the tests however, the packs were put back into the laser engraver to seal the packs shut with 2 parallel lines on the opening.

The packs were cooled down at -21 degrees Celsius before testing them for impact.

After the first impact test, where the striker was dropped from 120cm, the cooling pack instantly exploded. After lowering the height to 60cm, the only packs that did not tear open after the first try were the solid water pack and the partly solid solutions.

Figure 36

The packs consistently tore open at the same spots, which were the corner points at the opening (figure 37). The filling spouts were made with sharp edges rather than rounded off edges, this might have resulted in having the laser engraver stay at the cornerpoint for a slighly longer time than other parts of the seal line, which could be the cause of the weakpoints. Next to that, since the packs were sealed all around, the pressure can not flow away during an impact.

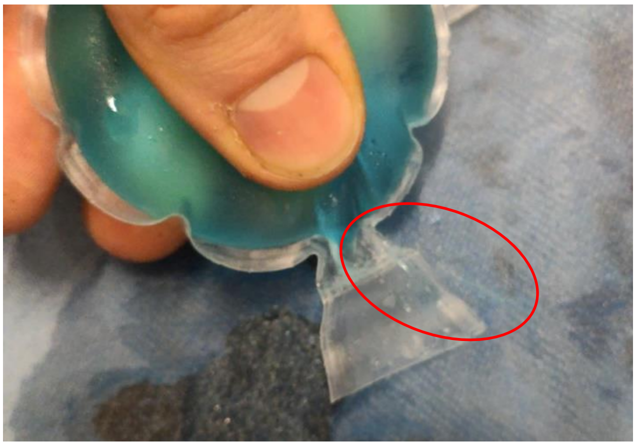


Figure 37

With this information, new packs had been made to allow the fluid to flow away inside the cooling pack to the neighbouring compartiments. This would reduce pressure at the point of impact, allowing a higer impact energy to be exerted on the cooling pack before tearing. Also, the sharp edges had been adjusted to rounded edges (figure 38). These packs had only been tested with the three levels of thickness of the gel and water, without cooling them down before the tests. These packs could withstand a higher impact energy but at a dropping height of 70 cm, the pack would break after about three impacts.

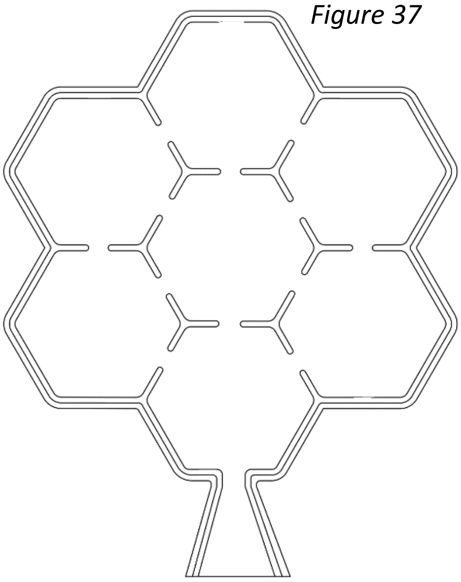


Figure 38

Figure 39 shows that the packs would fail at the connecting points of the compartiments.

seeing that the sealing lines between the compartments were only 2mm apart, new packs were made with the lines put 4mm apart with even where the rounded edged had a larger radius (figure 40). To one of the newly tested packs, a layer of neoprene was added as well.

Figure 39

The newly designed packs again could withstand a higher impact energy, the striker was dropped form 90cm and after two to three impacts the packs would break, again at the same spots (figure 41) . The pack with the added neoprene layer could was tested at a dropping height of 70cm with 20cm increments on each following impact test. The pack failed at a height of 150cm, which is coming close to the desired 160cm which has an impact energy of roughly 40J.

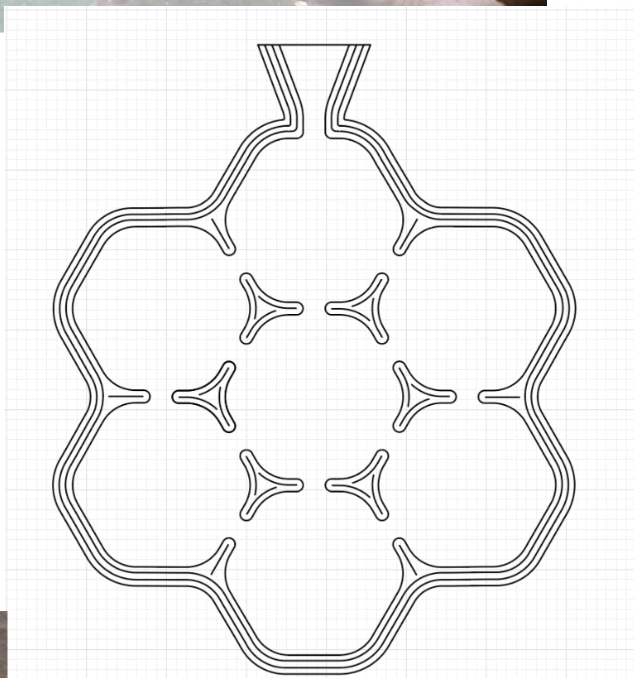


Figure 40

At this point I could not think of ways to make the cooling packs stronger using the current method of sealing the thin TPU sheets with the laser engraver. Therefore, another thicker type of PU plastic was used to create new packs (INUTEQ-SEAL® Polyether | Polyester Polyurethane). This type of plastic was not able to be sealed by the laser engraver and therefore another way had to be found to seal the plastic (which will be explained in the next chapter: Redesign).

Figure 41

This new cooling pack shown in figure 42 (above) could withstand a dropping height of 150cm. After the third impact at this height on this cooling pack, it started leaking at the connection between two hexagons as shown in figure 42 (below). This first test already gave some promising results.

Figure 42

4.5 Redesign

After finding out that the laser sealed cooling packs could not be designed in a way to pass the impact tests, a new approach had to be taken to make the cooling packs tougher. Looking at the cooling packs made at Inuteq figure 43 you can feel that the plastic is thicker and less stretchy. At Inuteq, two different types of joining the plastics are used. One of them is ultrasonic welding (mostly for welding straight lines), where two layers of plastic are pressed together and due to high frequency vibrations that create heat through friction, the two layers are joined together. In the other method, an aluminum mold is heated up and pressed against 2 layers of plastic on either side, melting the plastic and joining the layers together. These molds are usually manufactured using a cnc milling machine.

Figure 43

In order to test a sealing method, a cheap method for proof of concept was tested. By putting small aluminum shapes in the oven (figure 44) (set at 225 degrees Celsius) and pressing them onto 2 sheets of PU sheet with some greaseproof paper in between the aluminum and the plastic to avoid sticking, a quite reasonable result was achieved after a few tries (the seals were not able to be torn apart without tearing a single layer of plastic first)

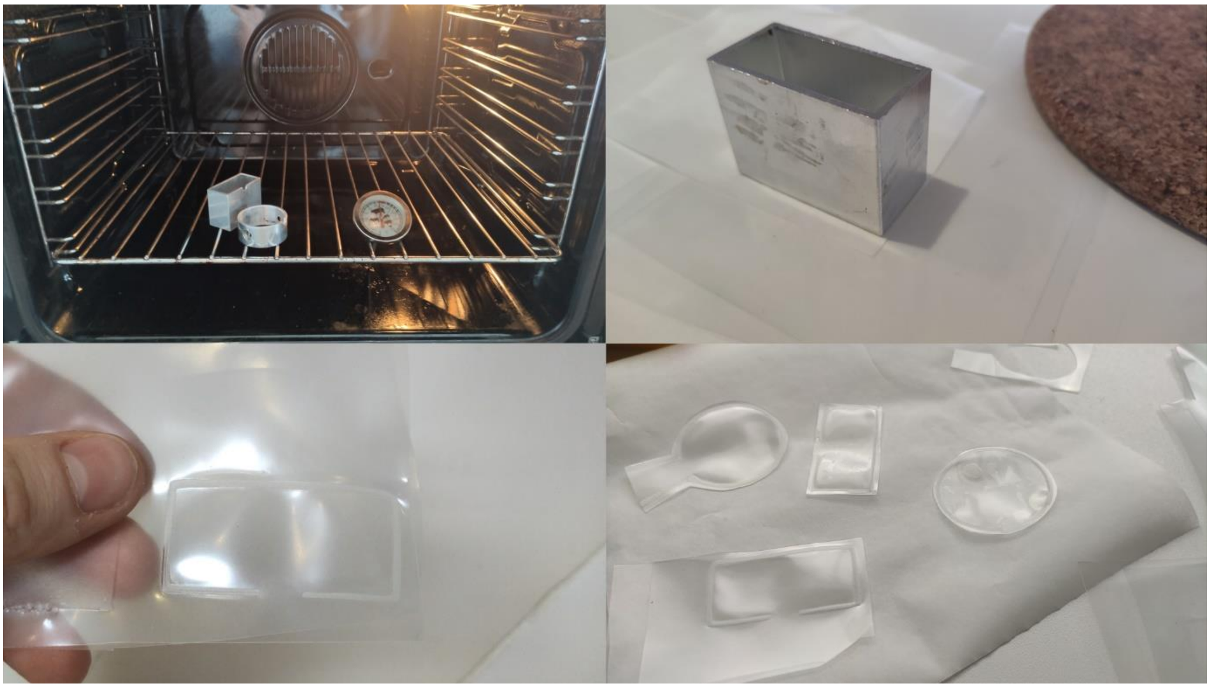


Figure 44

After these small tests, a mold had to be made in order to make a test sample for the impact tester.

Figure 45

In order to keep the costs and production time low, the mold was made out of 4 layers of 2mm aluminum sheets (since the laser cutter could cut up to 2mm thick aluminum) that were welded together (figure 46).

Figure 46

This mold was then heated to 225 degrees Celsius and pressed on two layers of PU sheet, using a cork plate to press on to avoid burning. This took a couple of tries to come to a satisfactory result since it was harder to evenly press the aluminum on the plastic sheets. Other issues were that at the moment when the contact points were pressed together at different points, the plastic sheets would shift a bit resulting in seals at undesirable spots. In the end, a good seal was made, but it had to be touched up with a flatiron (figure 47). The first impact tests gave a promising result, therefore it was decided to follow up with this sealing method.

Figure 47

In order to create a more consistent seal, a heated press (figure 48) was used to control the pressure force and heat. A heat proof silicone mat was placed under the plastic sheets to even out possible bumps in the aluminum mold and ensure a good seal everywhere. In the first tests, the bottom and top plater were both heated to 160°C. the layers were stacked outside of the press in the following sequence: steel protection plate, silicone mat, greaseproof paper, two sheets of PU, greaseproof paper, mold, steel protection plate.

Figure 48

After pressing the layers together for five minutes, the seals were completely melted through. After a few iterations, the packs started to look better, however, the heat could not escape from within the mold, resulting in deformed in the hexagons (figure 49). Since the plastic would already warm up while the press was being

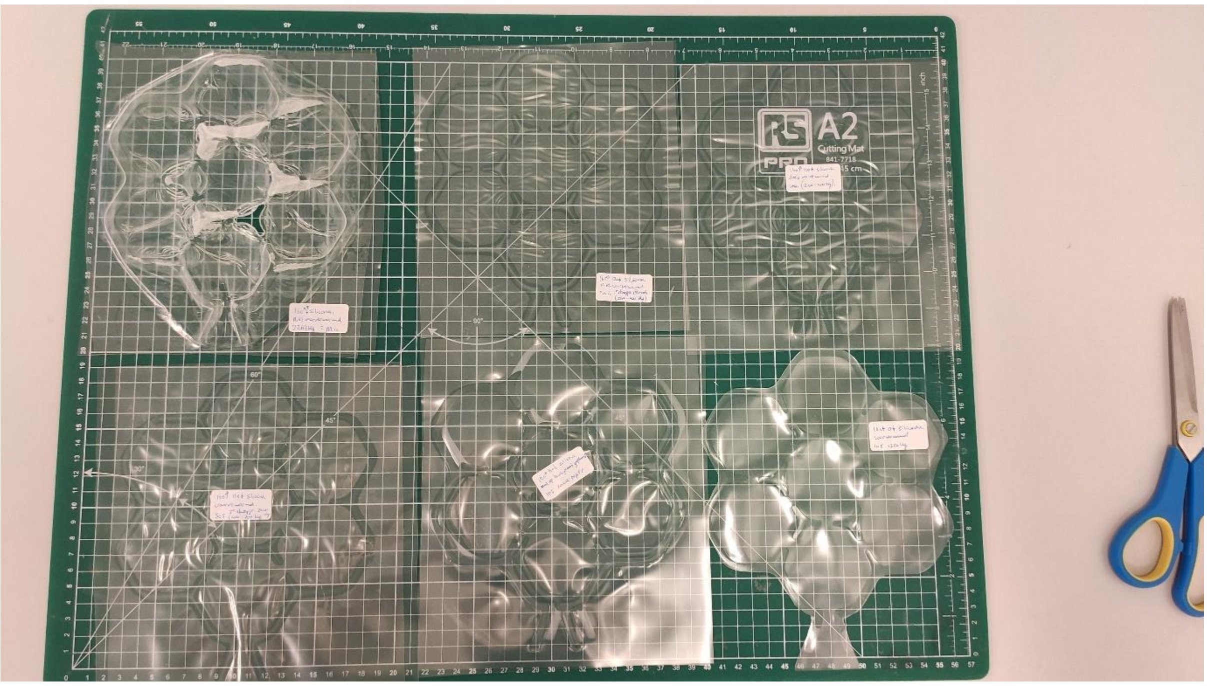


Figure 49

pumped, the plastic was already deforming before any pressure was exerted on the mold. In order to prevent this from happening, the bottom heating plate was turned off and the mold was fixed on the top plate using heat resistant tape (figure 50). the final two test gave a satisfactory result (160 °C top, room temp bottom, pressed for 10s with 1250kg). The tape would however only hold on long enough for a single press. Therefore a tool was made to fix the mold to the bottom of the upper heated plate (figure 51).

