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Cryogenics in the Kitchen

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Probably, most foodies’ introduction to the use of cryogens (substances that change state at low temperatures, typically well below ca. \(-60 \, ^{\circ}\mathrm{C}\)) was to see an ice cream or sorbet being frozen at the tableside using liquid nitrogen. As the cold liquid is added to the ice cream mix, the bowl overflows with white clouds of fog, creating the appearance of an alchemist’s cauldron and setting up expectations of a wonderful dish to come. But although many restaurants do indeed use liquid nitrogen in this way, there are far more uses that occur behind the scenes that customers never see.

A Short History of How Cryogens Came into Restaurants

The use of liquefied gases in food preparation has a long and interesting history, much of which involves the regular ‘rediscovery’ of particular uses over time. The first recorded description of the use of a cryogen came very soon after gases were first liquefied.

However, it was only recently that Myhrvold and Young (2001) managed to unearth the full history of making ice cream using nitrogen. As recently as 1994, in their _Scientific American_ article, Kurti and This noted that, despite many people who said they had heard of someone making ice cream in this way, the first time they could be certain it had happened was when I demonstrated the process at one of the Erice Workshops on Molecular and Physical Gastronomy (Kurti and This-Benckhard, 1994). However, the story is much more interesting and is full of strange twists and turns as the wheel kept on being invented and re-invented over a century.

In her magazine _The Table_, A.B. Marshall wrote: “Persons scientifically inclined may perhaps like to amuse and instruct their friends as well as feed them when they invite them to the house. By the aid of liquid oxygen [sic], for example each guest at a dinner party may make his or her own ice cream at the table by simply stirring with a spoon the ingredients of ice cream to which a few drops of liquid air has been added by the servant” (Marshall, 1901).

Air was first liquefied in 1877 (Dumas, 1877) by Louis Paul Cailletet in France and Raoul Pictet in Geneva (but in very small quantities), but it was only in 1884 that James Dewar managed to prepare enough liquid air that he could show it to the public. By 1894, Dewar was ready to make a number of public demonstrations of cryogenic gases including whole air, nitrogen and oxygen. On 19 January 1894, he gave a particularly well-attended lecture, which is when it has been surmised, but not proven, that Marshall may have seen liquid air added to water to make it freeze quickly and got the idea for the article she later published in her magazine (Marshall et al., 1988). One of the reasons why the achievements of Marshall are not as well known as they probably should be is that after her death in 1905, her estate was sold to Isabella Beeton’s publisher Ward Lock, who had little interest in keeping her work in print.

In 1957, William Harrison in the USA patented a process to make nitrogen ice cream using pretty much the same method described by Marshall, but no records have been found as yet showing anyone actually using this patent, and it seems to have been forgotten for many years. Then, in 1974, William Chamberlain, working in the USA, took some liquid nitrogen home and played with it to try to make ice cream; after a number of failures, he settled on a technique, adding nitrogen to an ice cream mix that was being stirred in a food mixer on a stand. This proved successful (and is the technique used in most nitrogen ice cream parlours today), but although he gave a number of parties where he made ice cream for his friends and colleagues, again, it appears to have been forgotten.

In 1976, after seeing a demonstration of using nitrogen to freeze bovine sperm, André Daguin, the chef of the restaurant Jardin des Saveurs, started using nitrogen to make ice cream at the tables of his guests; this spectacular dish gained a lot of publicity, which continued into the early 1980s, but no other chefs took it up, and once again it was largely forgotten (see the chapter by Daguin in this book).

During the early 1980s, as a result of a drive to encourage school pupils to take up studying science, scientists started giving ‘inspirational’ talks in schools. I had used a demonstration of making ice cream with liquid nitrogen to teach undergraduates about entropy and adapted this in 1983 to give a series of school talks. These soon expanded rapidly as more young physicists, and later chemists and biologists, were trained to give similar talks. Brian Coppola and colleagues published details of how to make nitrogen ice cream in 1994 (Coppola et al., 1994). Today, pretty much any science department in any university can provide an...
As the use of nitrogen to make ‘instant’ ice cream became widely known through these school talks, chefs were introduced to liquid nitrogen not just to provide spectacle and make instant ice cream but also, for example, as a means to prepare finely ground herbs and spices. I well recall taking a dewar of nitrogen to the Fat Duck restaurant as I was driving close by on my way back from a school talk one afternoon in 2000 and then spending an afternoon in the garden with Heston Blumenthal and his chefs, simply seeing what could be done. Not long after that, Heston Blumenthal introduced the green tea amuse bouche (Nitro Poached Green Tea and Lime Mousse) with the accompanying spectacle of dragon’s breath coming from the nostrils of the diners, that captivated his customers at the start of their meals. This was quickly adopted by Ferran Adrià, and similar dishes were served at El Bulli. As these two restaurants were at the time frequently voted the best in the world, it is not surprising that other chefs quickly started investigating how to use liquid nitrogen for themselves, and so, within less than a decade, it became almost compulsory for any Michelin restaurant to make some use of liquid nitrogen in the restaurant, usually at the table, to provide a combination of spectacle and deliciousness.

How Do Cryogens Work?
When a substance undergoes a change of state (or first-order phase transition), its internal energy changes, often by a large amount, so it either absorbs or releases this energy in the form of heat, which is often termed the latent heat. When a solid is heated (for example, an ice cube in a cocktail), it starts to melt when the temperature reaches its melting point (0 °C in this case). But, to be able to melt, it has to absorb a large amount of heat (334 kJ/kg), so it can take some time for all the ice to melt as it absorbs this heat from its surroundings. As we know from experience, it takes typically 10 to 20 minutes for the ice in our drinks to melt. As the ice melts, it extracts the heat required for the change of state from a solid to a liquid from the surrounding liquid, and so cools that liquid. In the case of a typical ice cube in a gin and tonic, the temperature is reduced by about 5 °C as the ice cube melts.

