

Insulation Explained, part 2: How Clothing Works

by **Matt Fuller, Dr Matthew Morrissey, and Dr Mark Taylor** 🗓️ 20/Dec/2012

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In [part 1](#) of this comprehensive two-stage article outdoor-obsessed boffins Matt Fuller, Dr. Matthew Morrissey and Dr Mark Taylor discussed some of the science surrounding insulation and the physiology of staying warm. Here in part 2 they present a brief history of insulated clothing and equipment, weigh the pros and cons of down vs synthetic, describe testing methods used for assessing a garment's warmth and offer some interesting ideas about how clothing might be made warmer in future.

Insulating layers are important in many climbing and hillwalking situations, separating ourselves from the often harsh environment. Through over a hundred years of mountaineering, the same principles of keeping warm have been employed: windproofness, staying dry, and trapping still air. Although insulated clothing has changed significantly since mountaineering's inception, there is still considerable room for development. Some of these possibilities are discussed below.

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The more skin that's covered the warmer you'll be.

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'Good quality down is thought to be warmer for its weight than any fibrous synthetic insulation - more compressible, possessive of better compression recovery and a longer lifespan'

A brief history of insulated clothing

Many cold weather garments have their origins rooted in Arctic exploration. As early as the 1820s explorers were working hard to develop or obtain garments that performed better than their existing clothes. The Victorian Explorer John Rae took to wearing Inuit clothing, including moose skins. The problem with furs is that they were too warm to wear when working hard, reputedly stank, and eventually could rot. While shell fabrics such as gabardine, Burberry and Macintosh were being developed, people began to experiment with layers of wool and cotton to stay warm. Suitable equipment for mountaineers created more problems than for polar explorers because their activity levels were so inconsistent. The same is true today.

The use of down has become synonymous with the ascent of Everest and other high mountains, but its first use in high altitude garments, in 1922, was not met with enthusiasm, rather with ridicule. George Finch's down jacket was very warm but not durable enough, and after the expedition down was not used in clothing for another ten years. By the time of Hillary and Tenzing's successful Everest summit bid, down was de rigueur for use at extreme altitudes. Relatively little has changed in down garments over the last 50 years, since the development of the down suit in the 1960s.



Down clothing - keeping hillgoers happy for the last half-Century or so
 UKC Articles, 19 Dec 2012
 © Dan Bailey

Helly Hansen pioneered the use of pile in the 1960s and '70s and its moisture-management properties made it a popular choice. Due to its low density inner and high density backing it could easily transport water away from the wearer by capillary wicking, therefore feeling dry. However, pile pilled quickly, and when fleece was developed and embraced by [Patagonia](#) sales of pile soon diminished. Synthetic fillings originated in the 1960s and continue to improve as manufacturing techniques develop. Polarloft, Polarguard, Thinsulate and Primaloft are all common synthetic fills.

A brief history of sleeping bags

Ajungilak is probably the world's oldest commercial sleeping bag manufacturer, having been founded in 1890. Their early sleeping bags were likely to have been filled with kapok seeds. Other very old sleeping bags were furred, and some eider down bags were developed. A major problem in this period, however, was that few available fabrics were down-proof, meaning that down could escape the outer shell of the sleeping bags. Eider down has an incredible warmth-to-weight ratio, surpassing goose down and only when mountaineers realised that a kilo of eider down could make an extremely warm sleeping bag did the use of eider down become more widespread. By the 1930s sleeping bags were widely available, and Blacks sold eider down bags for £2.37 each while some Alpinists, notably Pierre Allain, developed half-length bags that could be used alongside a down jacket. These bags were successfully used on the first ascent of Annapurna.

Down insulation

Down is the name given to the under-feathers of waterfowl. Geese, ducks, swans and many other birds possess down. In most cases down is harvested as a by-product of the meat industry, which is one reason why goose and duck down dominate the produce of other birds. Recently, animal rights groups created furore surrounding the live plucking of birds, and some major brands were implicated. This led to the European Outdoor Group founding a Down Task Force that is currently investigating ethical issues in the down supply chain. It is a very complex issue: for most manufacturers, down is collected from many different farms, and to check the practices in every farm is almost impossible. Also, down is only a small fraction of a bird's overall value – down holds little economic sway. However, most if not all major outdoor brands intend to source down where no live plucking occurs and from farms without foie gras production. [Mountain Equipment's](#) Down Codex is an impressive move towards traceability that industry is trying to follow. Of course, even disregarding live plucking, geese and ducks are killed for meat before their down is harvested.