Figure 50

This is a 1.5mm steel plate with two bends on either side to fit around the heated plate. On the bent up sides, holes are drilled to attach wing screws on the outside and nuts on the inside to fix the plate using the friction on the ends of the wing screws against the heated plate.

To fix the mold on this plate, some holes were drilled in the plate and threaded accordingly, allowing small screws to hold the mold in place (figure 52).

Figure 51

Figure 52

A downside of welding the four layers of aluminum together is that it is hard to achieve consistent welds that do not deform the contact surface of the aluminum.

Figure 53

Final prototype

For the final prototypes to be used is the helmet and body protector, new aluminum molds had to be fabricated as well. In order to avoid welding, use thicker layers of aluminum and keep the costs low, a water cutter was used to cut molds which consist of two 4mm aluminum sheets fastened together. Instead of welding the sheets together, small holes were cut and threaded to be able to screw the sheets together. Although threading the holes is a bit more time consuming than welding the sheets, it results in a more consistent contact surface. The triangles are connected to avoid the small parts to fall in the water bath in the waterjet cutter. After water cutting, the connection points were sawed off and ground down

Figure 54

In order to fit the shape of the body protector inside the water cutter (which has a 300mm by 300mm bed)(figure 55), the outer shape had to be slightly adjusted by removing roughly 1cm from the top and bottom.

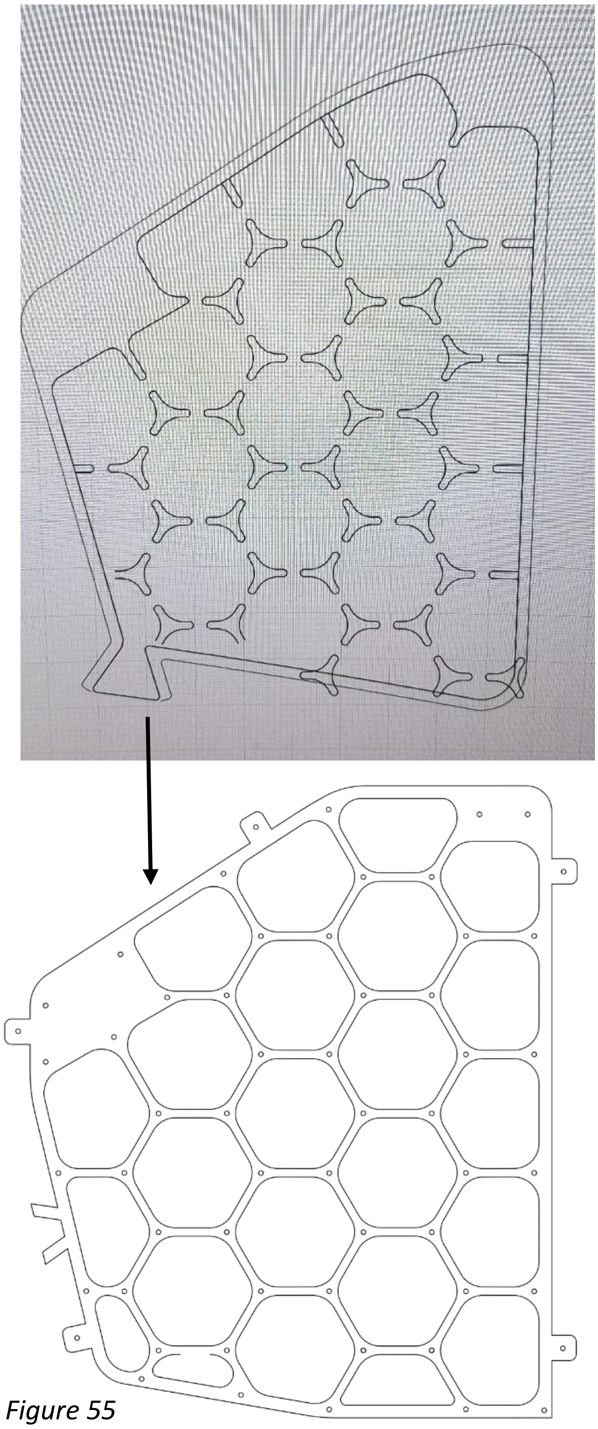


Figure 55

Figure 56

The result after water cutting can be seen in figure 57. The four holes that stick outside the shape of the trunk mold are used to secure the mold to the top heated plate of the press. The edges of the bottom side of the aluminum became sharp after water jetting. The sharp edges were oriented upward in the assembled mold to reduce the chance to cut through the plastic when the mold is pressed against it. The mold for the head cooling pack has been assembled in the same way.

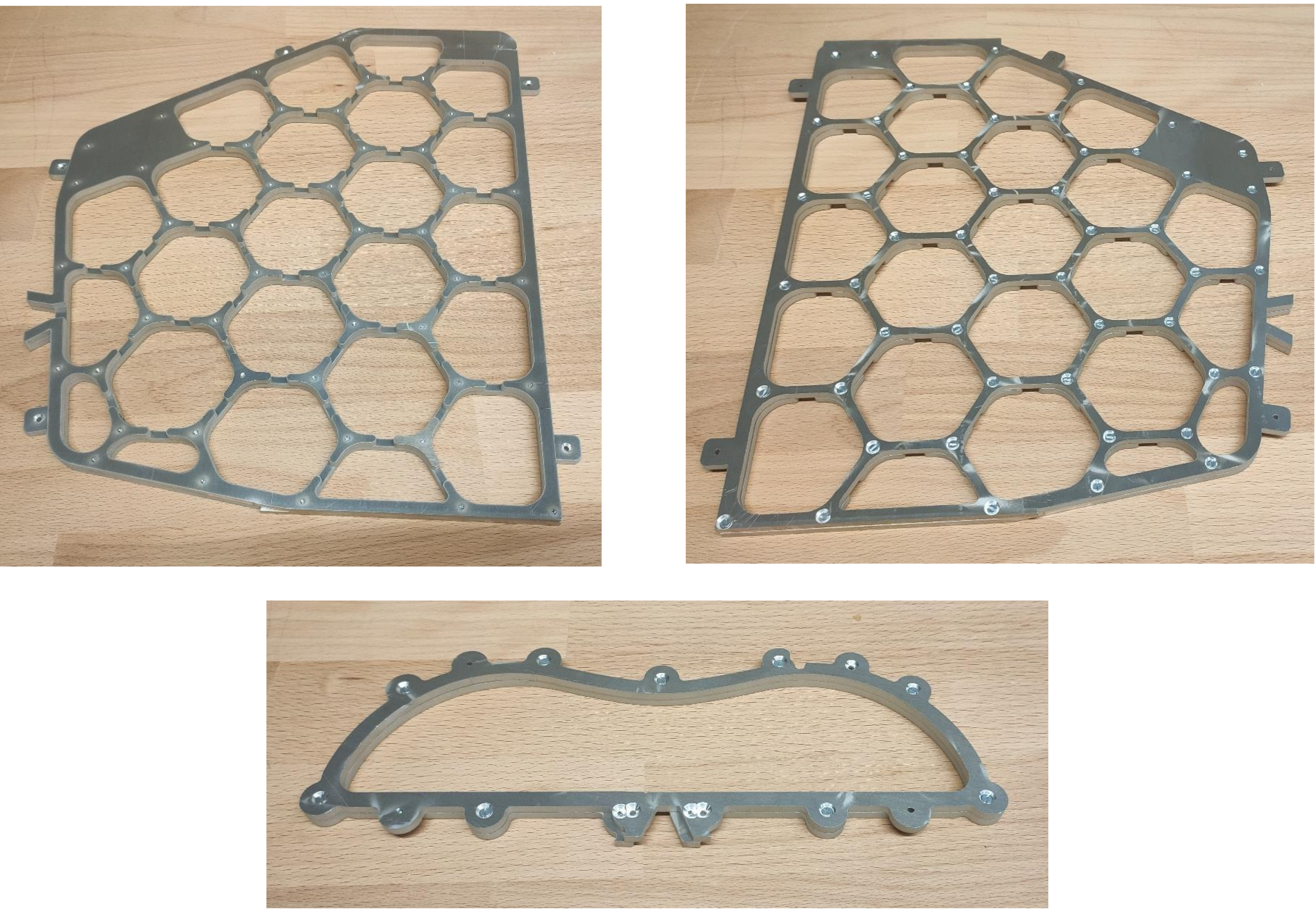


Figure 57

After using these molds in the press, the resulting seal varied at various points. A satisfactory seal for the head cooling pack was easily achieved. For the trunk cooling packs the pressure of the press would vary. In the end it was possible to seal the parts that had not been properly sealed by the mold and press by ironing it in those areas with a sheet of greaseproof paper in between the iron and the plastic. After filling the cooling packs and after the user testing the fill holes were sealed with the iron as well. The final result of the trunk and head cooling packs are shown in figure 58.

Figure 58

Cooling liquid

During the tests in the climate chamber, the packs filled with the alcohol and water mixture made use of denatured alcohol. Several additives are added to denatured the alcohol to make it poisonous, add a different color to distinguish it from regular ethanol and a foul fragrance to discourage drinking it. In the case that a cooling pack would fail for any reason during use, it is not desirable to have a poisonous and bad smelling liquid leaked onto your skin. Therefore, in the final product, regular ethanol will be watered down to create a solution that consists of 17% ethanol and roughly 83% water. A pigment will be added to give the solution a light blue appearance which would indicate the cooling effect.

Since the hexagon shapes are all connected, the liquid can flow from compartment to compartment. When the connections between the compartments is narrower, more pressure is needed in order to flow to another compartment and vice versa. Making the gaps too narrow will eventually cause the cooling pack to break at lower impacts. Making the gaps too wide would cause the liquid to accumulate at the lowest point of the cooling pack due to gravity.

Due to these facts and for the comfortability of the user, a thickening agent is used to make it easier to evenly distribute the liquid in the cooling pack no matter what position the pack is in. The thickening agent used is carboxymethyl cellulose, more information about this material can be found in appendix G. Half a teaspoon of this powder is used in 100ml solution to get the desired thickness. The powder has to be mixed together thoroughly in the solution. The mixing causes bubbles to form. In order to get rid of the bubbles in the solution, a vacuum chamber is used to quickly float the air bubbles to the top. This thickening agent results in a more smooth jelly-like substance compared to the grainy substance made of the blended hydrogel.

Validating the new cooling liquid

Since the new mixture is different from the previously tested mixtures, the heat capacity had to be validated. The test described in the chapter 'PCM Testing' has been redone with the new liquid. For the next tests, the maximum power has been increased to 72W, the heat plate was set to 35°C this time to avoid and for comparison, the following mixtures have been tested as well, the corresponding names in the graphs are written on the right:

Ethanol 17%, Water 83%	eth17_base
Ethanol 17%, Water 83% + E466	eth17_gel
Ethanol 17%, Water 83% + E466 + neoprene	eth_17_gel neo
Water 100%	H2O
IZI bodycooling 18 °C PCM	Izi18

Again, the tests were ended when the power output of the skin model was measured below 5W

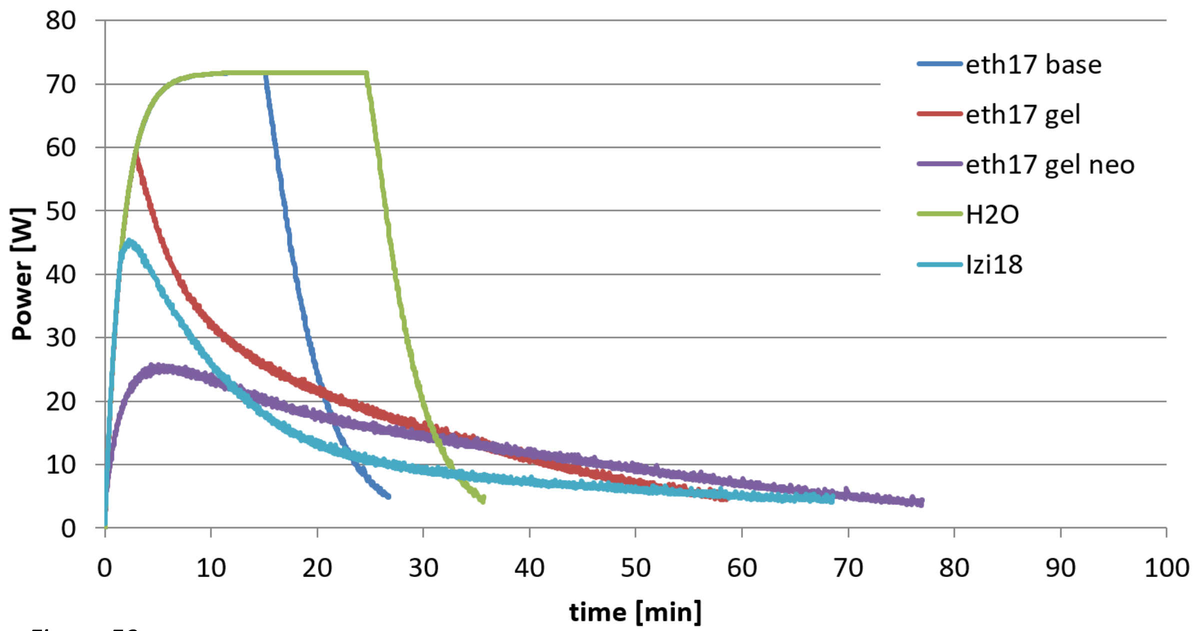


Figure 59

figure 59 shows that there is a big difference in the intensity of the cooling when the thickening agent is added. In order to further identify this effect, the eth17_base and eth17_gel have been placed on the skin model simultaneously with thermocouples attached to the top and bottom of the cooling packs as shown in figure 60. The results of this test can be seen in figure 61