Similarly, if we heat a pan of water to its boiling point (100 °C), as it boils, the temperature remains at 100 °C, and the heat applied to the pan goes into the latent heat required to change its state from a liquid (water) to a gas (steam). The absorption of heat as a liquid boils is the basis for the operation of nearly all air conditioners, refrigerators and freezers we use at home and work. In these devices, the coolant is kept in a closed system and is made to boil by reducing the pressure in the place where the temperature needs to be reduced and then compressed back into a liquid outside, where the excess heat released as the gas turns into a liquid can be vented into the atmosphere.

One disadvantage of using conventional freezers in cooking is that the cooling can take a long time, as the heat is extracted from the foodstuff by transfer through the air inside the freezer. It would be much more efficient if the food were placed in a liquid rather than a gaseous environment, as the heat transfer through the denser liquid would be much greater. So, if we have a liquid that boils at a very low temperature, we can use that to cool things down to that temperature; as the liquid boils, it will extract heat from whatever we want to cool, and, provided there is enough of the liquid available, it can cool our object right down to its own boiling point.

Cryogens change state at low temperatures (typically well below ca. −60 °C) and as a result can be used to cool systems down to these temperatures. Provided they are also inert and safe to eat, drink or breathe, then they can be used in direct contact with foods. Two commonly available cryogens that are completely non-toxic are liquid nitrogen and solid carbon dioxide. Liquid nitrogen boils at −196 °C, and carbon dioxide sublimes (turns directly from a solid to a gas) at −78.5 °C. Thus, if solid carbon dioxide (often referred to as dry ice) is dropped into some liquid that you want to freeze, or cool rapidly, it will very quickly sublime, causing the liquid to bubble up as if it were boiling as the carbon dioxide gas emerges; the sublimation process extracts a lot of heat, and, depending on how much carbon dioxide was used and the amount and type of liquid being cooled, it will cool to its own freezing point and then, as further heat is extracted, it will start to turn solid. Dry ice is often dropped into buckets of water in this way, not to cool the water but to generate white clouds of carbon dioxide vapour and small ice crystals to provide the special effects of rolling clouds of fog we see at many events. Indeed, I recall back in the 1960s buying dry ice from a local supplier as the stage manager for my school play, Macbeth, so we could have a bubbling cauldron on stage for the witches’ scenes.

Similarly, solid foods can be dropped into liquid nitrogen, which, as it boils, will rapidly cool them down (again generating the fog-like effects). The limit to how fast the food cools depends largely on the size of the pieces; larger pieces take longer to cool, as the heat has to get from the inside to the outside by thermal conduction, which can take some time. If there is sufficient liquid nitrogen that it does not all boil off, then the food will eventually cool down to its boiling point (−196 °C), which is of course far too cold to eat!

If cryogens are used in the kitchen, great care must be taken to ensure safety. First, the proper equipment is needed to store the cryogens safely and to prevent them from simply evaporating before they can be used. Secondly, as any contact of cryogens with naked skin can lead to severe frostbite (or cryo-burns), personal protective equipment such as gloves, aprons, and face masks or goggles are necessary. You will also need to take care that, if the gas evaporates quickly, there is sufficient oxygen in the room to avoid the risk of suffocation. For example, when liquid nitrogen boils, the resulting gas takes up about 700 times the volume of the liquid, so 1 litre of liquid nitrogen dropped on the floor will rapidly become 700 litres of nitrogen gas, which will displace 700 litres of air from the room. If you work in a small kitchen, a few litres of liquid nitrogen boiling could easily displace enough oxygen that you could die of suffocation. Some details of the necessary equipment and safety procedures and how to perform a proper risk assessment for the use of cryogens in the kitchen will be addressed later in this chapter.

You might reasonably ask whether, with all these difficulties, it is worth the trouble of using cryogens in the kitchen. However,
there are plenty of things that can only be achieved with the use of cryogens. For example, some disadvantages of normal freezing are easily overcome by freezing at low cryogenic temperatures. The very low temperatures that can be quickly achieved greatly affect the formation of ice crystals; very many crystals nucleate in a short time and grow quickly, so the overall crystallite size in ice formed using cryogenic cooling is very much smaller than that of ice formed by freezing in a standard freezer. Thus, instead of large needle- or tree-like crystals that grow relatively slowly during relatively slow cooling and can puncture the cell walls inside many foodstuffs, giving coarse and grainy textures as well as leading to both structural damage and negative flavour changes, cryogenically frozen foodstuffs contain very small (sub-micron) crystals that have smooth and creamy textures and do not normally damage structure or flavour. The food industry uses significant quantities of both dry ice and liquid nitrogen in the preparation of many different foods, not just in frozen produce. As we shall see later, many of these techniques have in recent years found their way into professional (and even a few domestic) kitchens.

