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THE SCIENCE OF SKI WAXES

1.0 INTRODUCTION

This winter season, nordic ski racers and coaches of all levels will select a specific wax to use for each race. This significant decision could lead the athlete to their best race of the year or one of their worst. Temperature, humidity, snow type, and the coach's instincts effect the decision, but underlying those factors is a complex array of chemistry and physics. This paper will explain those principles and how they relate to ski waxes and also how ski waxes work to help a skier ski their best.

The sport of nordic skiing consists of two different types of cross-country ski races. The traditional style is "classical", sometimes known as diagonal stride. This is when the skier is in a set of tracks and their skis remain parallel during the entire race. Kick wax is applied to the middle of the ski so that when the skier is going uphill he/she will not slide backwards, and on flat terrain, he/she will have some grip to kick off the snow to push themselves forward. The second type of skiing is called skating, also known as "freestyle". This technique resembles an ice skater, only on skis. The ski tips are angled away from each other with the skis forming a "V". The skier pushes off one foot at a time. In this type of skiing no kick wax is needed because the angle of the skis prevents the skier from sliding backwards on a hill.

With both types of skiing, glide wax is applied to the bottom of the ski to decrease friction and allow more glide with less effort. Kick wax is only used in classical skiing. Both kick and glide waxes are available in different formulas to match the temperatures and conditions.

For success in ski racing, a racer must excel in waxing, physical and mental condition, and technique. A racer's success will depend on these components and if one is lacking, the racer's performance will suffer. Being an avid nordic ski racer and an alpine skier, I am interested in performing the best I can in races. To be a better racer on my skis, I must understand the science behind what happens when the bottoms of my waxed skis touch the snow underneath me. Also, I am fascinated by how different kinds of wax react with snow to reduce the friction between the ski base and the snow. Finally, I believe that by gaining knowledge in physics and chemistry I will be better prepared for future science classes. These are the reasons I chose this topic.

The goal of this paper is to explain to ski racers, recreational skiers, and students in my class the chemistry and physics working underneath a pair of skis. To meet this goal, this paper will cover the history of ski waxes, the properties of friction, ski construction and base composition, the science of glide and kick waxes, and how wax is chosen for different snow conditions.

2.0 BACKGROUND AND HISTORY

Skiing has been around for over two thousand years. The people of Finland, Sweden, and Norway invented it as a mode of transportation. They used skis to hunt and fish in the winter, and soon skis were used in wars. Skiing didn't become a sport until the 1800's when it spread to North America.

Racers began developing secret "wax" formulas to make their skis faster. Their "wax" was referred to as "dope" and contained ingredients such as bear fat, spruce sap, honey, and lamp oil. None of the first waxes contained any paraffins, microcrystalline, or synthetic waxes (ingredients that makes up today's modern ski waxes). (Raguso 1999)

Modern wax and waxing procedures came to be in the early 1900's. SWIX, the worlds largest ski wax company, started in the mid-1940's. They had the breakthrough in the "evolution" of ski waxes. They introduced synthetic waxes, which worked well compared to the previous types. They also made the choosing the right wax simpler by replacing the peculiar materials and recipes used before with a three-color system, as they called it. This system narrowed the many combinations and ratios of previous ingredients to three simple choices. Soon SWIX waxes were found all over the world (SWIX 2002). Other companies emerged, such as Toko, STAR wax, and Dominator. These companies used similar formulas and temperature systems as SWIX. Today waxes are available in hard, liquid, and paste forms and new additives can be found in waxes such as graphite and fluorocarbons. There are also more than three choices to more accurately match the snow and temperature conditions.

3.0 TECHNICAL INFORMATION

Although the decision of what ski wax to use for each race seems simple, there are complex scientific principals behind ski waxes and how they interact with the ski base and the snow. There are different types of snow and there are chemical and physical reasons why one wax will work better than another will. Glide waxes are for reducing friction and kick waxes are for increasing friction. Both types of waxes are available in many chemical formulations to allow the skier to excel in different conditions. To understand how waxes work to improve a skiers performance, an understanding of the forces that effect the skiers movement is necessary.

3.1 Forces Effecting the Movement of a Ski on Snow

Many forces effect a skier's progress and how much effort must be exerted to maintain the desired speed including gravity, wind resistance/aerodynamics, and friction. This report will only address forces effecting the ski base/snow interface zone and how ski waxes effect these forces. The primary force effecting this movement is friction. There are two types of friction: kinetic and static. Kinetic friction slows an object already in motion and static friction prevents a stationary object from moving. A secondary force effecting a ski's movement is water suction developed when the heat of friction melts the snow creating a water layer under the ski.