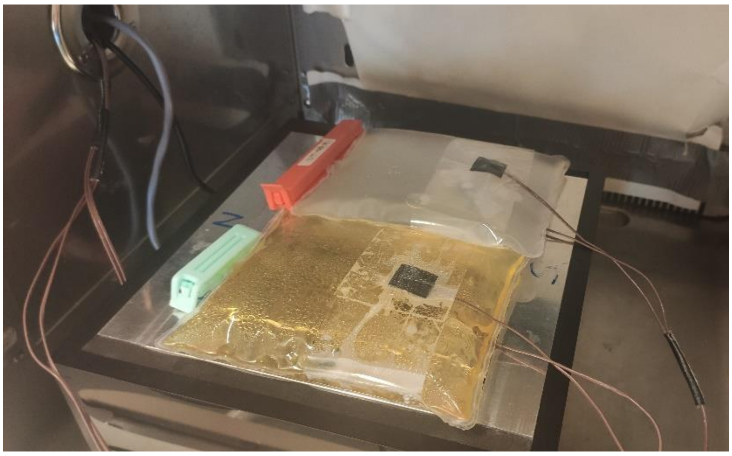


Figure 60

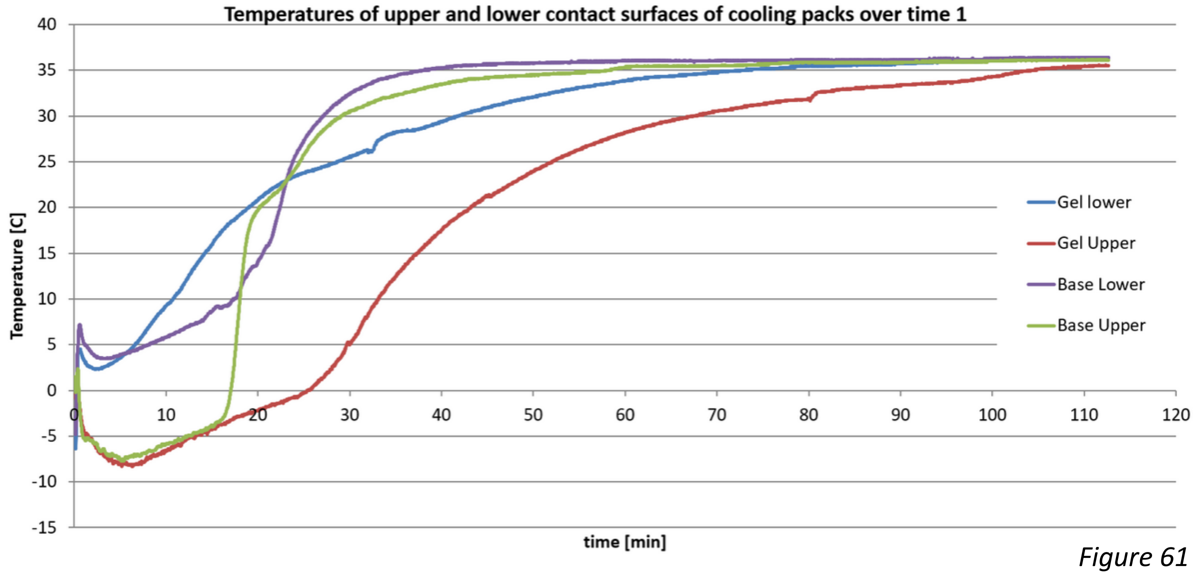


Figure 61

The upper and lower thermocouple of the base pack reach the same temperature after roughly 22 minutes of testing, while the upper and lower thermocouples of the gel pack do not reach the same temperature. This means that the addition of the thickening agent lowers the heat transfer rate within the cooling pack. After 45 minutes, the power output of the skin model fell below 5W even though the temperature of the top of the gel cooling pack was only 21°C.

Since the cooling pack is stationary during this test, there is little to no flow in the liquid. When the cooling pack prototype is used during a match, the cooling packs can be squeezed an/or moved. This would cause the heat transfer rate to go up again.

To measure the total cooling capacity of the gel pack compared to the base pack, the data of these two separate tests have been extrapolated to reach a power output of 0W, as shown in figure 62:

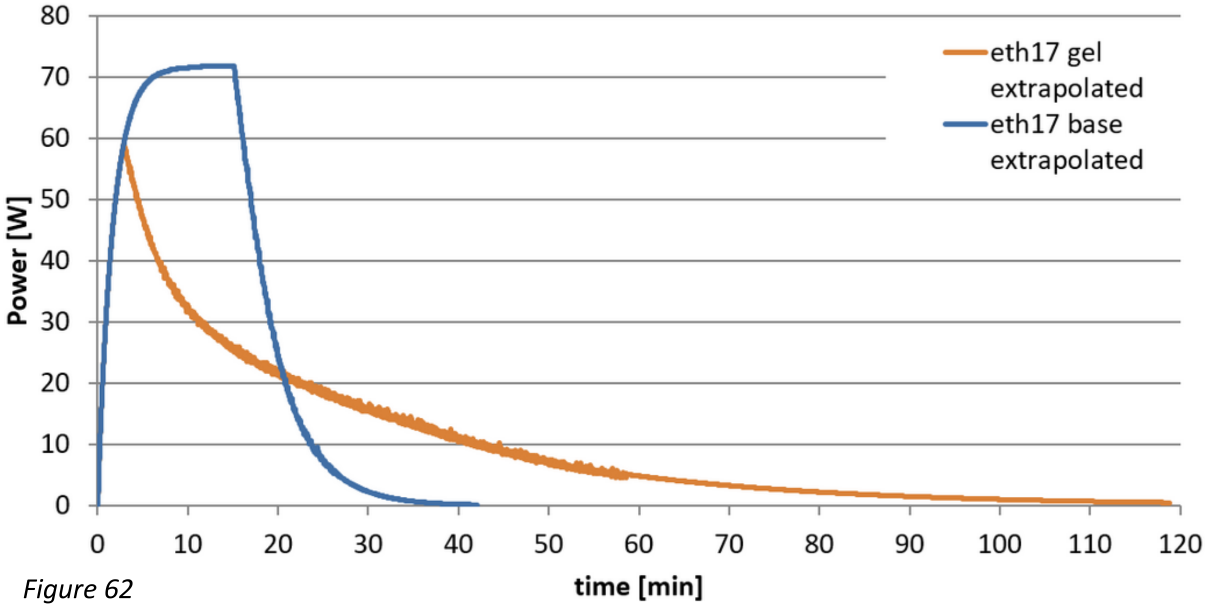


Figure 62

The total cooling capacity for the gel pack is 75,0kJ and 77,3kJ for the base pack. Thus the addition of the thickening agent results in a decrease of cooling capacity of 3% as well as a significantly lower intensity of cooling.

Determining the cooling capacity of the prototypes

To determine the cooling capacity of the trunk prototypes, the honeycomb shaped sample from the first mold has been tested on the skin model figure 63. As a comparison, two extra packs were made with the same outer shape but without the honeycomb seal lines in the middle. The names and details of these packs are as follows:

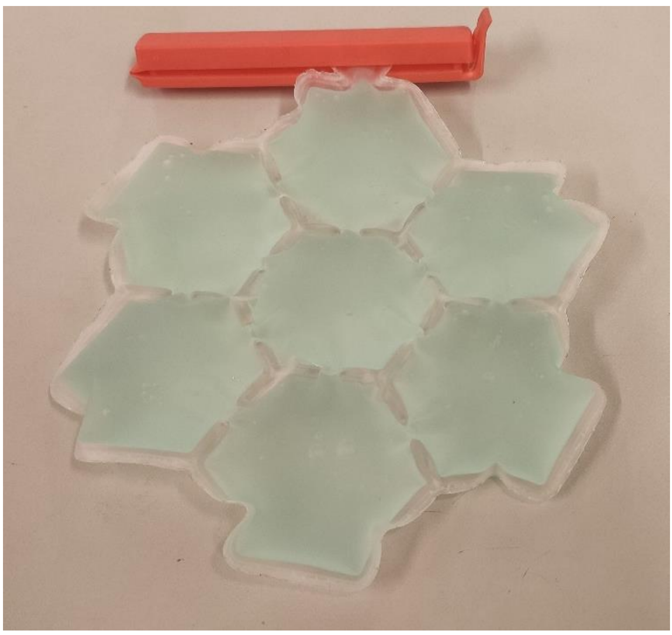


Figure 63

Eth17_gel_hex: 150g full honeycomb structure as seen in figure 63

Eth17_gel_nohex: 150g Only the outlines are sealed, same volume as Eth17_gel_hex (figure 64 left)

Eth17_gel_nohex vol: 250g Only the outlines are sealed, same thickness (18mm) as Eth17_gel_hex (figure 64 right)

Furthermore, the contact area of these packs have been determined using the following method:
The packs have been placed between two flat pieces of plexiglass. In order to see where the sample pack touches the plexiglass, a small amount of water was distributed over the surface of the top plexiglass plate, causing the contact areas to show a clearer outline. A 1kg weight was put on top of the plexiglass of every tested sample when placed in the freezer before testing. Pictures of the sample packs in between the plexiglass have been made from the top view with a 53mm tele lens to minimize the effect of distortion due to perspective.

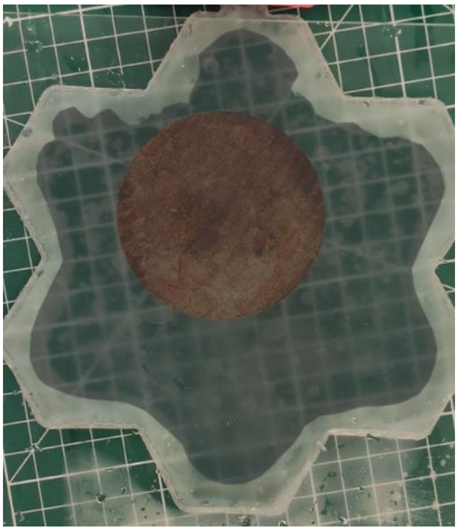
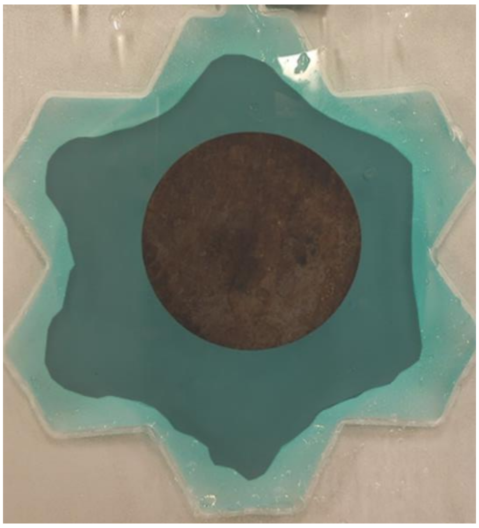


Figure 64



The outlines of the surface areas have been traced in photoshop (darker areas) and the pixels have been scaled to millimeters to be able to measure the contact surface in SI units.

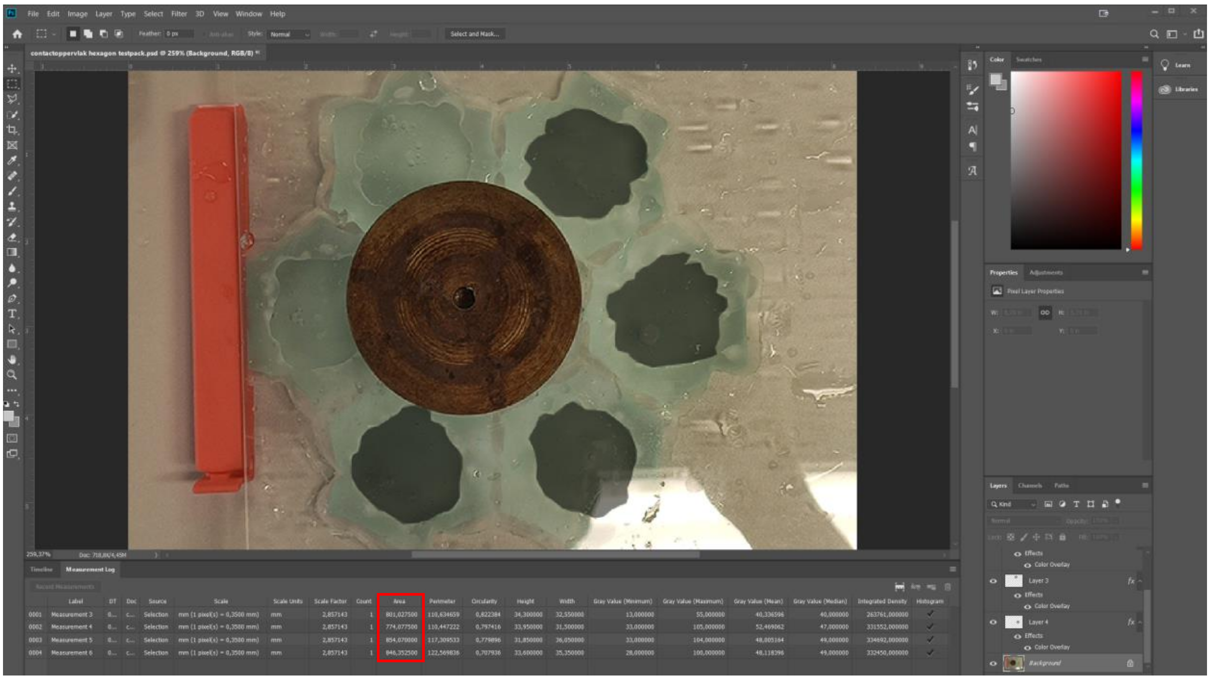


Figure 65

The average of the four best visible contact surfaces have been calculated in order to determine the total contact surface:

(801+774+854+846)/4= 819mm^2 per surface area
819*7= 5731mm^2 (57,31cm^2) total surface area of Eth17_gel_hex.