### Why Are Cryogens Useful in Food Preparation?

Many foods have soft textures that make them difficult to cut into very precise thin slices, or to grate or grind to make garnishes, etc., as they will tear, rather than cut, and will, if ground, simply turn into a paste rather than a fine powder. However, if they can be frozen completely solid, then they can readily be ground or sliced as required. The problem is then how to freeze them so that they are truly solid throughout and the texture is not damaged. When you freeze food, the liquid water turns to ice, but the water is not pure, as it has dissolved in it a number of molecules that provide taste and flavour to the food, e.g., salt, sugar and amino acids. We all know that salty water has a lower freezing point than fresh water, which is why putting salt on the roads helps prevent ice formation in winter. So it is when we freeze our food; as some of the water turns to ice, it increases the concentration of these solutes in the remaining water, which in turn reduces the freezing point of the water, and thus a very low temperature is required before all the water becomes frozen and the product is fully solid. This temperature is known in the sciences as the eutectic point, i.e., the temperature below which all the phases present will, at equilibrium, be solid. For a solution of common salt, the eutectic temperature is −21.1 °C, for sucrose it is −9.5 °C, and for most amino acids it is around −12 °C. Most oils, such as olive oil, only freeze at temperatures around −40 °C, and any alcohol in the food generally will not freeze until the temperature is below −110 °C. So, to be sure your food is truly a solid so that it will not form a paste when ground, for example, it needs to be at a very low temperature (lower than −30 °C and preferably much colder). Although some professional freezers can reach such low temperatures, it is much simpler (and faster) to use either dry ice or liquid nitrogen to freeze the food you want to grind or slice.

Further, if the texture is to be retained (for example, if you want to make sub-millimetre slices of a cream cake), then it is most important that the ice crystals do not damage the texture when they form. There are two ways in which ice crystals damage the texture of foods: firstly, from the expansion of ice when it freezes, and secondly, by growing large needle-shaped crystals that can puncture cell walls.

We all know that ice floats on water, because, when ice forms at 0 °C, its density is lower than that of water at the same temperature; another way of looking at the phenomenon is to note that water expands when it freezes (anyone who has lived through a really cold winter will probably have had experiences of water mains that burst because the water inside froze and the expansion fractured the pipe). So, if the water inside a cell freezes at around 0 °C, it will expand and is likely to burst the cell wall, which can massively affect the texture of some frozen foods. However, if the ice forms at a much lower temperature (lower than −20 °C) then it is much denser and the effect is much smaller, resulting in little or no damage to cells.

The size and shape of ice crystals that grow when food is frozen depend not only on the molecules that are present in the water but also on the temperature at which the crystals actually grow. While ice can form at any temperature below 0 °C (in pure water), in practice creating a crystal is very difficult, so crystals do not usually start to grow at all until the temperature is well below zero, typically from about −4 °C and lower. The reason is that, as a crystal forms, there is an interface between the growing crystal and the surrounding liquid. While converting a liquid to a solid (at a temperature below the freezing point) liberates a lot of energy in the form of heat (the latent heat noted earlier), creating the interface actually requires the use of significant amounts of energy, so there is an energy balance between the interfacial energy (which is proportional to the surface area) and the energy released due to crystallization, which is proportional to the volume of the crystal. Thus, small crystals, which have a relatively high surface energy, are unstable, while large crystals, where the surface to volume ratio is low, are stable. The upshot is that, if a liquid is cooled quickly, it is possible to start the crystallization process at temperatures well below the melting temperature, where small crystals are quite stable and can grow quickly, leading to an overall small crystal size. If foods are frozen at a low temperature in this way, the ice crystals can be small enough that they cause little or no damage to the surrounding tissues and hence leave the texture of the frozen food, once defrosted, just as it was before it was frozen.

### Industrial Use of Cryogens in Food Processing

Before looking in detail at the various uses of cryogens in the professional and domestic kitchen, it is worth quickly reviewing industrial uses, as many techniques that have found their way into modernist kitchens and much of the so-called molecular cuisine lexicon have their origin in industrial food science. However, as we shall see, many of the real advantages that are offered by cryogenic freezing are much better suited to the small professional kitchen than to industrial-scale processing, where long transport and storage times are involved.
Freezing Fresh Foods

When food is frozen by simply placing it in a freezer and waiting for it to cool down, there is a major risk of damage to the food caused by the formation of large ice crystals. These can not only break the cell membranes and distort the surrounding tissues but can also lead to denaturation of some proteins (Parenti et al., 2004; Salinas et al., 2005; Gordillo et al., 2010).

Liquid nitrogen has been used in the industrial-scale freezing of foods since the early 1960s (Davidge, 1981). In particular, it was used in tunnel freezers, where the food to be frozen is passed on a conveyor belt through a tunnel where the temperature is steadily decreased until the food is completely frozen. In the entrance region, food is cooled using cold air (or gaseous nitrogen or carbon dioxide); then, as it passes along, liquid nitrogen is sprayed from nozzles in the top of the tunnel directly onto the food; this reduces the temperature below ca. −30 °C so that the food is ready for packaging, storage and distribution.

In tunnel freezers, the rate of cooling can be quite high. High freezing rates lead to small crystal sizes, due to the high nucleation rate of ice at the lower temperatures achieved during rapid cooling. This can have a number of benefits; the food quality is perceived as being better in terms of texture and appearance as well as flavour (Awonorin, 1997). Furthermore, not only can using cryogenic freezing lead to reduced losses from dehydration, prolonging the overall shelf life (Awonorin, 1997; Ramakrishnan et al., 2004), but it is also more cost effective (Miller and Roberts, 2001). It can be shown through a number of simulations, modelling and experimental studies that the faster the freezing, the smaller the ice crystal sizes and the better the quality of the products. For example, Martino and Zaritzky (1988) demonstrated that frozen meat benefits from the fastest possible freezing using the greatest possible thermal gradients. Although they note that direct immersion in liquid nitrogen gives the best results, they also speculated on how much better it could be if greater thermal gradients were to be achievable (e.g., using pressurized systems). Other authors (e.g., Sanz et al., 1999) have demonstrated the superior quality of a range of produce, including dates, peas, pineapples and even sausages, when frozen at the highest possible rates (Alhamdan et al., 2001; Biglia et al., 2016).