3.1.1 Kinetic Friction

Kinetic friction is of more concern to the ski racer than static friction because it will determine how much effort must be expended to maintain the desired speed. It is caused by the rough surface of the moving object rubbing with the rough surface of the non-moving object. If force is continuous on the moving object, small pieces of each object will be chipped away and release energy in the form of heat (Bueche 1965). This is why your hands warm up when you rub them together. A number called a coefficient of friction expresses the resistance between two materials. The coefficient of friction of a waxed ski to snow is about 0.05 (Tipler 1976). Additional examples of coefficients of friction are presented in Table 1.

Table 1: Example Kinetic Coefficients of Friction (*u*)

Material	***u***
Ice on ice	0.035
Waxed ski on snow	**0.05**
Brass on ice	0.075
Rubber on wet cement	0.97
Rubber on dry cement	1.02

The coefficient of friction of a waxed ski on snow is an estimate because there are different kinds of waxes, conditions, snow, bases, and ways to wax a base. Depending on those factors the coefficient can range from 0.3 to 0.001. Using the kinetic coefficient of friction you can calculate the frictional force against the objects movement and then how far the object will move before it slows to a stop. Assuming that a correctly waxed ski has a coefficient of friction of 0.05, a skier with a mass of 63.5 kilograms (140 pounds), gliding at 5 meters per second (about 10 miles per hour) he would glide 25.5 meters before stopping without adding additional thrust. This calculation is presented in Table 2. If a skier does not chose the right wax, then the coefficient of friction might increase to 0.15. At this coefficient of friction, the same skier, at the speed would only glide 8.51 meters. This is almost 17 meters of glide less than if the coefficient had been 0.05. Thus, with more friction the skier must apply significantly more effort to maintain speed and cover the racecourse.

Table 2: Calculation of Glide Distance using Kinetic Coefficient of Friction (Arfken 1984)

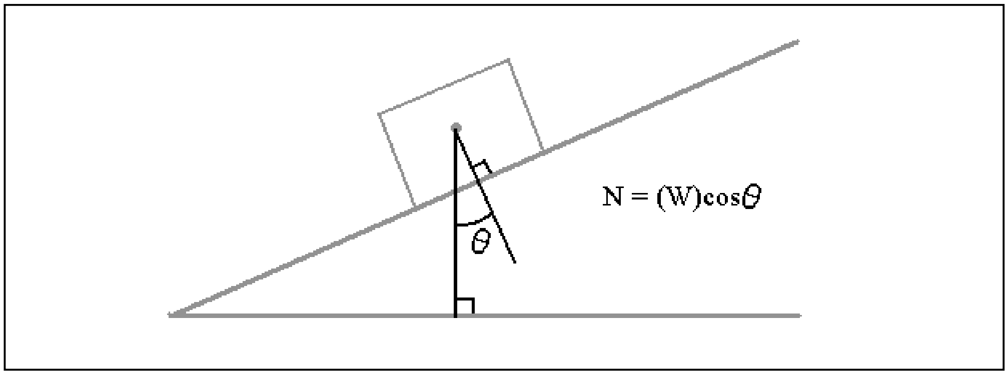
<table>
<tr><th>Applicable Formulas</th><th>Unit Definitions</th></tr>
<tr><td>$f=uN$
$F=ma$
$v^2=v_0^2+2ax$</td><td rowspan="2">f - frictional force
u - kinetic coefficient of friction (0.05)
N - normal force of the object (9.8m)
F - opposite of the frictional force
m - mass of the object moving (63.5 kg)
a - acceleration or deceleration
v - ending velocity of the object (0)
v_0 - starting velocity of the object (5 m/s)
x - distance to reach the ending velocity</td></tr>
<tr><td>Calculation
Finding Frictional Force:
63.5 x 9.8 = 622.3N = normal force
$f=uN$
622 x 0.05 = 31.1N = f
Finding Deceleration Rate
$F=ma$
-31.1N = 63.5 x a
a = -0.49m/sec^2
Finding Distance Before Stopping (x)
$v^2=v_0^2+2ax$
$0^2=5^2+2(-0.49)(x)$
x = 25.5m before stopping</td></tr>
</table>

3.1.2 Static Friction

Static friction is overcome when a skier applies a force greater than the force of static friction. In a freestyle race, skiers only have to overcome static friction at the beginning of a race because they are usually moving throughout an entire race. In a classic style race, some static friction is desired to overcome gravity (sliding backwards on a hill). In classic skiing, static friction is increased by applying kick wax to the middle of the ski.