Using this method, the contact surfaces of the other sample packs have been determined:
Eth17_gel_hex: 57,31cm^2
Eth17_gel_nohex: 125,99cm^2
Eth17_gel_nohex vol: 102,26cm^2
All rectangular samples: 78,82cm^2

The results of the skin model tests are shown in figure 66. The data has been extrapolated by drawing an exponential equation using the last value measured (5w) and all values measured up to 20 minutes before the last measured value. The total cooling capacity for has been calculated by adding all values up to 100 minutes which gives the following results:

Eth17_gel_hex: 34,3kJ
Eth17_gel_nohex: 44,7kJ
Eth17_gel_nohex vol: 71,6kJ

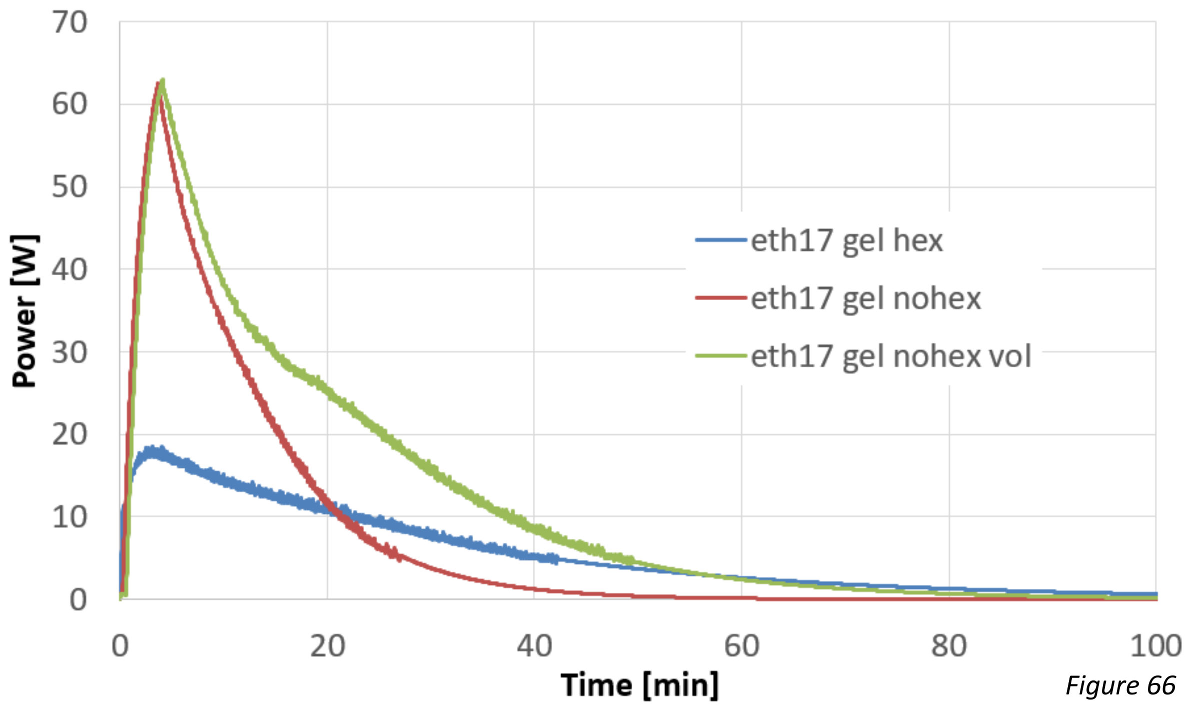


Figure 66

Using the surface area from the Eth17_gel_hex pack, the surface area of the trunk cooling pack can be approximated. The average surface area of one hexagon is 819mm^2. The trunk cooling pack consists of approximately 21 hexagons which translates to 172cm^2, which is three times the surface area of the tested pack. When the prototype is filled with three times the volume of the tested pack (3 * 150 = 450g), the total cooling capacity would be 103kJ.

5.1 Evaluating the final designs

In order to validate the calculations made to determine the functional duration of the cooling packs, a practical test has been carried out. For this test, a room has been turned into an environmental chamber that mimics the Tokyo environment during the summertime. With the use of an electrical heater and a hot shower, the temperature could be held at 30°C and the humidity at 70-75%. During the testing these values were monitored using a digital thermometer and hygrometer. When the humidity dropped below 71%, the hot shower would be turned on to bring the humidity back to 75%.

A bicycle roller was placed in the room with a built-in speedometer that also showed the power output and calories burned. A racing bicycle was placed on the bicycle roller.

Each cooling pack contained two thermocouples except for the head cooling pack, which only contained a single thermocouple. The monitor was placed next to the user and was connected to a laptop on which you could monitor the temperatures of the cooling packs live. The thermocouples were inserted through the filling holes of the cooling packs, the filling holes were then sealed with a bag sealing clip as shown in figure 67.

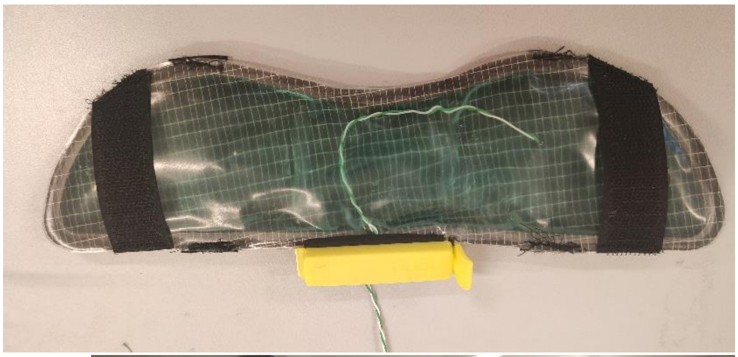


Figure 67

The cooling packs were removed from the freezer (-21°C) right before the start of a test and it would take approximately 4 minutes to gear up the user in an 18°C room. The test would start immediately after that. The full setup can be seen in figure 68.

The cooling packs were filled with the mixture of 17% ethanol and 83% water with the thickening agent (E466). The following volumes were used:

Body (trunk) right:	360g
Body (trunk) Left:	430g
Head:	92g
Back:	220g

Figure 68

For the final design, the left and right trunk cooling packs will contain the same amount of volume. The goal of the two different volumes here is to see how a certain increase in volume will increase the functional duration of the cooling packs.

For the trunk and back cooling packs, the neoprene layer was positioned in between the cooling liquid and the user. For the head cooling pack, the neoprene layer was positioned between the helmet layer and the cooling liquid. A sweatband was placed in between the cooling pack and the forehead.

Two tests have been carried out with the same user with a weight of 90kg. During the entire first test, the power output of shown on the speedometer was between 100 and 107W (20km/h). during the second test, the power output was between 140 and 147W (30km/h). Both speed and power output these values were monitored on the built in speedometer of the bicycle roller.

The MET values given for the tests are found to be 6.8 for the first test and 8.8 for the second test REF. The power output of a goalie during a match is estimated to be lower than the power output during these tests, but this depends highly on the amount of action a goalie gets.

Unfortunately, one of the thermocouples inside the right trunk cooling pack could not be monitored due to a connection error. After the thermocouples are connected to the monitor, it takes some time to see the correct temperature. After about three minutes, the correct temperature is displayed. The results of the first tests can be seen in figure 69 and the result of the second test are shown in figure 70

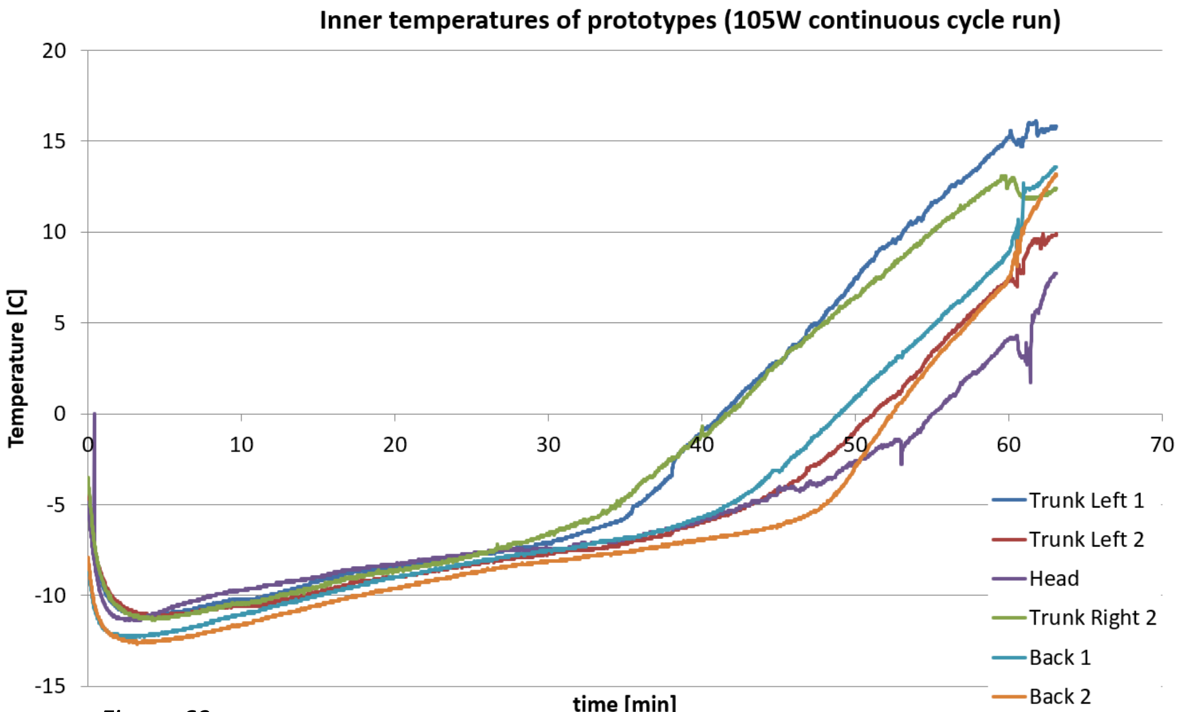


Figure 69

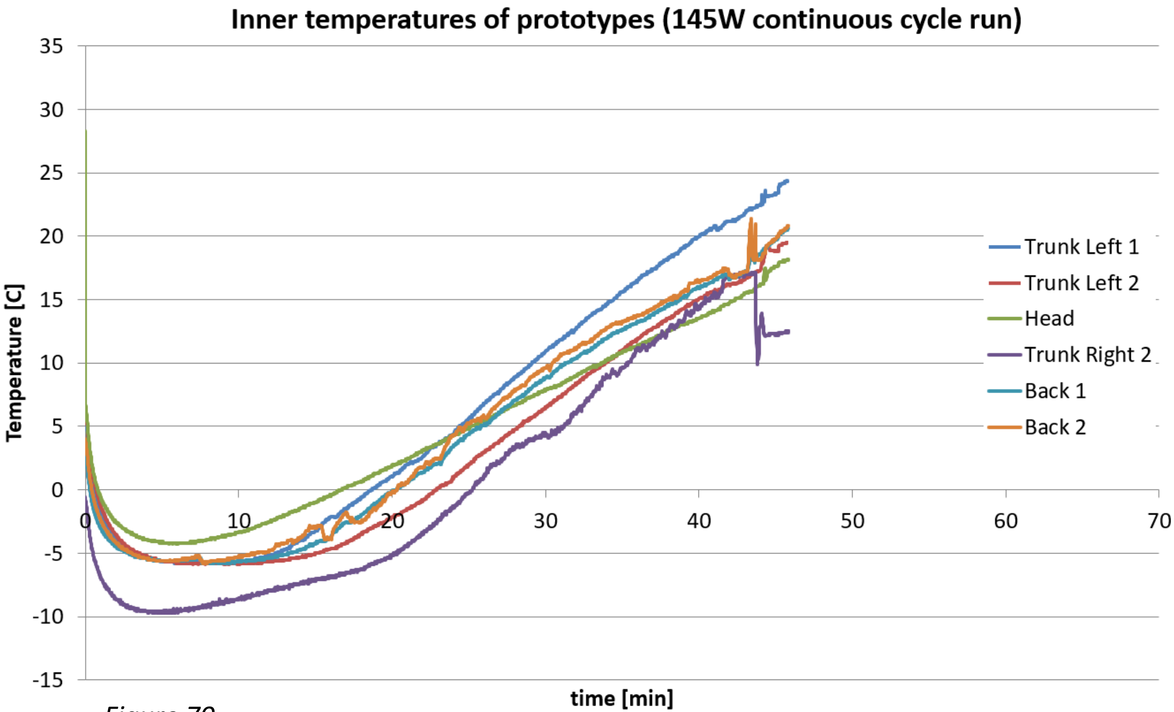


Figure 70

Between the two tests, the user had a resting time of 2 hours. It appears that during this resting period the cooling packs have not cooled down to the same temperature the internal temperature of the freezer (higher initial temperature and greater variation in temperatures). The first test was stopped after the 60 minute mark. Right after the test, the cooling packs were taken out and inspected, hence the spikes seen in the graph at that point.