Despite the multiple advantages imparted by the very small crystals (<< 1 micrometre) that form when using fast cryogenic freezing, these all have limited lifetimes, as the overall average crystal size will slowly and steadily increase as the product is stored (Carrington et al., 1994; Carrington et al., 1996). This process, known as Ostwald ripening, is driven by the fact that, the smaller a crystal is, the less stable it is, so larger crystals grow larger at the expense of smaller ones in a continuous process. As a result, some of the advantages of freezing in liquid nitrogen can be short lived and hence not suitable for industrial processes where long storage or transport times are required. This is most notable with nitrogen-frozen ice cream, where the initially extraordinarily smooth and cream texture can change noticeably within an hour after preparation.

Producing Powders and Ground Spices

When spices are ground to make fine powders that can be used to season or flavour dishes, it is important to try to avoid the loss of important odorant compounds during the process. These volatile compounds can be lost if the spices are heated from the action of the grinding machine itself. Also, as the surface area of the ground spices continually increases as they are ground to ever finer sizes, so the rate of loss of volatile compounds will increase. However, of course, to impart the maximum possible flavouring effect in food, it is usually preferred to have spices ground to as fine a size as possible.

If spices are ground at very low temperatures, this will avoid all these issues, and so in specialist and high-quality systems grinding machines are often cooled with cryogens (Balasubramanian et al., 2012). Cryogenic grinding of spices leads not only to improved flavour retention but also to better perceived physical qualities such as colour and texture in products that use ground ingredients, such as sausages.

The production of powders by spray freeze drying, where a liquid is sprayed into nitrogen, is a relatively expensive technique used in industry mainly for pharmaceuticals. However, it is becoming more widely used in the food industry, as it can provide much lower loss of volatiles and better final products. Examples of foodstuffs for which the use of spray freeze drying has proved beneficial include apple juice and egg albumin (Malecki et al., 1970).

Flavour Extraction in Wine and Oil Production

(Cryomaceration)

The fact that the solubility of different flavour compounds in fruits varies quite widely with temperature means that the relative amounts of different compounds present in extracted juices will depend on the temperature at which they are extracted. In winemaking, the solubility also depends on the alcohol content at the time of extraction. To maximize the extraction of some desirable compounds, it has been found that it is best to carry out the initial extraction (or maceration) at a low temperature when fermentation is very slow or absent, thus keeping the alcohol content at that time as low as possible. Generally, many winemakers seem to prefer a cold maceration for 2 to 10 days at a temperature below 15 °C (in some cases as low as ca. 0 °C), depending on the grape variety and desired final wine characteristics.

Some winemakers use a cryomaceration process whereby the grapes are cooled directly with nitrogen or dry ice. This leads to freezing of the interior of the grapes and, if the cooling is not too fast, to fracture of internal structures in the grapes, leading to an internal process of flavour development prior to the grapes being mechanically broken to extract the juice further (Allen, 2007). Wines prepared in this way (especially those for which the grapes were cooled using dry ice) have been shown to have more aroma, intensity and stability of taste properties than those prepared by traditional processes (Parenti et al., 2004; Salinas et al., 2005; Gordillo et al., 2010).
In a similar fashion, the processing of olives to make high-quality olive oils can be markedly improved when the olives are exposed to dry ice before the initial milling process. The expansion of the water in the olives, as it freezes to form ice crystals during the relatively gentle cooling rates applied, breaks up the cells and promotes the diffusion of these flavour compounds that are eventually dissolved in the oil, providing both increased flavour and nutritional value. In particular, the use of dry ice has been shown to significantly increase the yield of tocopherols without increasing the phenolic fraction of the oil. Furthermore, the use of carbon dioxide creates a gaseous layer that prevents oxidation and thus further improves the final quality of the product (Di Giovacchino et al., 2002).

Ice Cream

Liquid nitrogen has found several uses in the manufacture of some luxury ice creams; for example, dipping an ice cream in liquid nitrogen or spraying it with liquid nitrogen gives the outer layers a quick hard freeze so that, when it is put into a bath of warm chocolate, the chocolate will stick well without melting the ice cream at all and then set to give a nice hard outer coating. Similarly, layers of different flavours can be built up by successive dipping in liquid mixes that are then quickly set with a short dip in liquid nitrogen.

There is one commercial ice cream product that is entirely frozen by immersion in liquid nitrogen. ‘Dippin dots™, which are exclusively available in the USA, are produced by letting ice cream mixes drip into a liquid nitrogen bath where they freeze into small (ca. 5 mm diameter) spheres. To prevent them from sticking together, they have to be stored, transported and kept before being sold at quite low temperatures (<−40 °C), and so they are only available at specialist outlets, usually shops or stands in shopping malls and at major events that serve only ‘Dippin dots’.

In the last decade or so, a number of nitrogen ice cream parlours have sprung up around the world, and these stalls and shops all make ice cream to order in front of the customers. Using nitrogen as the coolant means that they can make single servings of any desired flavour, so the wastage can be very low.

**Use of Cryogens in Restaurants**

A whole host of techniques that involve the use of cryogens to help prepare dishes in the professional kitchen have been developed in the past 20 years or so. Many of these techniques have been given names that refer to the ways in which they appear similar to more conventional techniques. In this section, I will address a range of these techniques and try to show how they can be used to advantage in any kitchen.