Down is an amazing material: it has been estimated that there are 70,000 filaments in a typical gram of down, making it occupy a huge volume. There is less than a gram of down in the picture below:

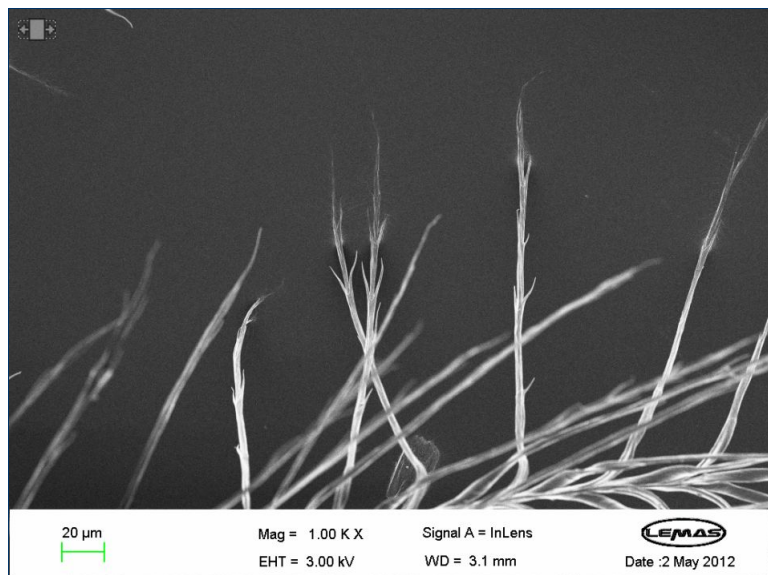


This much down weighs less than one gram!

© Matt Fuller, Nov 2012

Down's insulating performance is incredible: good quality down is thought to be warmer for its weight than any fibrous synthetic insulation, more compressible, possessive of better compression recovery and a longer life-span. Its only major flaw is that its performance is marred when it is saturated with moisture. Goose down is usually superior to duck down (with the exception of eider duck down, which is extremely difficult to obtain).

Detailed research into down's structure has shown that its geometry is close to perfect for trapping air. Its compression resistance stems from its microscopic nodes (see the electron microscope image below) that cover its finest filaments (barbules). Under compression, these nodes lock together to resist the stress. Under strong compression the barbules bend and the down will lock together in this strained state. In order to recover the loft, the down must be shaken to unlock these barbules.



Down as seen through an electron microscope

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The major factor determining down's quality is its fill power. A higher fill power means a specific weight of down occupies more volume when compressed to a predetermined pressure. Fill power testing has many variations, but each method shares the same principles: that a specified mass of down is put in a cylinder, aerated, and then compressed with a certain mass. The height of the sample is then measured and the down's volume calculated. An EU fill power of 750+ means that a 30 g sample of down will occupy at least 750 cubic inches when exposed to a certain pressure. Most manufacturers quote either EU or US down filling powers, which are unfortunately not equivalent. It is difficult to give direct comparisons between the two figures, but EU-rated down is superior to US-rated down of the same fill power. The difference is greatest for the highest quality downs. Be aware of EU-sourced down tested to US standards.

Down of 900+ fill power has been commercially-available only recently, and one supplier even quotes fill powers in excess of 1000+. Twenty years ago these figures were practically unobtainable from goose down. The change is partly because of improved down sorting techniques, but mostly because of the way in which down is now conditioned before testing: it is now steamed before testing as this leads to greater efficiency, less error, and improved performance figures. The hydration levels in the down clearly have huge influence on its performance, and this is one reason why wetting down does not always hinder

its performance – it can increase it, providing excessive wetting and/or compression do not damage the down. Down's resistance to water is far better than most people think: when loose down is put in water it does not sink or immediately collapse; instead it maintains its structure for some time and to submerge it requires considerable force to be applied. Despite this, down should not be wetted for long periods, especially if it is to be compressed, as this can eventually lead to damage that is difficult to reverse.