The user indicated that the trunk and back cooling packs felt comfortable regarding the temperature during the entire first test. The head cooling pack felt a bit below comfort level cold at first. After 5 minutes in the test, a cooling effect on the forehead was not perceived.

As concluded from the comparison test of the Eth17 mixtures with and without the addition of the thickening agent (E466), the side of the cooling pack facing the body heats up significantly faster than the side facing the protective gear. Controlling the placement of the thermocouples on the inside of the cooling packs was difficult. If the thermocouple was placed closer to the body, it would read a higher temperature as compared to a thermocouple further away from the body. As can be seen in test one, the thermocouple ‘trunk left 1’ heats up in the same fashion as ‘trunk right 2’, even though the right trunk cooling pack has a 17% smaller volume and nearly the same contact area.

The goal to see how a certain increase in volume will increase the functional duration of the cooling packs can thus not be achieved with this test. What can be achieved is a rough estimate of the functional duration of the cooling packs, which would be a little under an hour for each of the packs with a steep decrease in functionality from about 40 minutes onward (given the user exercises a MET value of 6.8).

These results are satisfactory since half a match can take between 34 and 44 minutes (excluding the time before the match when the cooling packs are already placed).

5.2 Final designs & usage

Trunk cooling pack:
Before sealing the fill holes, the volumes of the trunk cooling packs have been adjusted to 400g as this would be enough for half a hockey match. The mesh pocket inside the body protector has been made to fit the new shape of the core cooling pack. While the body protector is strapped on tight, the cooling pack can not be placed, therefore the Velcro fasteners on the front should be loosened. At this point there is enough space between the body protector and body slide the cooling pack in the mesh pocket and fixing them to the Velcro fasteners. The cooling pack can be removed without having to loosen the body protector by simply pulling it out from the chest area.

Figure 71

Figure 72

Back cooling pack:
The shape of the compartments in the back cooling pack have been adjusted to be able to achieve the same thickness as the trunk cooling pack. Since the back is not subjected to the impact forces of a hockey ball, the laser sealing technique has been used for this prototype. The cooling pack cannot be placed by the user when the body protector is strapped on. The pack can be placed by another person, or the goalkeeper has to take off the body protector in order to do it himself. The long rectangular shapes of the compartments in a running bond pattern make it easier to place the pack in the mesh pocket because when the pack is frozen, the freedom to bend the pack breadthwise is limited. A Velcro patch is added to the top of the pack on both sides to be able to secure it in place whether the user wants the pack placed directly to the skin or with the insulating neoprene layer in between. During a training or match, the cooling pack can be easily removed by pulling the hole handle.

Figure 73

Figure 74

Head cooling pack:
The top bubble has been removed from the head cooling pack as this did not feel comfortable when wearing it. The easiest way to attach the cooling pack to the helmet was to use the Velcro that is already placed in the helmet around the forehead area. To attach the Velcro to the cooling pack without deteriorating the polyethylene, stitches were used to secure the Velcro at the edges of the cooling pack. The Velcro is places on the far left and right side to keep the contact area of the pack as large as possible. The Velcro is placed on either side to be able to secure the sweatband in between the cooling pack and the forehead.

Figure 75

Figure 76

5.3 Conclusion

Figure 77

In the end, 4 functional prototypes have been produced. With the Use of the molds made during this project is it possible to reproduce these prototypes.

Functionality
The cooling packs provide adequate cooling for the goalkeeper for about half a match.

Ease of use
All cooling packs are easily removable when needed. The back cooling pack can not be placed by the user while staying strapped in to the body protector. The trunk cooling packs can be placed by the user by only having to loosen the Velcro bands at the front of the body protector. The head cooling pack can be replaced as easily as the sweatband.

Safety
The final prototypes have not been tested on impact. However, The sample pack that has been manufactured in the same way has passed the impact tests. Knowing this, it can be assumed that the cooling packs made of the Inuteq SEAL PE should pass the impact tests as well. The packs do not provide a poisonous hazard when failing in usage.

Weight
The trunk packs each weigh in at 400g, the head pack at 92g and the back pack at 220g. since the packs are placed at the core and head of the body, the decrease in overall mobility should be limited. The mobility in the arms and legs is not affected.

5.4 Recommendations

For the further development of these cooling packs some recommendations will be given below:

As stated in the report, the cooling packs could only have the maximum dimensions of 30 by 30 centimeters. For small and medium sized body protectors, this should be sufficient. With large and extra large body protectors, a new mold would have to be made to accommodate the users with larger bodies. This could either be done by using a bigger waterjet cutter, but my preference would go out to a CNC milled mold as these can give a more accurate result.

the materials cut in the water cutter need finishing after working. The two layers of the mold have to be screwed together which means every hole has to be threaded. This can be very time consuming and in a practical sense maybe cost more than having it milled.

Since the waterjet cutter can only shoot the jets downward, it is impossible to create fillets on the edges. Fillets would be recommended to have on the edges to minimize the chance of tearing the plastic when the heated mold is pressed down against the plastic. The rounded edges could also be realize by using a CNC mill.

Another problem found during the sealing process is that the parts of the mold that were further away from the middle of the press, would tend to give a worse seal as compared to the part of the mold that is positioned in the middle of the press, therefore the final product had to be touched up with an iron. This could have several causes:

- The mold or pressing plate is not flat
- The mold is not heated evenly
- The pressing plate deforms when pressing since the pressing rod is positioned in the middle of the pressing plate

Although it would feel less comfortable, another PCM could be used in the back cooling pack that has a higher melting point than the Eth17 mixture, since the back is not subjected to high impacts.

References

Figures:

Figure 2: Factors affecting thermoregulation in the human body, retrieved from: https://ppt-online.org/531361

Figure 5: Tajima Seiryo products, retrieved from: https://www.japantrendshop.com/ES-tajima-seiryo-jacket-cooling-system-p-3564.html

Figure 6: Inuteq PCM Cooling pack retrieved from https://inuteq.com/images/medium/EntryPCMCoolOver_21G.png

Figure 8, 9, 10: OBO ROBO goalie gear, retrieved from: http://www.obo.co.nz/ranges/robo

Figure 11: OBO ROBO Body Armour image details, retrieved from: http://www.obo.co.nz/images/uploads/6619f8ade71c601c5b353fc14275d6f0.png

Figure 13: Oi Hockey stadium retrieved from: https://www.google.com/maps/place/Oi+Hockey+Stadium/@35.5926128,139.7512535,17z/data=!3m1!4b1!4m5!3m4!1s0x0:0xac61e7a6daf3b154!8m2!3d35.5926128!4d139.7534422

Figure 14, 15: Average weather in July in Tokyo, retrieved from: https://weatherspark.com/m/143809/7/Average-Weather-in-July-in-Tokyo-Japan

Figure 16: Humidity comfort levels in July, retrieved from: https://weatherspark.com/m/51381/7/Average-Weather-in-July-in-Amsterdam-Netherlands

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https://nocsae.org/wp-content/uploads/2018/05/1515793119ND06114MfrdFieldHockeyHeadgearStdPerformance.pdf

Appendix B: Sealing material specifications

INUTEQ-SEAL®

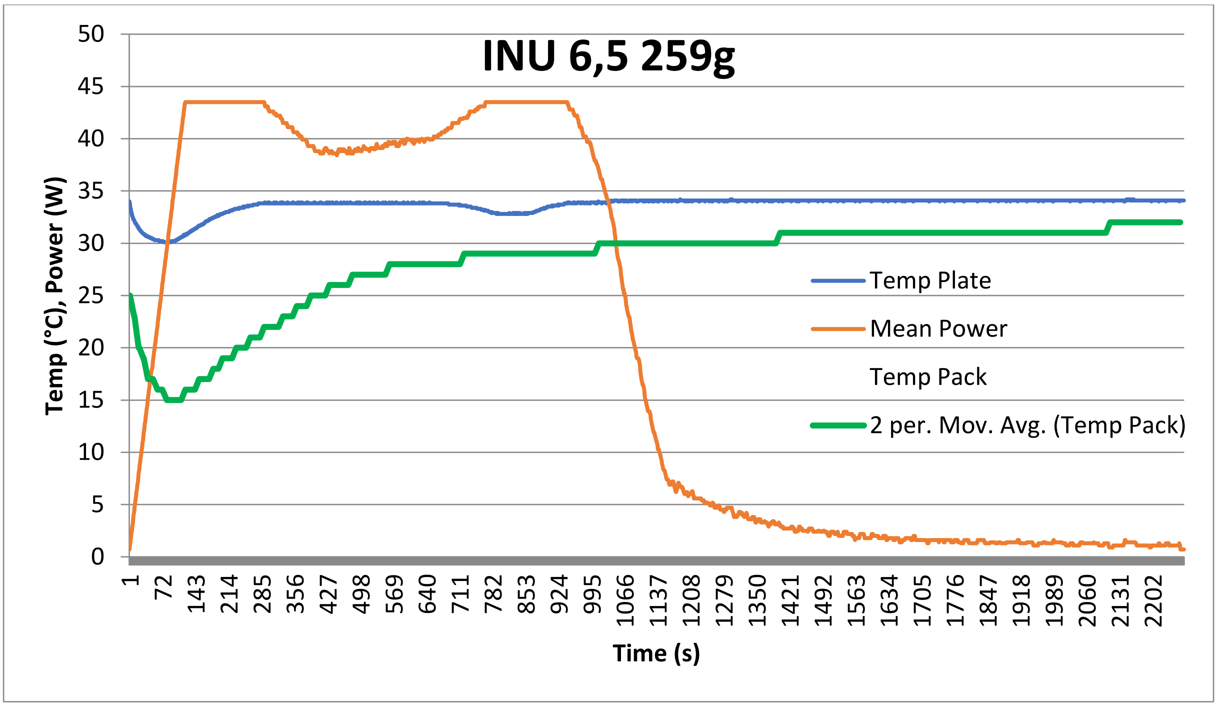
Polyether | Polyester Polyurethane

INUTEQ-SEAL® is non-toxic and therefore contains no toxic substances (according to the German Hazardous Regulations)
INUTEQ-SEAL® is not water-soluble
INUTEQ-SEAL® does not require EC Guidelines

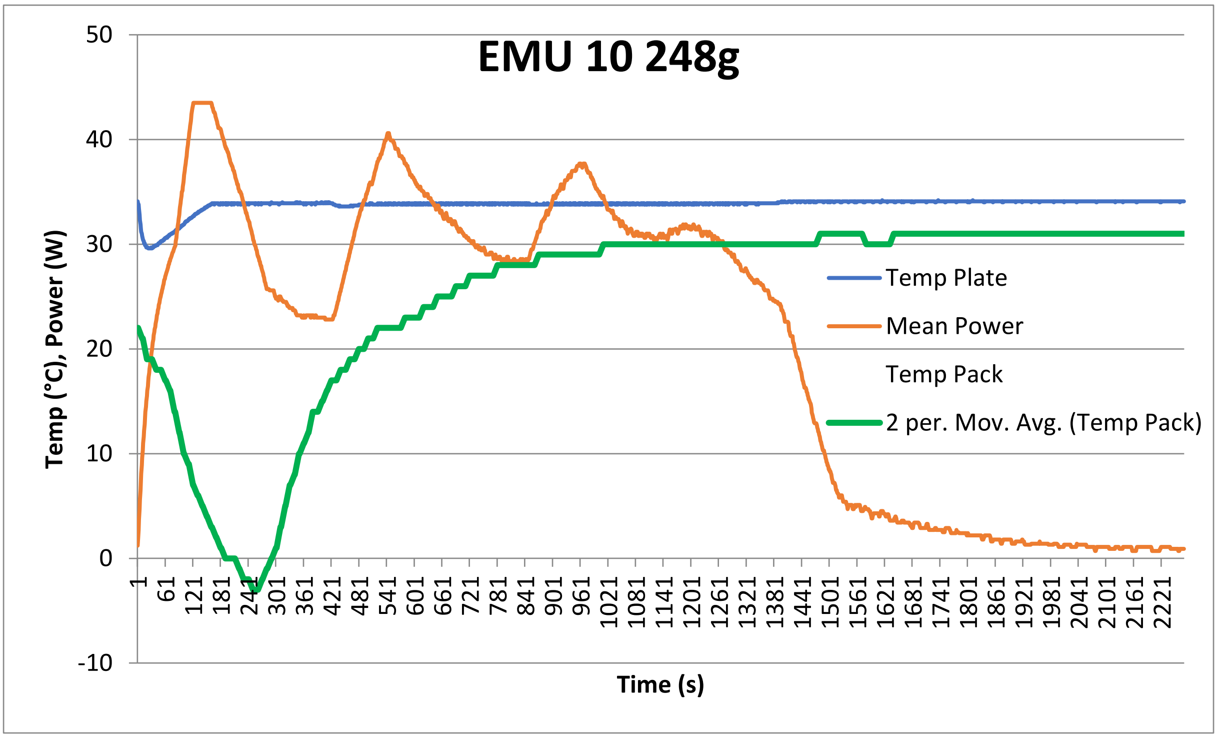
Typical properties

Test	Typical Value	Units
Melting temperature	110-180	°C
Ignition temperature	> 250	°C
Density	1.10 - 1.30	g/cm^3