**Cryo-Grinding (Cryo-Powders)**

As noted earlier, if a food is fully frozen so that no liquid phase remains, then it can be ground down to a powder. The key is to ensure both that there are no liquid phases present, which normally means the temperature needs to reach below ca. −50 °C, unless there is any alcohol in the product, in which case it may need to be as low as ca. −120 °C, and that the temperature is not raised by the frictional heat that will be generated during the grinding process, to avoid any melting of the solid phases.

The simplest way to achieve this is to immerse the food to be ground in liquid nitrogen and then grind it. However, the bowls of many electric grinders may not withstand being cooled to liquid nitrogen temperatures, and the seals around the shaft may fail at such low temperatures, so it is usually best to use a manual grinder. Most coffee grinders are quite robust enough to withstand having liquid nitrogen in the grinding bowl, and any ceramic mortars are also usually more than strong enough to withstand the low temperatures. Of course, using manual grinders means that care must be taken not to touch any cold surfaces with bare hands, so proper protective gloves should be worn. In kitchens with Pacojet machines, these can be used as grinders, provided the temperature of the frozen Pacojet beaker is not lower than about −40 °C, which is low enough to freeze most foods completely solid. The food can be simply frozen initially in liquid nitrogen and then the beaker allowed to warm up in a freezer set to about −30 °C.

Once ground, powdered foods usually store well, provided they are kept in air-tight containers in the freezer so as to prevent any melting and coagulation of the fine powder particles. Herbs and spices really work very well, as the low temperatures prevent the loss of most, if not all, of the volatile compounds that impart their aromas. The ground herbs and spices are ideal for adding at the last minute, just before service, as garnishes or as seasonings to provide truly fresh flavours.

Finely ground powders used as a garnish can also create a remarkable aromatic effect, as the powders can simply blow up into the nose of the diner if they get close; a particular favourite of mine, which arose during some experimentation at the University of Copenhagen when I was working with one of the chefs from Noma in the experimental kitchen at the University, is a very fine pea powder prepared from a deeply frozen pea puree at about −40 °C using a Pacojet machine. If this is sprinkled on a plate, a diner can get a small dose of pea powder in the nose as they start to eat, and the result is a spectacular and clean hit of pure pea flavour.

A slightly different use for cryogens with grinders or mincers is simply to use them to prevent the heat generated during normal grinding from damaging the product being ground. This can be particularly useful when grinding or mincing meats to make sausages, when it is desirable to retain the fat in individual pieces rather than allowing it to melt from the heat generated as it passes through the mincing blades. In this case, it is probably not necessarily desirable to freeze the meat, but the grinding blades should be kept as cool as possible. Thus, simply grinding in small batches using either dry ice or liquid nitrogen to cool the blades and hopper of the grinder between batches will significantly reduce the effect of frictional heating – not only will the cold blades and walls of the grinder keep the meat cool, but also, since the colder the blades are the sharper they become, it will also reduce the amount of heat generated in the process.
Cryo-Grating

This is very similar to cryo-grinding in that it involves freezing a soft piece of food (such as a mushroom) so that it is completely solid throughout before grating off small pieces using, for example, a micro-plane. It differs from cryo-grinding in that it is a technique used at the pass to add a final garnish to a dish. Here, the purpose is to enable a chef to create small flakes of odourant and flavoursome foods that will release sudden short bursts of flavour on a dish. By grating at very low temperatures, the all-important volatile molecules that impart the required aromas and flavour cannot escape during the grating and remain in the tiny flakes on the food until they are warmed as they enter the diner’s mouth.

It is, of course, necessary for any chefs using this technique to ensure they use appropriate safety equipment (most importantly, they must never hold the food being grated with a bare hand, and either a thick insulating glove or a pair of tongs should be used to avoid the risk of frostbite).

Cryo-Slicing

It can be difficult to slice some vegetables, meats, breads and cakes very thinly. But if they are pre-frozen using a cryogen so as not to damage their texture and to ensure there are no liquid phases present, it is possible to produce extremely thin slices using a standard bacon slicing machine. If even thinner slices are required, then a carpenter’s plane can be used to produce slices of thickness less than 1/10 mm. Such thin slices can be very delicate and prone to fall apart when handled, especially after they have warmed up and defrosted when the ice that was helping to hold them together melts. Thus, it is advisable to keep the frozen slices in the freezer until required and put them on the plate as required while still frozen — note that such thin slices will heat through very quickly, so they should reach room temperature in the time it takes to complete the dish and deliver it to the table.

An example of the use of cryo-slicing is to make a salad that looks as though it is still in plastic packaging, but is in fact simply covered with extremely thin slices of cucumber. Use a plane (or mandolin set to cut slices of about 0.1 mm or less) to shave off thin slices along the length from a peeled cucumber that has been frozen in liquid nitrogen. The squared-off cucumber can be held in a cloth in a bench vice and the plane pre-cooled by pouring liquid nitrogen over it. As the resulting transparent slices of cucumber are shaved off, they are allowed to fall directly into liquid nitrogen. The thin slices can then be taken directly from the dewar (using long stainless steel forceps) and carefully placed on top of a previously prepared salad — as the slices heat up and defrost, they quickly deform to provide a shiny transparent covering over the salad, giving the appearance that someone forgot to unwrap it! Thinly cryo-sliced lemons or limes make interesting garnishes floating on the surface of cocktails.

Cryo-Shattering

This is a technique whereby thin sheets of liquids or gels are cast in trays that are frozen by the application of cryogens before being shattered using a small hammer or spoon — the remnants are then stored either under liquid nitrogen, in a cool box lined with a layer of dry ice or in a standard freezer, depending on the temperatures at which the now shattered fragments will melt. The thin sharp fragments make excellent, if short-lived, garnishes for a number of dishes.