Looking after down

Down equipment will outlast most synthetic gear if it is cared for properly:

- Avoid getting down wet. When it inevitably gets wet try to manually break up any lumps that form and dry the down as soon as you can.
- Don't pull protruding feathers from your down gear: any holes in the outer fabric will get bigger and make it more likely for down to escape in future.
- Store your down gear uncompressed. The International Down and Feather Laboratory (IDFL) have shown that compression of sleeping bags over a long period detrimentally affects their performance.
- Down is not impossible to wash, just be careful. If you are at all unsure then get a professional cleaner, such as W.E.Franklins in Sheffield, to clean your product for you.
- When your down gear seems to have lost significant loft, tumble dry it (if the garment label allows). Adding a soft object such as a tennis ball or rock climbing shoe can aid loft recovery by 'unlocking' intertwined barbs.
- When you use any down product that has been compressed, give it a thorough shake to unlock the microscopic barbs that stop it lofting.



Changeable weather is the hardest to dress for and so potentially the most dangerous.

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'Despite their inferior compressibility and warmth-to-weight ratio, synthetic garments are arguably better suited than down to use in the UK'

Synthetic insulation

Synthetic insulation is a broad church, covering fleeces and knitted fabrics, as well as nonwoven fabrics such as Primaloft or Thinsulate. Here, we will mainly discuss the synthetic insulations that are typically used in a sleeping bag or belay jacket.

The commonly cited advantage of synthetic insulation is that it does not absorb water. However, the truth is more complex and deserves a more detailed inspection. The first question is how the fabric or clothing becomes wet. If synthetic and down insulations are submerged then obviously in both cases the spaces between the fibres which are usually filled with air become filled with water. However, if the wetting of the insulation is from rain or other precipitation then the behaviour really depends on the waterproofness or water repellence of the outer layer. Another case is if the insulation absorbs evaporated sweat or moisture vapour or that this sweat condenses in the insulation. In any case, the primary difference in the behaviour of down versus synthetic insulation is that when wet, the structure of down (its loft, responsible for trapping air and therefore providing insulation) collapses and clumps together. Synthetic insulation is generally constructed from fibres that are effectively bonded together at the points where they cross. Therefore, even when the insulation is wet it retains its loft, thickness and resultant insulation.

There are also differences in the durability of down and synthetic insulation. It has already been stated that down is very durable, and this is certainly true of the individual plumes: their resilience (recovery from repeated compression) is better than that of synthetic insulation but when down and synthetic insulation are incorporated into garments there are obviously some large differences in their durability behaviour, particularly that if the outer fabric of a down garment is damaged, the down is liable to escape its container; obviously the same cannot be said of synthetic insulation.

The insulation found in belay jackets and other synthetic waddings is usually nonwoven (a textile made up of fibres bonded together by methods other than knitting or weaving). Primaloft is one such example and is patented as 'Artificial Down'. It has numerous incarnations, but Primaloft One is currently Albany International's highest

performance product and Primaloft Sport is close behind. Primaloft One is widely-regarded as the highest performing synthetic fibrous insulation when compared on a weight-to-weight basis, though Thinsulate supposedly offers higher performance for a specific thickness.

Despite the inferior compressibility and warmth-to-weight ratio of synthetic insulation versus down, synthetic garments are arguably better suited to use in the UK as they can be more durable in use and perform well when wet. However, when backpacking or travelling light, the weight benefits of using down products may well be justified.

Down provides superior insulation per mass, but synthetic insulation provides better insulation per thickness. The practical implications of this are negligible in terms of thickness: a down jacket and a Primaloft jacket of the same warmth will be roughly the same thickness, though the synthetic jacket would be significantly heavier. Each user needs to make up their own mind about whether weight, durability or performance in wet conditions is most important to them, based on where and how they plan to use their equipment.

Construction techniques

Synthetic insulation is quite easy to make into garments: it can be glued or sewn in place and, generally speaking, it stays there. Down, however, is a loose material that must be contained to stop it shifting around and leaving cold spots. Construction methods include stitch-through, box-wall, and trapezoidal. Only very warm garments are anything but stitched-through; sleeping bags are routinely made with more complex methods, such as those described in the table below:

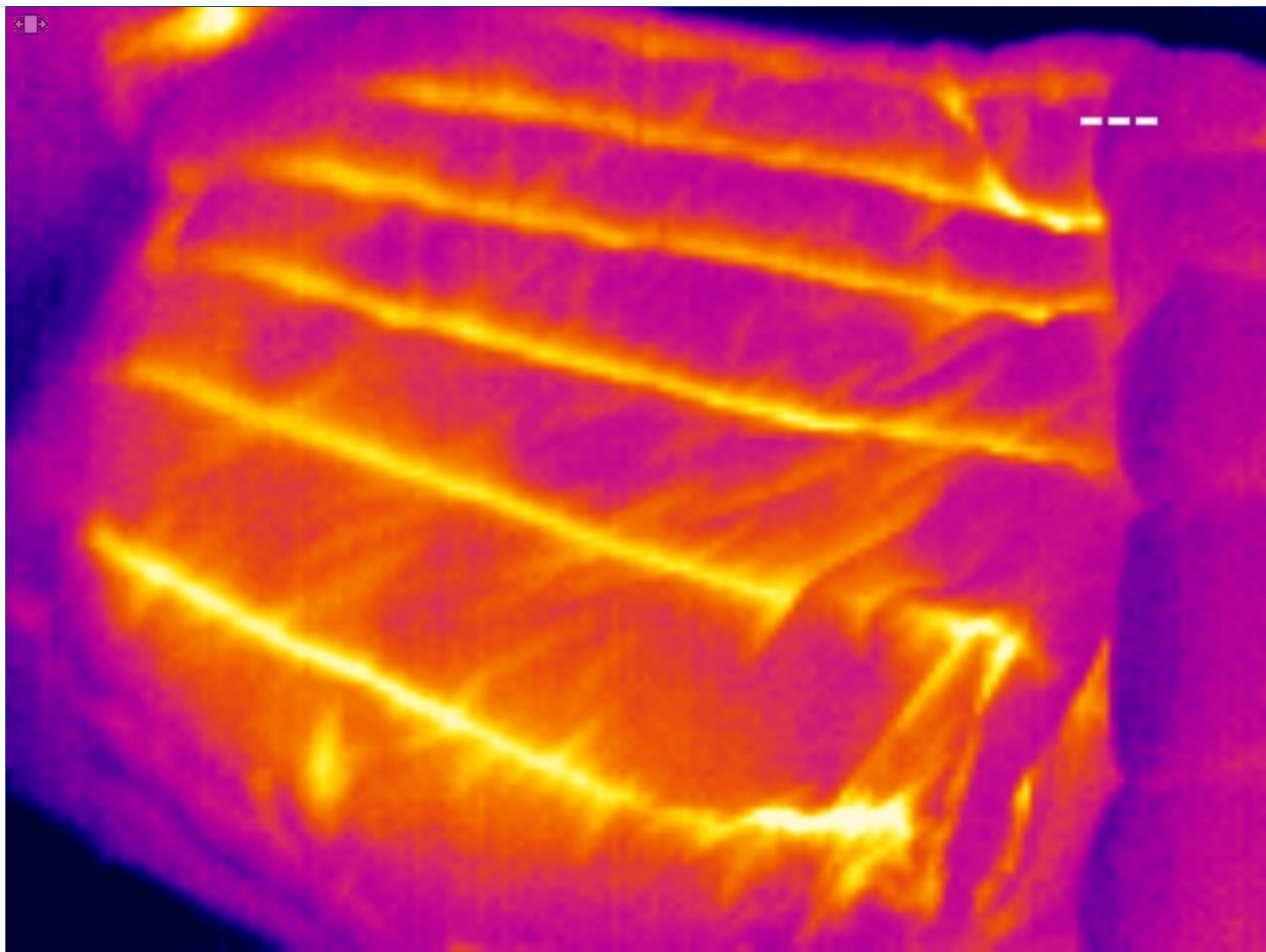


Prime conditions for a synthetic belay jacket
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Method	Cross-sectional baffle shape	Advantages	Disadvantages
Stitch-through		Cheap, lightweight	Leaves cold spots, limited warmth
Box-wall		Leaves no cold spots, can make very warm garments or sleeping bags	Heavier and more expensive than stitch-through, more liable to collapse than trapezoidal
Trapezoidal		No cold spots, very warm, compression resistant	Heavy and difficult to construct. Expensive

Construction techniques
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The effect of stitch-through construction can be seen in the infrared image, below, of a Mountain Equipment Lightline jacket being tog tested. The outline of the heated circular disc can clearly be seen and the stitch points, where thickness is minimal, are in yellow (hot):



Infra-red image of tog testing
© Matt Fuller, Nov 2012

How insulated equipment is assessed

There are two main methods used to test clothing and sleeping bags:

1) Thermal resistance ('tog') testing. The tog rating, much maligned by comedian Rhod Gilbert, has been in use for approximately 70 years. In principle it is a simple test: the thermal resistance of the test sample is compared to the thermal resistance of a known reference, producing a rating in togs, with 1 tog equal to $0.1 \text{ m}^2 \text{ K} / \text{W}$. More togs equate to more thermal resistance and is consequently warmer. A tog testing machine consists of a large flat insulating disc mounted on heaters. It is very good at giving a precise assessment of a material's insulating properties, but it does not assess the effect of air layers between the body and the clothing, or design features such as zips, collars, or cuffs, which all impact on a garment's warmth. Alternative testing methods involve measuring the power required to maintain a certain temperature difference across a sample, either between two metal plates held at specific temperatures or by maintaining a lower plate at a higher temperature than the climate-controlled ambient temperature.

2) Manikin testing. This testing method is expensive but crucially tests garments and not just fabrics. Thus, manufacturers can see where major areas of heat loss are, and how features such as hoods or hems could be improved. Manikins can also ascertain the impact of fit on a garment's performance, though it is obviously vital that the relationship between the garment and the manikin is similar to that between the garment and the target consumer. EN 342 (Protective clothing — Ensembles and garments for protection against cold) is a clothing standard based on manikin testing; EN 13537 is a sleeping bag standard that uses a manikin.

Sleeping bag testing - EN 13537

EN 13537 is a standard that was released in 2002 and updated in 2012. It aimed to make sleeping bag testing more consistent. Before the standard, five sleeping bags of identical performance could be given vastly different temperature ratings, depending on which country they were tested in. The standard has largely achieved its objective, though arguably still has flaws.

The standard states dimensions for the manikin, clothes that it must wear, and numerous other aspects of its design. It also specifies an 'artificial ground' on which a sleeping mat is placed. The fit of the sleeping bag around the manikin is crucial, and in particular, hoods can be fouled by the presence of the manikin's cables leaving the sleeping bag.

The four main values that EN 13537 testing yields are the comfort temperature, the limit temperature, the extreme temperature, and the maximum temperature, each designed to model different scenarios:

Term	Posture	Subject	Comfort Level	Notes
Comfort Temperature	Relaxed posture	Standard woman	"Just not feeling cold"	
Limit Temperature	Curled-up body posture	Standard man	"Just not feeling cold"	
Extreme Temperature	<i>Unstated</i>	Standard woman	"Risk of health damage by hypothermia"	"...point of danger which can lead to death."
Maximum Temperature	Partially uncovered	Standard man	"Just does not perspire too much"	

EN 13537 testing values
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Strictly speaking, EN 13537 does not apply to "sleeping bags intended for specific purpose" such as those for use in extreme climates. This means that the method in the standard may struggle to accurately measure very warm sleeping bags, and the ratings of bags intended for extreme use should be treated cautiously: the test is not really designed for testing these bags and so errors could be large. The fit of all sleeping bags is crucial and temperature ratings are of little use to you if the sleeping bag is far too roomy or tight. The comfort limit temperature is the most relevant temperature rating for most consumers.

'Humans can learn a lot from polar bears. Fabrics and insulation mean nothing if they are not used wisely, both when a garment is designed and when it is worn'

Future and biomimetic insulations

Down's insulating properties cannot easily be improved. However, its use can be improved, by ensuring it is perfectly arranged in garments. Also, water resistant coatings for down continue to be developed and may increase performance in wet conditions (Berghaus have led the way in this area, and Patagonia may once-again provide a ground-breaking product with their upcoming Encapsil down). Genetic modification of animals is understandably a contentious subject, but could produce incredible down for little economic cost: imagine a cow that produces eider down! Goats have already been bred that make spider silk, so it isn't impossible, merely controversial and difficult.

Synthetic insulation is still not as effective in terms of insulation-per-weight as down but with improved understanding of heat transfer mechanisms and developments in manufacturing techniques, its performance may one day equal or improve upon that of down. For example, improvements could be made by reducing fibre diameter to improve the blocking of heat transfer by radiation, though this might detrimentally affect durability. Further improvements could be made by imitating the barbed and tertiary structure of down which may aid in limiting radiative heat loss and increasing resilience (recovery from compression). Plasma deposited metal layers may be useful in creating durable, flexible reflective layers with low emissivity with negligible effects on breathability.