Static friction is also measured with a coefficient to find the force needed to move the object (the frictional force). The frictional force is found with the formula $f \leq u_s N$, where u_s is the static coefficient of friction (Tipler 1976). If the object is on a hill, the normal force that is usually the weight of the object becomes the weight multiplied by the cosine of the slope angle, as seen in Figure 1.

Figure 1: Calculating Normal Force with a Slope



3.1.3 Water Suction

The third force effecting the ski/snow interface zone is water suction. In temperatures of about 26 degrees Fahrenheit and lower, the heat of kinetic friction meets the snow under the ski, and produces a thin layer of water. This layer is only about a one thousandth of a centimeter thick. If the temperature is above 26 degrees the layer is thicker and can create a suction effect on the ski. To reduce this effect, skis are designed with a groove down the middle of the ski base to drain water (Charonnat 2000).

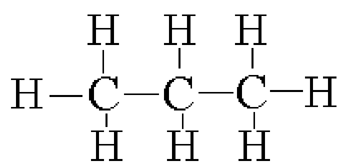
3.2 Glide Wax

The purpose of glide wax is to increase a skier's glide by decreasing the kinetic friction produced underneath the ski. Choosing the wrong wax or not waxing their skis at all will increase friction, decreasing glide, as shown in Section 3.1.1. This section will go over the construction of a ski base, how glide wax is applied to the base, what different types of glide waxes are made of, and how glide waxes interact with different snow conditions.

3.2.1 Ski Base Construction

Ski bases are made of a hydrocarbon called polyethylene. All hydrocarbons are chemical compounds containing carbon (C) and hydrogen (H) atoms. Basic hydrocarbons are chains of C atoms each having two H atoms attached with a H atom on each end (U. S. M.).

Figure 2: Sample Hydrocarbon Chemical Makeup



Hydrocarbon (propane)

Polyethylene is a compound containing thousands of CH_2's. The longer the chain of CH_2's, the higher the melting point (Brescia 1974)(Murphy 1969)(Hart 1972). Because polyethylene has very long chains, its melting point is very high. Although the bottom of a ski looks smooth to the naked eye, it actually has a fine texture made up of hair-like strands. To create this structure, fine particles of polyethylene are polymerized into a crystalline material by a process called "sintering", which uses heat and pressure to change the original substance.

This structure creates are gaps and spaces where wax can be absorbed like water into a sponge. When wax is applied to a ski base, it is melted and then ironed into a thin layer. When cool, the excess is scraped away and then even more excess is removed from the base with a stiff brush. After this process, a very thin layer of wax coats the polyethylene and fills the deepest gaps. This application process maintains the rough structure of the ski base so that only some of the ski touches the snow. If more wax was left on, then more of the ski would touch the snow and that would create more friction.

3.2.2 Types of Waxes

Materials used in glide waxes are chosen because they have low coefficients of friction, are easy to apply, and are durable. Basic ski wax is made from solid hydrocarbons. Some wax companies also sell wax that has fluorine in it. With these waxes, some, most, or all the hydrogen atoms in the hydrocarbons have been replaced with fluorine atoms. This new compound is called a fluorocarbon, and offers very low coefficients of friction and high water-repellency.

3.2.2.1 Hydrocarbon Waxes. Like ski bases, regular glide waxes are made from hydrocarbon compounds. Hydrocarbon is the group that contains fuels, waxes, and plastics. The difference between them is only that their chain of CH_2's is a different length. Propane is a string of three C atoms, and polyethylene is a string of thousands of C atoms (Brescia 1974)(Murphy 1969)(Hart 1972). Both are hydrocarbons. Ski waxes are primarily made up of three types of hydrocarbons: paraffin, microcrystalline, and synthetic waxes. These three are combined together to make a ski wax.

Paraffins are soft, candle-like waxes, containing 20 to 35 C atoms (Britannica 2001). They have low coefficients of friction allowing the ski to glide easily over the snow crystals. Microcrystalline waxes are a branched type of hydrocarbon with 25 to 50 C atoms. These waxes have a higher coefficient of friction but are more durable than paraffins, so they do not wear off the ski. Synthetic waxes are slightly branched hydrocarbons with 50 to 60 carbon atoms. They are used to make the wax stronger so that it doesn't wear away with cold snow.