Many liquids, such as honey, olive oil and wines, lend themselves to being made into fractured frozen shards in this way. However, the ways in which they can be used and the time it takes between service and their melting can vary widely, depending not only on the actual liquid used but also on the thickness and temperature of the frozen sheets. So, for example, 1 mm thick shards of frozen honey that have been stored at −20 °C can be put into an ice cream cone and will remain frozen for up to five minutes, while a similarly sized shard of frozen port will need to be kept on dry ice until service if it is to remain solid for up to two or three minutes after being served on top of a slice of stilton. This is an area where careful experimentation, varying the thickness of the sheets to be fractured and their storage temperatures, is essential if a useful product is to be made.

Cryo-Searing

Another process where very careful experimentation is required to achieve a consistent outcome is cryo-searing. Cryo-searing — the dipping of a foodstuff that is already partially cooked into a bath of liquid nitrogen for a short time — can allow deep frying to crisp up the outside without overheating the interior. Because of the large thermal gradient created between the outside and the centre by the short dip in liquid nitrogen, the outside can be heated up to ca. 200 °C, while the interior is heated much less and remains near room temperature (or at the original cooking temperature). The technique has been used to create well-browned crusts on steaks that have been cooked sous vide at low temperatures (ca. 40 °C) and as a means of creating a wonderfully crisp skin on almost rare duck breasts.

Cryo-Shaping

Many foods are so soft that even if they can be extruded or moulded into any required shape, they will quickly deform and lose that shape. But if the shaped object is quickly frozen by either spraying with liquid nitrogen or simply dropping into liquid nitrogen, it will become hard and stiff enough to retain the shape as long as it is kept cold — so, provided the shaped objects are kept cold in the fridge or freezer until service, it becomes relatively simply to make some very delicate and complex shapes from the most unlikely foods — maybe a rose shaped from frozen honey, or a basket made from a salmon mousse. In another twist, the Indian chef Gaggan Anand makes a wonderfully light, almost spherical mango mousse — by preparing the mousse mix in a cream whipper, then injecting it into a balloon, which is dipped into liquid nitrogen to set. Then the balloon is peeled off and the mousse kept refrigerated until service. Another form of cryo-shaping is to drizzle molten chocolate into liquid nitrogen. If chocolate is piped into liquid nitrogen, it freezes in shapes that resemble twigs on a tree — these can be used to great effect in some creative desserts. However, if the chocolate is allowed to pour slowly so that it forms a very thin stream,
then when it comes into contact with a very cold surface, it will solidify into a fine hair-like strand – with practice, it is possible to create the same sort of delicate structures that can be made with spun sugar simply by careful pouring of molten chocolates onto a mould that has been cooled using liquid nitrogen.

**Cryo-Carbonation**

The usual method to make fizzy drinks is simply to inject carbon dioxide at high pressure into the carbonated liquid. However, it is also possible and (if you have dry ice pellets at hand) easier to make fizzy drinks of all kinds simply by adding a couple of dry ice pellets to the liquid to be carbonated. Carbon dioxide is much more soluble in water at low temperatures than it is at high temperatures, and it is also much more soluble in alcohol than in water (Cargill and Maclennan, 1981) – so if you add solid carbon dioxide to cold water, then as it sublimes, much of the resulting gaseous carbon dioxide simply dissolves in the water. Now, if the liquid with dissolved carbon dioxide is warmed up – e.g., by putting it in a glass, or in the mouth during drinking – the temperature rises and the solubility of carbon dioxide decreases, releasing gaseous carbon dioxide in the form of bubbles, thus making the liquid appear fizzy.

So, you can make any drink become fizzy simply by dropping in a couple of pellets of dry ice and waiting until all the solid carbon dioxide has sublimed. The maximum solubility of carbon dioxide in water at 0°C is 3.4 g carbon dioxide per litre of water (and up to twice that amount in alcoholic drinks), so a typical dry ice pellet weighs around 2 g, just adding one pellet to a glass is sufficient to make the drink fizzy. But always make sure you check the weight of your own pellets, as they do vary!

One interesting example is the slightly fizzy milk shakes invented by Juan Mari Arzark. You simply make a thick milk shake (using pureed fruits, skimmed milk powder and a thickener, e.g., gum Arabic, with sugar and cream to taste) and once it is in a glass, or in the mouth during drinking – the temperature rises and the solubility of carbon dioxide decreases, releasing gaseous carbon dioxide in the form of bubbles, thus making the liquid appear fizzy.

Cryo-Freeze Drying

Many foods, such as leafy vegetables, bananas and cucumber, do not freeze well – the large crystals that can grow during conventional (slow) freezing can damage the cell walls so that on defrosting they become soggy and textureless. Fast freezing in nitrogen can ensure very small crystals and reduce or remove the cell damage so that on defrosting the structure is maintained. Freezing a bunch of flowers is a standard demonstration used in many talks about cryogenics in schools and colleges around the world. If you want to serve freeze dried vegetables (which really pack a punch of flavour as they rehydrate in the mouth), you need to retain their structural integrity during the initial freezing process – so for example you can prepare freeze dried Brussel sprouts only by first freezing them in nitrogen before transferring them into the freeze drying chamber – at the completion of the freeze drying process they come out looking exactly as they did when freshly picked but without any of the water. Olives do not freeze dry well as they tend to break during freezing but if quenched in liquid nitrogen the damage is limited so they can be freeze dried and then rehydrated in, for example in soda to make the perfect garnish for a Martini.