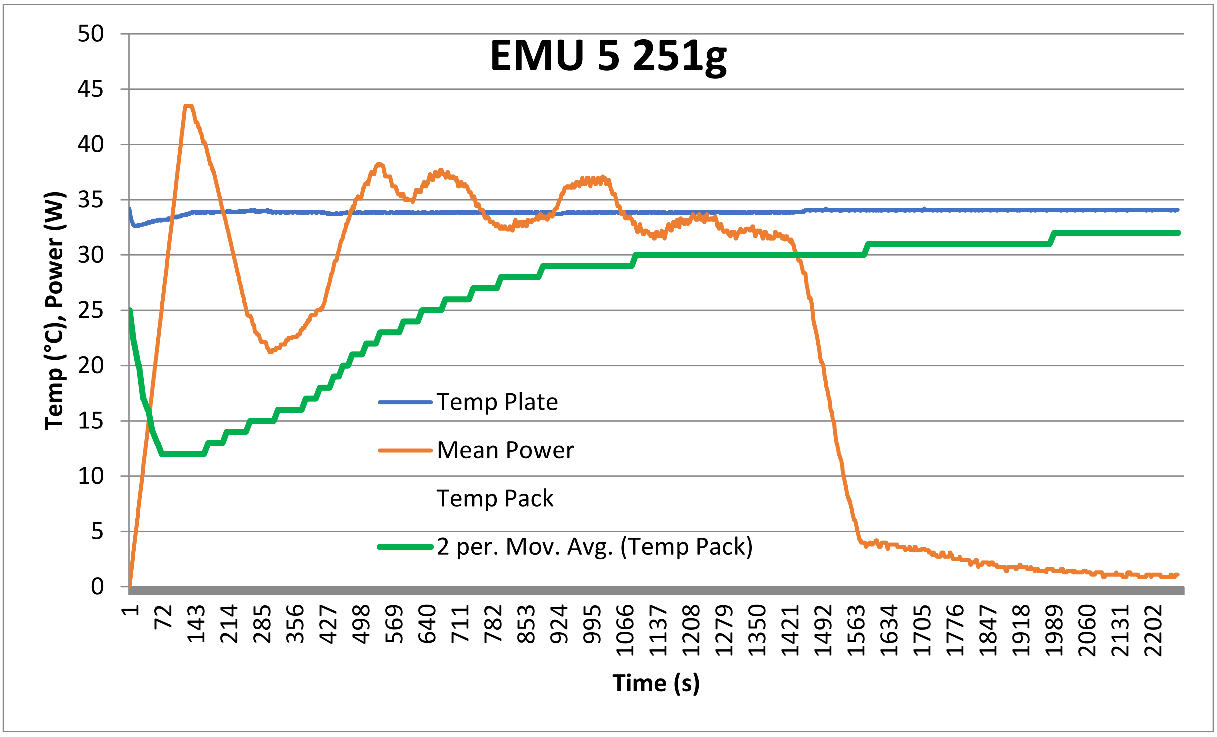
Appendix C: Initial PCM Testing



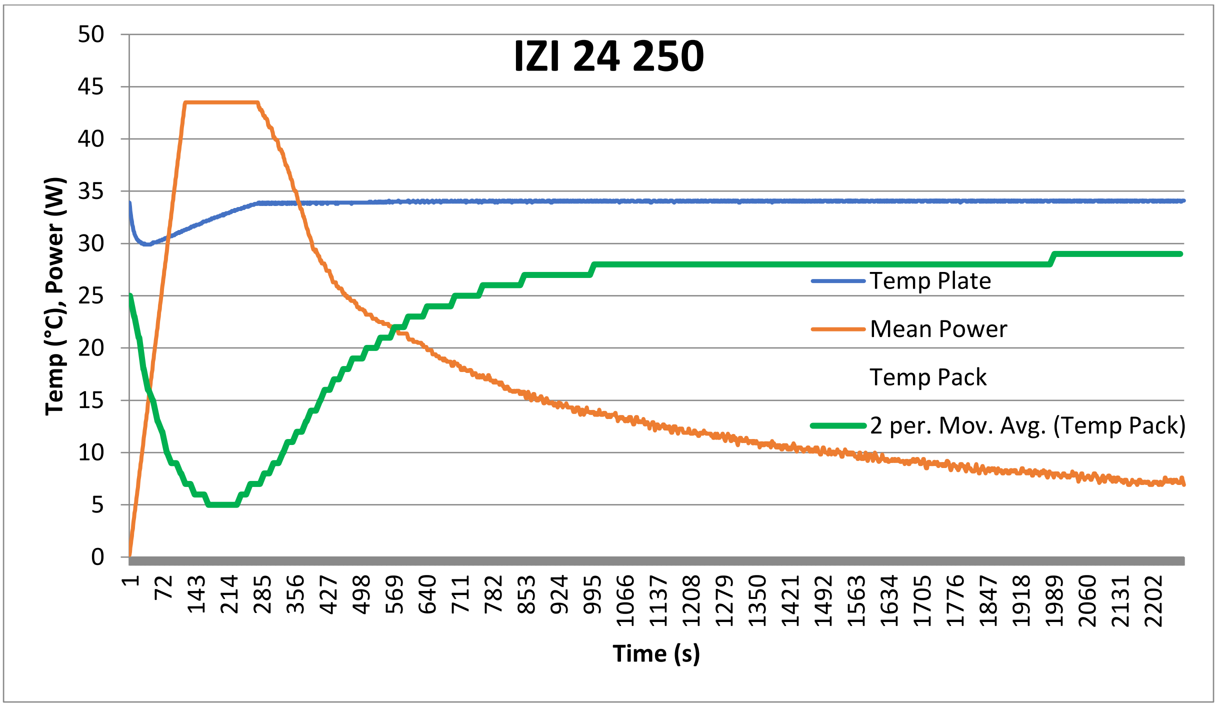
Power consumed after 1000s: 39.42KW, after 2100S: 45.17KW



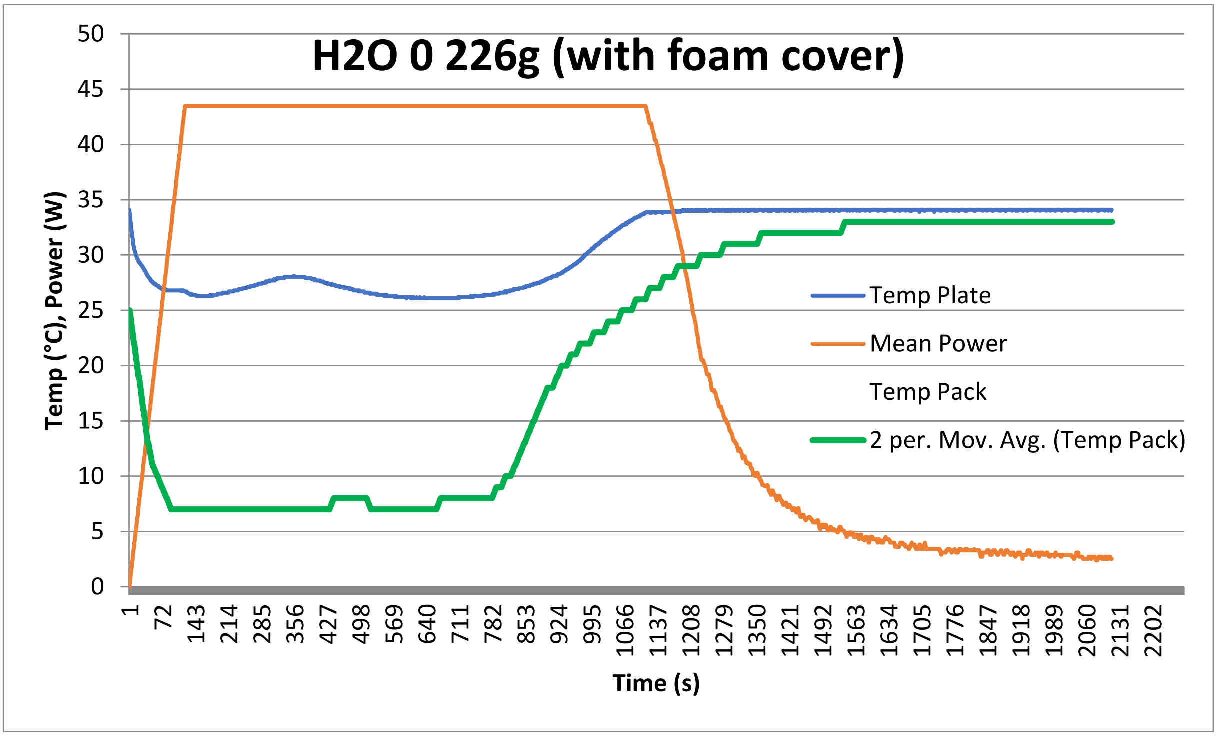
Power consumed after 1000s: 31.4KW, after 2100S: 46.6KW



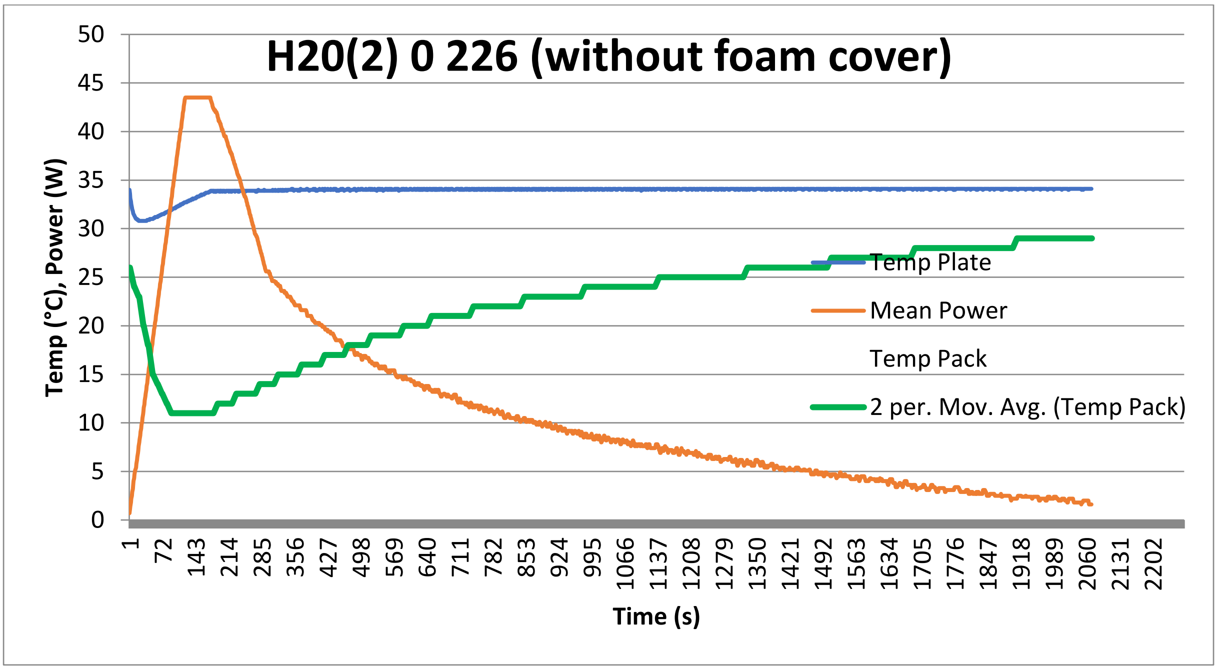
Power consumed after 1000s: 31.5KW, after 2100S: 49.3KW



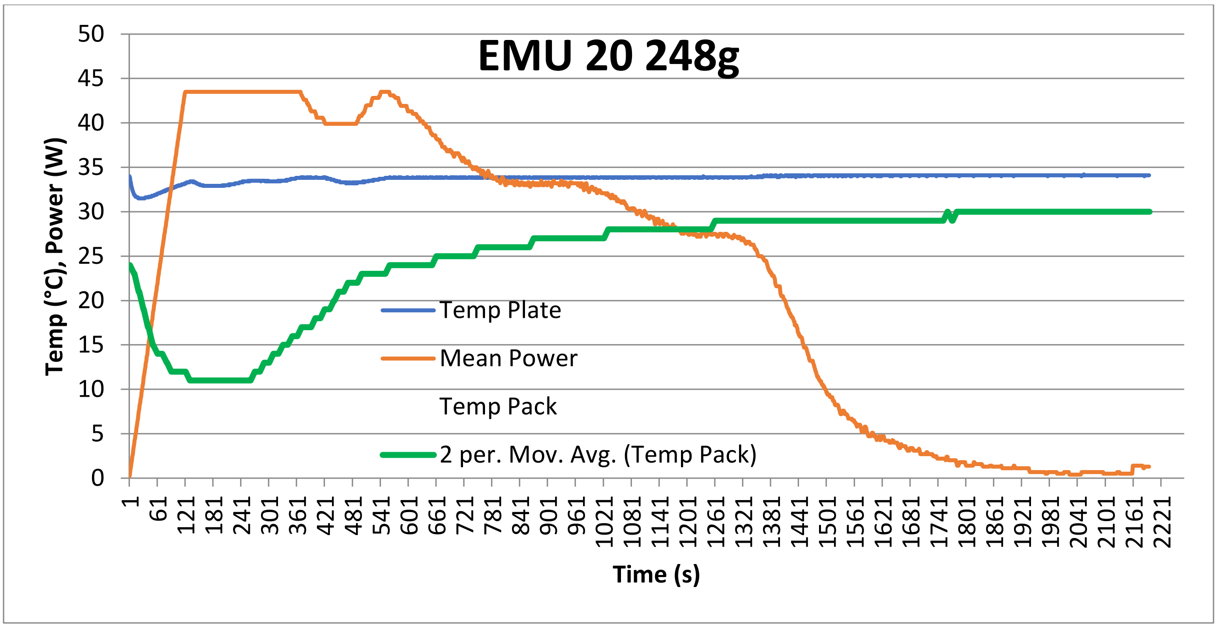
Power consumed after 1000s: 25.6KW, after 2100S: 36.6KW