3.2.2.2 Fluorocarbon Waxes. Fluorocarbons are hydrocarbons where some or all of the H atoms have been replaced with fluorine atoms. Fluorine is the most electronegative of all elements. It is very hydrophobic, meaning that it does not chemically react with water molecules. Fluorocarbons give increased glide in moist and wet snow conditions by reducing capillary attraction between the water and the base. They are also helpful in dirty snow conditions, which are common for spring skiing. Dirt particles, negatively charged, are also repelled from fluorocarbon waxes, keeping the bases cleaner. Dirt on the bases significantly increases friction and slows the skis.

There are three basic types of fluorocarbons used in ski waxes. The first type is polytetrafluoroethylene (PTFE), know in the marketplace as Teflon®. It is made by polymerizing (repeated linking) molecules with two carbon atoms surrounded by fluorine atoms. Teflon is very water-resistant and has one of the lowest coefficients of friction ever known (Charonnat 2001).

The second type of fluorocarbons used in ski wax are long-chain carbon molecules called perfluorocarbons. The "per" of the term "perfluorocarbons" means that all the hydrogen atoms have been replaced with fluorine. The exact properties of the fluorocarbons can be altered by varying the carbon molecule structure (carbon to carbon atom bonds) and the purity or blend of the final compound. This allows the chemist to develop additives for different snow conditions and temperatures. Unlike other waxes, which are sold in solid blocks, perfluorocarbons are commonly sold in powder form. Ski waxes made with 100 percent perfluorocarbon are expensive, but offer exceptional glide in moist to wet snows (Charonnat 2001).

The third type of fluorocarbons are hybrids with half of the molecule being a hydrocarbon and the other half being a fluorocarbon. Hydrocarbons, which are electrically neutral, do not like to mix with fluorocarbons, which exhibit a negative charge on their surface. Mixing pure molecules of these compounds would be similar to trying to mix oil and water, the molecules would separate. By making a hybrid molecule, the hydrocarbon end will mix with the hydrocarbon paraffins and synthetic (polyethelene or plastic wax) components.

Waxes can also be made with both hydrocarbons and fluorocarbons. These waxes are found with high, medium, or low fluorocarbon contents. At least 3% fluorocarbon is needed to obtain the water repelling benefits of the fluorocarbons. Low fluorocarbon bar waxes contain 1-6% fluorocarbons, mid range about 6-10%, and high fluorocarbon bar waxes contain 10-16%. The 80-90% non-fluoro components still add significantly to the glide speed of the wax and that fluorocarbons would only make a difference in moist and wet snow conditions (Charonnat 2001).

3.2.3 Waxes for Different Temperatures and Conditions

To make a wax softer or harder, the amounts of paraffin, microcrystalline, and synthetic waxes are changed and the lengths of their carbon chains are lengthened or shortened. In harder waxes, there would be less paraffins and more microcrystalline and synthetic waxes. Also in hard waxes, the strings of C atoms are lengthened. This increases the wax melting point from what it was and makes the wax harder. Just the opposite occurs with soft waxes. The carbon chains are made shorter and more paraffins would be present than microcrystalline and synthetic waxes.

For nordic skiers, the combination of three conditions will determine what type of wax to use:

- Age: old or new
- Moisture Content: wet or dry
- Temperature: warm or cold

Crystals formed when water freezes into snow have six points. When snow is new, the points are long and sharp. If the temperature remains cold the snow crystals will maintain this shape. Because cold air holds less humidity, new, cold snow is usually dry. For new, cold, dry conditions, harder waxes are used so that the sharp snow crystals cannot stick into the waxed ski base. If the snow crystals stick into the wax the coefficient of friction is increased, reducing glide (Onion 2002).

When the conditions are warm and wet, snow the snow crystals melt and the six sharp points become rounded. This condition is described as old or transformed snow. In these conditions racers use softer waxes. When applied, soft waxes result in a more uneven surface which helps to break the suction of the water layer formed underneath the ski (see Section 3.1.3).

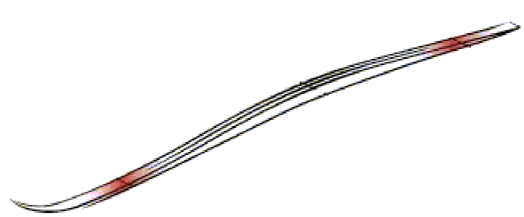
3.3 Kick Waxes

Kick waxes are used for classic type ski races and technique. They are the opposite of glide waxes in that glide waxes work to lower friction while kick waxes increase friction. On uphill climbs this friction prevents skiers from slipping backwards; on flat terrain static friction provides stability on which the skier can "push off."