By incorporating aerogels into fabrics or clothing, improvements may be possible. Aerogels are incredible synthetic solids of extremely low density and are essentially 99 % air. They have been threatening to revolutionise outdoor clothing for many years. They are created by making a gel and then replacing the liquid part with gas. Aerogels in block-form have a lower thermal conductivity than air and weigh next-to-nothing. Their use is still limited because they are difficult to contain and difficult to work with. Furthermore, the lowest thermal conductivity in aerogels is achieved by making solid, brittle blocks which are clearly not appropriate to incorporate into clothing. When aerogels are mixed with or deposited onto fibres or textiles, the performance increase is smaller, but incremental improvements are possible.

Clothing which heats its wearer has been in use for years but is yet to gain real popularity. Problems with charging bulky, vulnerable and expensive batteries have meant that few of these garments are used in the mountains, though they are more widely used elsewhere. Only when battery technology improves will these garments be taken more seriously.

Some fibres, notably wool, release heat when they get wet. Companies have developed technology to produce smart synthetic fibres that release significant heat on wetting, though there is a drawback to these fibres: if you are sweating into a garment then you do not want it to release more heat! Phase-changing fibres such as Outlast that change between solid and liquid according to temperature can both release and absorb heat. However, these effects are limited in extreme environmental conditions.

Copying natural insulation from animals, which has been refined over millennia, seems like a wise idea. Penguins and polar bears have both been studied extensively for this reason. Both penguin down and feathers have some interesting properties which may be applicable to clothing. Firstly, the diameter of penguin down is very close to the theoretical optimum fibre fineness for blocking radiation. Secondly, in one fairly obscure study it is suggested that the penguin's 'shell' layer, the feathers, actually acts to reduce the turbulence of air flowing over the surface therefore increasing thermal insulation at higher wind speeds (the opposite of conventional wisdom). The myth that the hollow fibres that constitute polar bear fur can transmit UV light to the skin, assisting in thermoregulation in the cold, has been discredited, but the fur remains a formidable insulator. However, it is primarily the physiology and behaviour of these animals that makes them so well adapted to surviving cold conditions. Humans can learn a lot from this, as fabrics and insulation mean nothing if they are not used wisely, both when a garment is designed and when it is worn.

Further Reading

The history of gear:

A patent for a very early sleeping bag [here](#)

A gear time-line [here](#)

Everest gear then and now, [here](#)

Paper: G. Havenith, Journal of Fiber Bioengineering and Informatics, 2010, 3, 121–129.

Clothing:

(Papers): 1) J. Fan, Thermal Manikins and Modelling, The Hong Kong Polytechnic University, Hong Kong, 1st edn., 2006.<

2) R. Rossi, in Textiles for cold weather apparel, ed. J. T. Williams, Woodhead Publishing, Cambridge, 1st edn., 2009, pp. 1–18.

3) B. Farnworth and R. J. Osczevski, Heat transport in cold weather clothing, Defence Research Establishment Ottawa, 1985, 1–47.

Sleeping bags:

A summary of whether to buy a synthetic or down sleeping bag, [here](#)

Sleeping bag construction techniques, [here](#)

A thorough document about sleeping bag testing, [here](#)

How to wash a sleeping bag, [here](#)

Down and fill power:

In-depth discussion about fill power [here](#)

The official home of fill power information [here](#)

Mountain Equipment's [Down Codex](#)

(Papers): 1) R. H. C. Bonser and C. Dawson, Journal of Materials Science Letters, 1999, 18, 1769 – 1770.

2) J. Gao, W. Yu, and N. Pan, Textile Research Journal, 2007, 77, 617–626.

3) R. H. C. Bonser and J. W. Farrent, British Poultry Science, 2001, 42, 271–273

Aerogels:

A lot of information on aerogels [here](#)

A video about aerogels [here](#)

About the Authors

All three authors are current or past members of Leeds University's internationally renowned [Performance Clothing Research Group](#). Matt Fuller is an experienced hill walker, keen mountaineer, and terrible rock climber. He is studying for a PhD investigating the insulating materials used in the outdoor industry. Dr. Matthew Morrissey is interested in all kinds of protective clothing and recently finished his PhD; he is most at home falling off waterfalls in a kayak but also harbours suppressed aspirations to climb back up them in winter. Dr. Mark Taylor usually prefers to go under mountains rather than over them. He has been testing outdoor clothing for the Performance Clothing Research Group since 2000.

Thanks to Tom Hartland for his helpful suggestions.

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