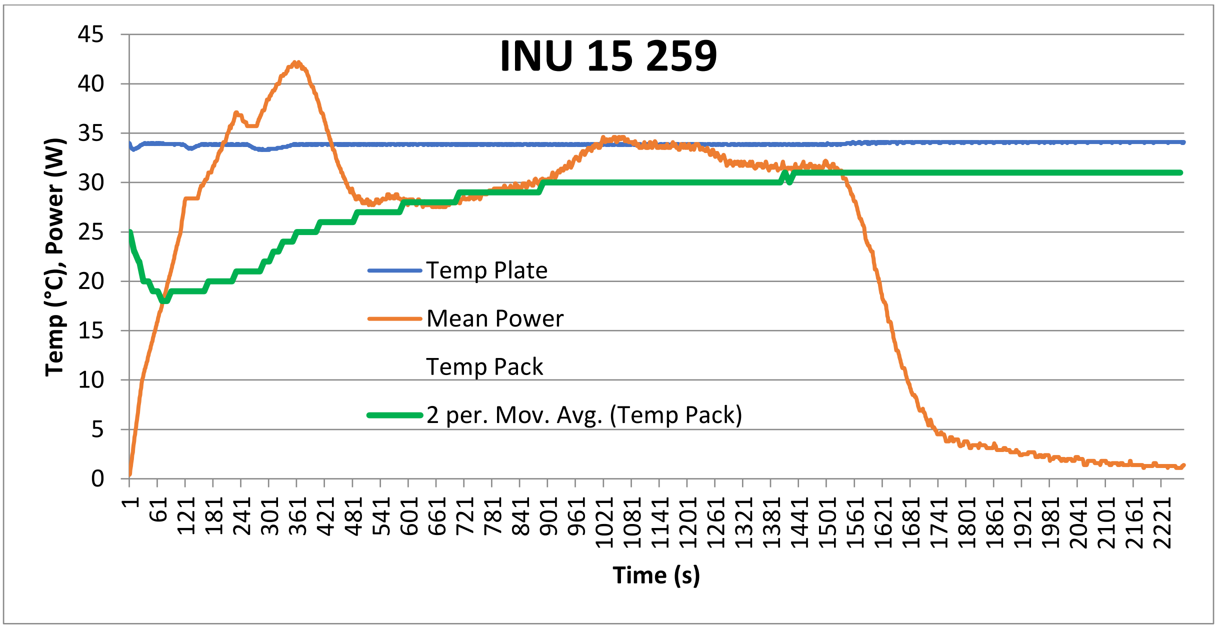
Power consumed after 1000s: 40.9KW, after 2100S: 54.6KW



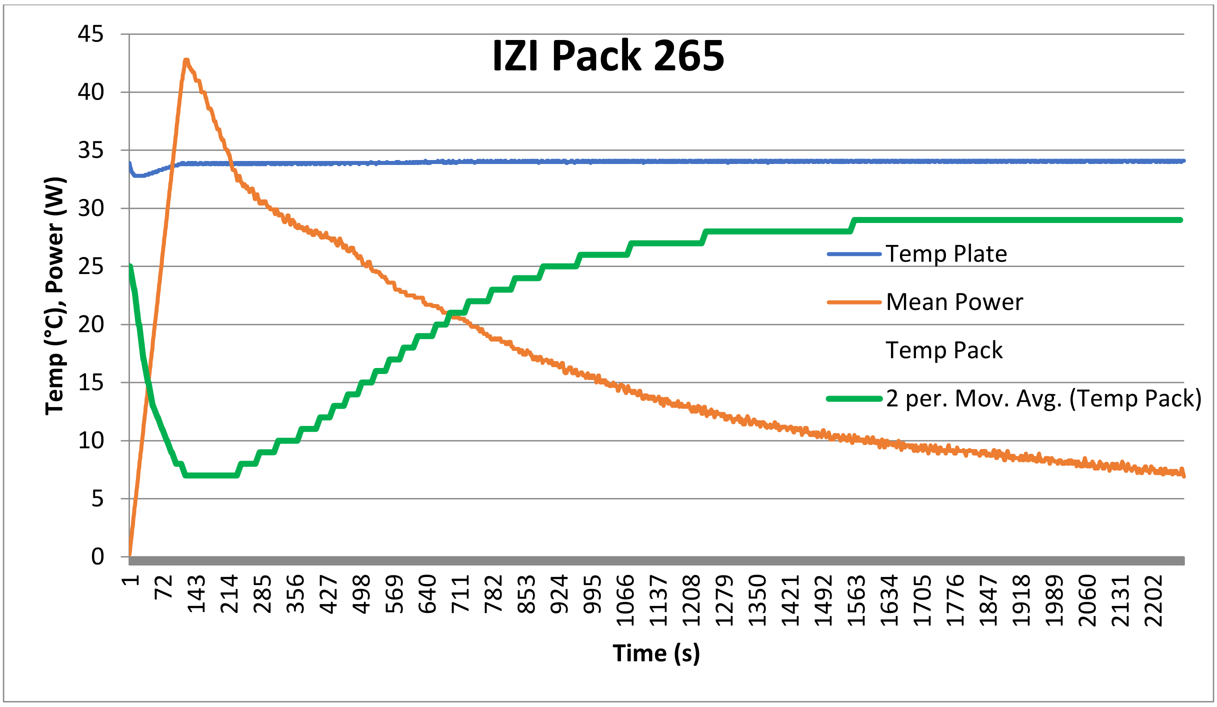
Power consumed after 1000s: 41.0KW, after 2100S: 48.4KW



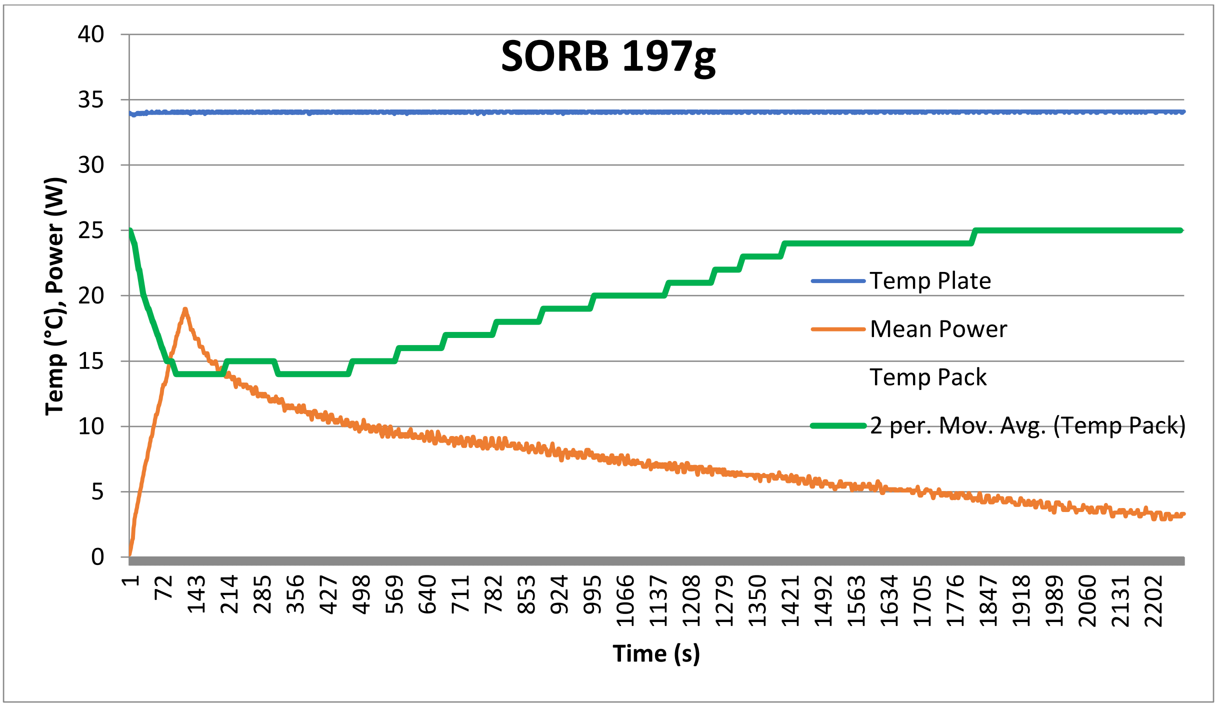
Power consumed after 1000s: 37.0KW, after 2100S: 51.4KW



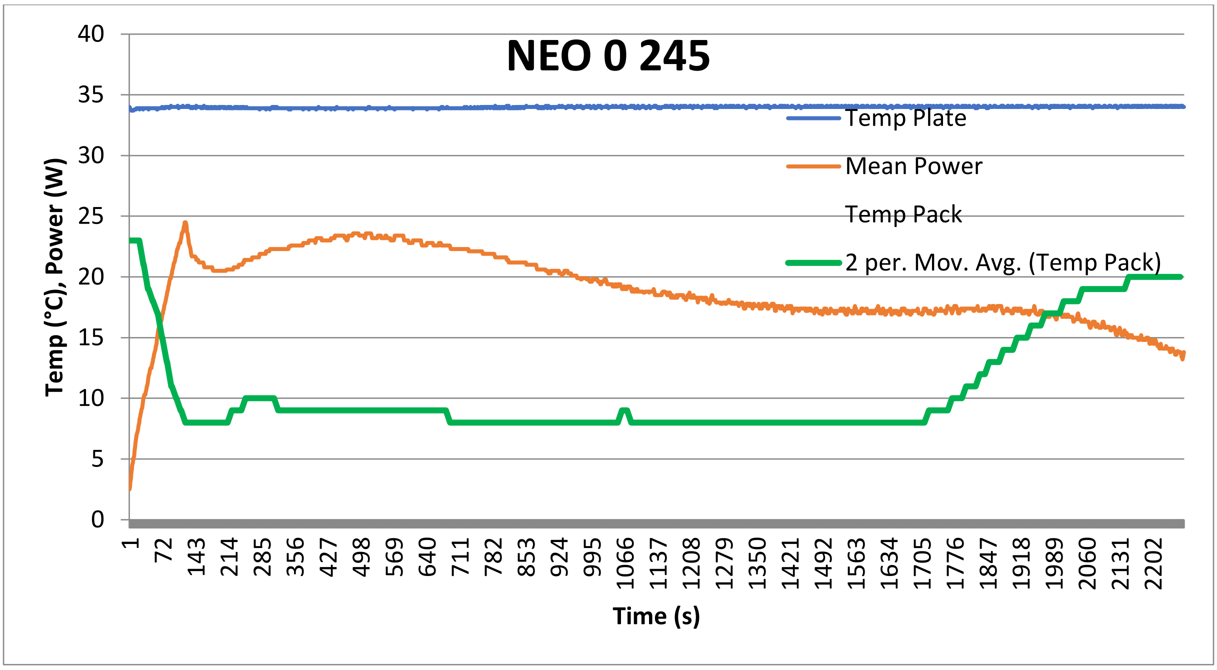
Power consumed after 1000s: 29.80KW, after 2100S: 51.7KW



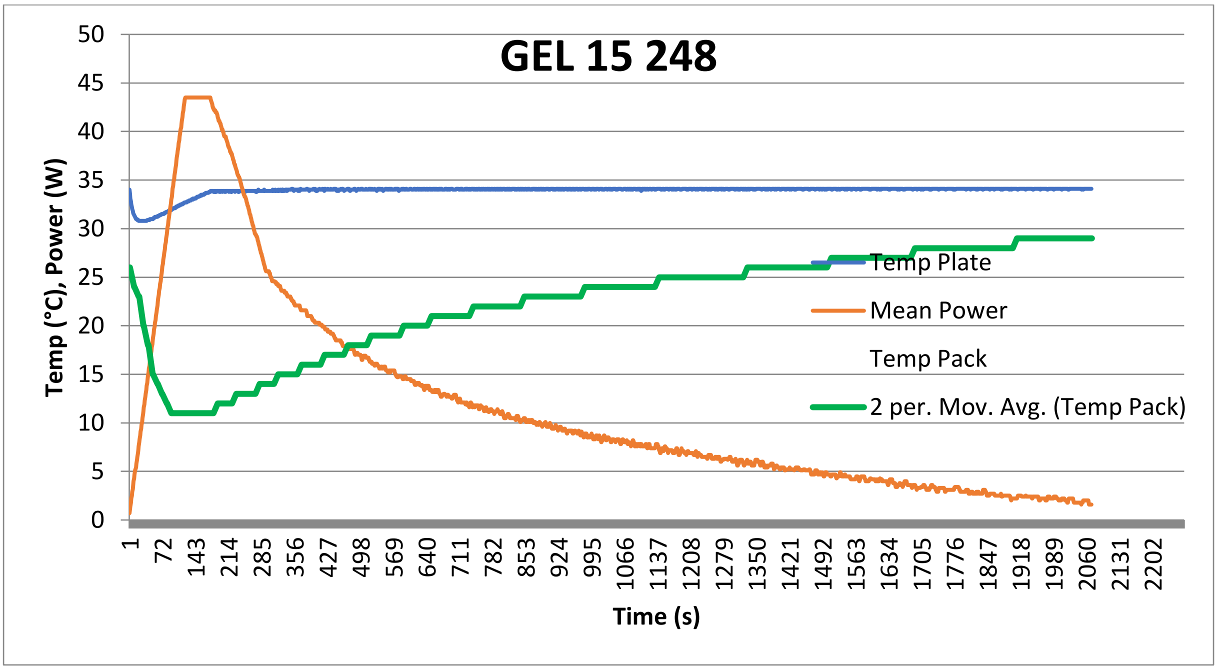
Power consumed after 1000s: 24.5KW, after 2100S: 36.2KW



Power consumed after 1000s: 10.5KW, after 2100S: 16.5KW



Power consumed after 1000s: 21.1KW, after 2100S: 40.48KW



Power consumed after 1000s: 19.5KW, after 2100S: 24.6KW

Appendix 3: Sample packs specifications

Opstelling:

Klimaatkast ingesteld op 35 graden Celcius en 80% luchtvochtigheid
Warmteplaat in klimaatkast ingesteld op 34 graden Celcius.
Twee temperatuursensoren (iButtons) geplakt op de bovenkant van de coolpack (wordt na de test uitgelezen)
Computer die realtime het verbruik van de warmteplaat waarneemt
coolpack wordt tijdens de test gedeeltelijk afgeschermd met een 5mm EVA Foam doos.