3.3.1 Ski Base Construction

Cross-country skis are designed with an arched base (Figure 2). This curve is called camber. The front and back ("tips and tails") of the ski always contact the snow. However, in the middle, the ski curves up off of the snow. Classic skis are fit to the athlete's weight. When the weight is evenly distributed on both skis, the camber keeps the middle of the ski off the snow. When their weight is transferred to one ski, the camber is flattened and the whole ski is touching the snow. In classic skiing, kick wax is applied to the middle of the ski so that the wax is not touching the snow, increasing friction, when the skier is gliding. When the weight is on one ski and the entire ski contacts the snow, the increased friction allows the skier to climb hills and gives the racer a fixed position from which to apply forward thrust.

Figure 2: The Camber of a Ski



Source: atomic.at

3.3.2 Wax Types

Kick waxes are made from the same hydrocarbons as glide waxes: paraffin, microcrystalline, and synthetic. Because the purpose of kick wax is to increase friction, the carbon chains are short to make the waxes melting point low and the wax soft to stick. Recently fluorocarbon kick waxes have been introduced. These waxes are better than hydrocarbons because they repel water in warm conditions resulting in less wear (Onion 2002).

3.3.3 Waxes for Different Temperatures and Conditions

There are many types of snow. One wax cannot work, in this case grip, all of the types. The softness of kick wax is adjusted to work better on these different types of snow. To adjust the softness, or melting point, C atoms are added or subtracted from the hydrocarbon chains. Adding C atoms increases the melting point, making a harder wax, and subtracting C atoms lowers the melting point, softening the wax.

Harder kick wax is used on cold, sharp snow crystals because it can grip to them but the snow will fall off the ski when it is lifted. It does not work on old, warm snow because there is too much water in the snow and it would not stick. Soft waxes are very sticky so that it can grip the round transformed snow crystals in warm conditions. It would not work on sharp snow crystals because the flakes would stick up in to the ski and not fall off. After doing this, a skier would find about an inch layer of snow stuck to the bottom of their ski. (Jacoby 2002).

4.0 CONCLUSION

Overall, ski waxes are important to any skier whether they are a racer or a recreational skier. The base which ski waxes are melted into, is an imperfect sheet of a plastic called polyethylene. The base is not a perfect sheet so less of it touches the snow so less friction is produced. Glide waxes help the skier glide further with less effort and also protect the ski base. They are made of hydrocarbons and sometimes fluorocarbons. The length of the chain of carbon atoms effects the softness or hardness. This can make the skier faster in all different temperatures and types of snow. Kick waxes help classic style skiers grip the snow to push themselves and keep them from sliding backwards when going uphill. Softer, stickier waxes are used to grip transformed wet snow, and harder dry snow can be gripped with harder less sticky waxes. Even though glide waxes try to reduce friction, and kick waxes try to increase friction, both are important in helping a skier ski better.

In the future of skiing, I believe ski glide waxes will come very close to a zero coefficient of friction. They will never reach a zero coefficient of friction as long as skis are still touching snow, because there will still be something to rub against to create friction. Kick waxes will probably become more efficient at gripping snow to the point that there is no way a racer's kick wax could wear out by the end of a race (a common problem for today's racers). Ski waxes have come a long way from being made out of bear fat. They have made our skis faster, leading racers to wins. Waxing is one of the most important things in ski racing. It is made up of chemistry and physical principles, and to some, it will always just be the question: Do I use the blue wax or the yellow wax

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5.0 REFLECTIVE ANALYSIS

I began this paper believing it would be fairly simple and I would not learn that much because I already knew a lot about ski waxes. I was wrong. The inquiry project assigned to me by Mr. Glick was much more complicated than I had expected. Even though I spent a lot of time scouring through the internet I eventually found the information I was looking for. My reason for choosing "The Science of Ski Waxes" was to learn more about how ski waxes work. I had hoped that by learning this information, I would become a smarter and better skier. I now am, I believe. I have gained a better understanding for my skis, the wax I melt into their bases before every race, and the snow, which changes with warmer and colder temperatures. By myself gaining a more in-depth understanding, I believe that others would also learn more by reading my paper. These were my goals when I chose this subject, and I believe I have reached them. Although there were very hard parts about this project, I had fun learning more about the sport I love.

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