**On Show – in the Dining Room**

Customers generally love the spectacle associated with any use of cryogens in the dining room. The very cold nature of cryogens means that they cool the atmosphere around them enough that the water vapour present in the air condenses and creates a fog. If the cryogen is mixed with water, then the fog simply pours over the top of the vessel and rises a little before rolling over the sides and gently flowing to the floor before dispersing. If the water to which the cryogen is added is perfumed, then the resulting fog also carries its odour direct to the diner, providing a hint of what is to come from the food being served at the same time. This is great theatre and can set up expectations that the restaurant is an exciting place to be, so it is hardly surprising that increasing numbers of chefs are finding ways to use cryogens front of house with a range of frozen mousses and ice creams and as an odour enhancer.

However, a word of caution is needed here. While dry ice and liquid nitrogen are not toxic or poisonous, they are extremely cold, and anything that contains them or has been on contact with them for any period of time also becomes extremely cold; so cold that if touched it can cause serious cold burns (or frost-bite). Therefore, just as no-one would ever provide cutlery that is red hot or serve food on a plate straight out of a hot oven, or at a temperature that will instantly burn the inside of the mouth, it is...
necassary to make sure that any food or utensils that have been in contact with cryogens are not so cold that they can harm any diners – remember that while chefs in the kitchen and waiters in the restaurant can wear insulating gloves and will have been trained in the safe use of cryogens, customers will have bare hands and most likely will not have had any training in the possible dangers from the extreme cold of cryogenic materials. Probably the most important message here is that it is imperative never to allow anyone to ingest liquid nitrogen or dry ice. Serving staff need to make sure all cryogens have evaporated from any food before presenting it to the customer.

Cryo-Poaching

The Nitro Poached Green Tea and Lime Mousse served as an amuse bouche at the Fat Duck from 2001 can be seen as the origin of modern use of cryogens in restaurants. As Heston Blumenthal’s Fat Duck became more and more famous and other leading chefs started visiting, so the dish was copied and modified around the world. This is a relatively simple dish to prepare. Basically a mousse made from green tea, lime juice and vodka is put in a cream whipper. At the table, the waiter squirts out a little of the mousse onto the surface of a bowl of liquid nitrogen, where it floats – the waiter then carefully spoons more liquid nitrogen over the mousse until it forms a hard external shell. This is picked up with a spoon, any liquid nitrogen remaining is allowed to drain off, and then it is placed on a plate in front of the diner, who is told to wait a few moments and then pick it up and eat it whole. The result is a melt-in-the-mouth immediate hit of a very cold glass to keep the drink cold as well as allowing a trail of smoky fog to trail from the glass when held.

Preparing ice cream at the table is always a spectacle, but also, and more importantly, by making the ice cream as quickly as possible you achieve an incredibly smooth and creamy texture. The smaller the size of the ice crystals in ice cream, the smoother it tastes. Our tongues can detect solid particles as small as 1/500th of a millimetre, so keeping the ice crystals smaller than that will ensure the ice cream is truly smooth. As anyone who has tasted freshly prepared liquid nitrogen ice cream will attest, it can have a truly wondrous texture. However, it is not quite as simple as it may at first sight appear to achieve this end. First, speed matters – as soon as any ice crystals form, they also start to grow larger. In the first few minutes after making some ice cream, the overall average crystal size will rapidly increase as the smallest crystals melt and larger ones just grow larger. So, it is important both to ensure the actual crystallization takes place at as low a temperature as possible (by adding and mixing the liquid nitrogen as quickly as possible, getting the maximum possible cooling rate) and then to serve it as soon as possible after it has frozen (but always remembering that it cannot be served until all the liquid nitrogen has evaporated and there are no super-cooled lumps in the ice cream).

To achieve the best results, you need first to know how much liquid nitrogen is required to freeze the amount of ice cream being made. There is no easy answer to this, as it depends not only on the water content of the ice cream mix but also, and more importantly, on how much of the nitrogen boils off into the surrounding atmosphere rather than just cooling the ice cream mix. So, you will need to experiment to find out just what is required in any particular situation. But as a very rough guide, and a starting point for any experimentation, I find I use about 0.8 litres of liquid nitrogen to make 1 litre of ice cream.

My favourite use of liquid nitrogen to make ice cream is the one used to make the bacon and egg ice cream that formed part of the ‘breakfast’ dessert at the Fat Duck some time ago. The waiter bought out a plate with the main ingredients of a full English breakfast: ‘fried bread’ represented by a sweet pain perdu, some tomato jam and some caramelized bacon. Next the waiter, stating that they were going to prepare some scrambled eggs, cracked a couple of eggs into a frying pan, added liquid nitrogen and stirred until an ice cream the consistency of scrambled eggs was ready, and then served that onto the plate alongside the other elements. The ice cream mix, which had been injected into previously blown egg shells, was a slightly over-cooked custard infused with bacon that had a remarkable bacon and egg flavour. The overall multisensory experience and the juxtaposition of breakfast and dessert makes this still one of my personal favourite dishes of all time.

Fogging Odours

A further use for cryogens in the restaurant is to provide localized odours at a table to correspond with the food being served. If water (preferably warm water) to which the required aroma has been added is poured over some cryogenic material (dry ice generally gives the best effect), then the resulting clouds of foggy vapour will carry along the volatile odorants – the effect is somewhat localized, as the cool vapour droops over the vessel containing the dry ice and then flows over the table before dropping to the floor and dispersing – thus, it is possible to limit the main effect of the odour to just the particular table where it is wanted.