Gewichten en volumes van de getestte materialmen:

Type	Gewicht(g)	Volume(ml)	
Inu6.5C.	259.	300	700-1000
Inu15C.	259.	310	680-990
Emu5%.	251.	290	690-980
Emu10%.	248.	300	690-990
Emu20%.	248.	300	680-980
Gel15C.	248.	270	680-950
Izi24C.	250.	230	680-910
H20 0C.	226.	225	700-925
NEO 0C.	245.	260	700-960

Het doel is om een materiaal te vinden wat zo lang en constant mogelijk warmte af kan geven, zonder dat de temperatuur van de koelpack een groot verschil heeft met de temperatuur van de warmteplaat.

Uit deze test is gebleken dat de het koelmateriaal INU 15 (Inuteq met smelttemperatuur 15 graden C) het meest geschikt zal zijn voor een koelpack bij keepers onder deze omstandigheden.

Appendix D: Relevant information from EN:13546

4.5 Restraint requirements

Hockey players' protective equipment shall be designed so that it should remain in place during normal play and during impacts. This restraint can be achieved using integral straps with buckles, touch and close fasteners, separate 'harness' or other items of protective equipment or clothing. The manufacturer shall give details of how adequate restraint of the equipment may be achieved in the Information supplied by the manufacturer, see clause 7.

The restraint systems for the protective equipment shall be assessed as described in section 5.8. The reference dimension for assessment is the width or length of the outer or complete protective zone measured in line with the direction of the applied test force. The equipment shall not be displaced by more than **X** % of the protective zone dimension, when the test force is applied and shall return to within **Y** % of its initial position when the force is removed. The forces to be resisted are given in Table 16, together with the values of **X** and **Y**.

Table 16 — The test forces to be resisted by the restraint systems of hockey players' protective equipment in Newton

Item	% Movement		Test force for products of particular performance levels, Newton				
	X	Y	1	2	3	4	5
Shin protector	15	5,0	15	15	30	30	30
Leg protector	15	5,0	30	40	50	50	50
Kicker	25	8,3	30	40	50	50	50
Abdominal protector	15	5,0	15	30	30	30	30
Thigh and hip protectors	25	8,3	15	30	30	30	30
Chest protector	15	5,0	15	30	30	30	30
Breast protector	15	5,0	15	15	15	15	15
Elbow and forearm protectors	25	8,3	15	30	30	30	30
Shoulder protectors	25	8,3	15	30	30	30	30
Upper arm protectors	25	8,3	15	30	30	30	30
Goal-keepers gloves	25	8,3	10	10	25	25	25
Soft genital protectors	50	25	15	15	15	15	15
Hard genital protectors	50	25	5	10	-	-	-

4.6 Impact performance requirements (excluding hard genital protectors)

Hockey players' protective equipment shall provide some protection from hockey ball impacts. For each item of equipment tested, as described in 5.9 and 5.10 with impacts of the energies given in Table 17, the mean of the peak force measurements made shall be less than the values given in Table 17, and no single value shall exceed the value in Table 17 by more than 50 %.

Table 17 — Impact energies for testing zones of protection on hockey players' protective equipment and the maximum permitted transmitted forces

Item of equipment and zone of protection		**Maximum transmitted force** kN	**Impact energies to be used to test different performance levels of equipment** Joule				
			Level 1	Level 2	Level 3	Level 4	Level 5
Shin protectors:	Zone 1, ankle area	3	[A1⟩ 1	1	1	1	1 ⟨A1]
	Zone 2, outer area	5	[A1⟩ 5	5	5	5	5 ⟨A1]
	Zone 3, central area	5	[A1⟩ 5	5	5	5	5 ⟨A1]
Leg protectors:	Zone 1, lateral aspect	5	3	6	9	12	15
	Zone 2, outer shin area	5	8	15	20	25	30
	Zone 3, inner shin area	5	15	30	40	50	60
	Zone 2, outer knee area	6	8	15	20	25	30
	Zone 3, inner knee area	6	15	30	40	50	60
Kickers:	Zone 1, outer area	3	10	10	10	14	20
	Zone 2, toe area	3	10	10	15	21	30
	Zone 2, lateral surface	3	10	10	15	21	30
	Zone 3, medial surface	3	10	15	25	35	50
Abdominal protectors		4	8	11	14	17	20
Thigh protectors		4	8	11	14	17	20
Hip protectors		4	7,5	15	25	30	35
Chest protectors:	Zone 2, outer area	4	-	5	10	15	20
	Zone 3, heart area	4	5	20	30	40	50
Breast protector with a chest protector of the same or a higher performance level		2	5	20	30	40	50
Shoulder protectors:	Zone 1	6	3	6	9	12	15
	Zone 2	6	8	11	14	17	20
Upper arm protectors		5	8	11	14	17	20
Elbow protectors		4	3	6	9	12	15
Forearm protectors:	Zone 1	4	3	6	9	12	15
	Zone 2	4	8	11	14	17	20

Table 17 (*continued*)

Goal-keepers gloves:	Zone 1 left hand	3	5	5	6	8	10
	Zone 1, right hand	3	5	6	8	10	12
	Zone 2, left hand	3	5	7,5	10	12	15
	Zone 2, right hand	3	5	7,5	10	12	15
	Zone 3, left hand	3	7,5	10	12	15	20
	Zone 3, right hand	3	15	20	30	35	35
	Zone 3, digit ends	2	15	20	20	25	25
Soft genital protectors		3	5	10	15	20	25

4.7 Impact performance requirements for hard genital protectors

Hard genital protectors shall be tested as described in 5.9.2 and 5.9.4. The requirements for genital protectors are that they do not shatter or crack during the test, that the rubber is not perforated, and that the internal depth does not fall by more than 5mm below the minimum value of dimension *A* in Table 1 during the test. Impact energies are given in Table 18.

Table 18 — Impact energies for testing zones of protection on genital protectors in Joules

Performance level	1	2
Impact energy (J)	15	25

Appendix E: Questions and answers from OBO

Q&A

1. Is it necessary for the protective gear to comply with this EN norm in order to be used during professional matches?
   Yes, for our products to be available for sale in the EU, they must be tested as per the directive EN 13546:2002+A1:2007

2. If I were to modify your current products (say cut out a part of the Foam in the helmet and replace is with a cooling solution), do I need to have it tested conform the norm and have it CE approved again?
   Yes, if the protective product is modified, and that modification is intended for sale in the EU, it must be retested.

3. If I were to design something for use under the body armour or helmet, it is technically not part of the protection. Do I need to perform certain tests for additional gear?
   It depends on whether that product is intended to provide protection. If it is not, it does not need to be tested under the regulation.

4. Are certain materials such as metals forbidden to be incorporated in the protection? (let's say for example I want to incorporate electronics to add fans or other cooling solutions in the gear).
   Not that I am aware of. If electronics are incorporated, the surrounding materials must be able to provide sufficient protection to comply with the regulation.

5. I see that helmets are not covered in EN 13546:2002+A1:2007. Which norm is used for helmets?
   Some of our helmets have been tested under the previous EU directive 89/686/EEC covering personal protective equipment. The regulation EN 13546:2002+A1:2007 supersedes the directive. All new products must be tested under the regulation.

   https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX%3A31989L0686

Follow up:

I am trying to do some tests right now with an impact tower on the helmet and body protector. However, I am not able to find any harmonised norms under EU regulation 2016/425 that cover the goalie helmet.

I did find an American standard for testing ice hockey goalie helmets for impact 'ASTM F1587'. I am still curious however what kind of test the helmet has to undergo in order to get it CE certified (and what the test setup looks like).

Could you help me find this norm/information?

I've spoken to Enoch. The helmet was tested according to the test houses own internal protocol and they were reluctant to give us any details regarding the protocol as they consider this to be their IP. All we have is an examination certificate showing that our helmets 'conform' with no specifics.

We understand the internal protocol is probably based on an American standard, NOCSAE DOC (ND) 061-14. Maybe you'll find something in that standard that will be of use.

Mike Lewis
OBO Hockey---
t. +64 6 356 6060 ■ f. +64 6 356 3939
e. info@obo.co.nz ■ w. www.obo.co.nz
The postie delivers our mail here:
P.O. Box 1782 ■ Palmerston North 4440 ■ New Zealand
We make stuff and hang out here:
21 Mihaere Drive ■ Palmerston North 4414 ■ New Zealand

Appendix F: Q&A KNHB

29-05-2019:

Beste Nathan,

Ik ben op dit moment bezig met een project met als doel: Het koelen van het lichaam van de hockey keeper. Daarbij ga ik iets ontwerpen voor onder of in de huidige body protector en/of helm.
In de spelregels op de KNHB en FIH website staat alleen informatie over de regelgeving voor handprotectors en beenbeschermers.
In de regels van de FIH staat ook dat voorafgaand aan de wedstrijd, de keepersuitrusting wordt gecontroleerd.
Mijn vraag is: Weet jij aan wat voor regelgeving de body protector en de helm moeten voldoen (welke ISO standaarden en CE markeringen)? En dus ook waar de keepersuitrusting op wordt gecontroleerd voorafgaand aan de wedstrijd. De meeste informatie die ik hierover kan vinden gaat voornamelijk over ijshockey bescherming...
Ik kwam bij jou uit via de KNHB website en jouw functieomschrijving leek mij het meest geschikt om deze vraag te kunnen beantwoorden.

Alvast bedankt voor een antwoord of een eventuele doorverwijzing.

Met vriendelijke groeten,

Joost Schootstra

Beste Joost,

Ik heb even navraag voor je gedaan. Er wordt bij een toernooi het volgende gecontroleerd:
Legguards en klompen: afmeting
Handschoenen: afmeting
Helm: veiligheid voor andere spelers (geen uitstekende voorwerpen/scherpe punten etc.)
Body protector: Er mag veel mbt de body protector, omdat deze onder het shirt gedragen wordt.

Alle vereisten mbt de normen staan vermeld in de spelregels.
Ik hoop je zo voldoende geïnformeerd te hebben.

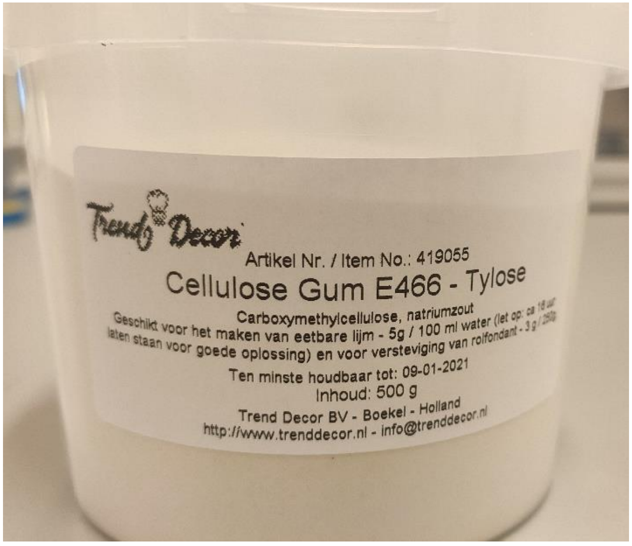
Met vriendelijke groet,

Nathan Kipp
Senior medewerker Expertisecentrum Technisch Kader

Appendix G: Carboxymethylcellulose + coloring agent

This thickening agent is non-toxic and is widely used in products such as ice cream, toothpaste, cakes, but also in hot/cold packs. In edible products in Europe carboxymethylcellulose can be identified as E466. This material is known under the following brand names:

- Cellulose gum
- Cellofas
- Tylose
- Courlose



The coloring agent used to give the cooling packs a light blue color is a food coloring from Dr. Oetker. To ensure non-toxicity, this edible food coloring was chosen