Liquid Nitrogen Cocktails

Over the past decade or so, many cocktail bars have started incorporating liquid nitrogen into their repertoire. A few drops of liquid nitrogen added to a cocktail give it that smoky effect that can excite customers. Holding empty glasses by their stems and dipping them in liquid nitrogen before adding the cocktail ensures a very cold glass to keep the drink cold as well as allowing a trail of smoky fog to trail from the glass when held.

Anyone using liquid nitrogen in this way needs to be very aware of the inherent risks and must ensure that all traces of liquid nitrogen have evaporated before the cocktails are consumed. There have been a number of serious incidents where staff were not properly trained or procedures not followed. For example, in 2015, Oscar’s Wine Bar and Bistro in Lancaster was fined...
£100,000 as a result of an incident where a customer was taken to hospital and had to have a large part of her stomach removed. It was found that no proper risk assessment had been carried out and bar staff had not received proper training or adequate warnings of the importance of not drinking the cocktail until all the nitrogen had boiled off.

Safely Storing, Handling and Using Cryogens

Cryogenics are not commonplace materials, so it is necessary to ensure that anyone dealing with them is properly trained so they understand the risks involved and know the correct procedures to follow. While much of this may be thought of as really little more than common sense, for example, just as most people do not need to be told not to grab hold of the metal handle of a pan that has just come out of a hot oven with their bare hands, not everyone will automatically appreciate that it is probably even more dangerous to grasp the metal handle of an uninsulated pan that is full of a cryogen. Both situations can cause severe burns, but when you hold a very hot or cold pan, your immediate reaction is to let it go as quickly as possible. This is fine for the hot pan – you can let it go and the burning will stop; but with the cold pan, as soon as you grab it, the moisture on your hand will turn to ice and your hand will become stuck to the pan so you cannot let go; the damage continues for some time and you can get a very severe cold burn, or frostbite. Hence the need for proper training.

Training can take many forms: on the job training from a very experienced person who has had some formal training and is able to pass on the necessary knowledge; online courses, external training courses run by professionals; or, probably the best, an external expert trainer giving workplace training to all the staff. All universities and colleges that use cryogens have to provide training for their staff and students and so run regular courses. Most universities are willing to allow external people to attend their courses; for example, many local chefs have been trained in the use of cryogens in my own Physics department by our cryogenics manager. All cryogen suppliers will be able to point their courses; for example, many local chefs have been trained in the use of cryogens in my own Physics department by our cryogenics manager. All cryogen suppliers will be able to point their own particular circumstances. Briefly, you will need to assess and handle and use on the internet, which you can adapt for your own particular circumstances. Briefly, you will need to assess and quantify the various risks associated with the use of cryogens: small spillages that can cause burns, larger spillages that may lead to oxygen depletion, the presence of very cold surfaces and the attendant risk of frostbite or cryo-burns if people come into contact with them, as well as the risk to customers from any accidental ingestion of cryogens. For each identified risk, you will need to develop procedures to reduce the likelihood of any potential injury to an acceptable minimum. This can be through the use of personal protective equipment, staff training detailed working practices, etc. Finally, you will need to ensure there are procedures in place to make sure that all the instructions are followed by all staff. For example, once you have prepared risk assessments and procedures for storing, transporting and using cryogens, you should make sure that all staff who may come into contact with cryogens have read and are fully aware of these. It is also advisable to make sure they are checked and revised as necessary, at least annually if not more often.

To store cryogens, properly insulated vessels are required – most suppliers of cryogens will only deliver to you if you have an appropriate container. For liquid nitrogen, a proper dewar (named after James Dewar, who invented the idea of using a vacuum flask to hold cryogenic liquids) is required. The dewar may be completely open so the liquid is constantly simmering, or it may be closed and held under a small pressure with a safety vent valve to prevent build up of pressure inside as the nitrogen boils off. All liquid nitrogen-filled dewars will give off a slow stream of cold nitrogen gas as it slowly boils off. The larger the dewar and the better its vacuum, the longer the liquid will last before it all evaporates. Most restaurants find that medium-sized dewars (typically around 40 litres), which they have re-filled weekly are sufficient. To store dry ice, an open dewar is best, but a well-insulated Styrofoam box, such as a cool box, can suffice.

Note that liquefied gases must never be stored in uninsulated or sealed containers – if an uninsulated container is used, the outside will cool to cryogenic temperatures and pose a major risk to anyone accidentally touching it. If a cryogen is stored in a closed container, then as it evaporates the internal pressure will build up, most likely resulting in the eventual fracture of the container in a powerful explosion.

When transporting cryogens, even within the premises for short distances, it is essential to follow proper safety guidelines – one of the most important being never to enter a closed space (such as a lift) with a container of a cryogen, as if you are trapped or the cryogen spills, the resulting gas will displace the air in the room or lift, leading to asphyxiation.

In the restaurant, the best way to carry and use liquid nitrogen is to obtain a small stainless steel dewar – these are available from many scientific suppliers – which can be used as required and will fit in with any modern restaurant décor.

When working with cryogens you need to wear appropriate protective clothing – thermal gloves and eye protection are usually the most important items. But you also need to be aware of risks of spills and splashes, so make sure that all clothing (especially footwear) worn is non-absorbent and will not trap any cryogens in the weave.

Risk Assessment

As with any process that carries the risk of injury, you should always perform a risk assessment. For cryogens, you can find many examples of standard risk assessment questions for storing, handling and use on the internet, which you can adapt for your own particular circumstances. Briefly, you will need to assess and quantify the various risks associated with the use of cryogens: small spillages that can cause burns, larger spillages that may lead to oxygen depletion, the presence of very cold surfaces and the attendant risk of frostbite or cryo-burns if people come into contact with them, as well as the risk to customers from any accidental ingestion of cryogens. For each identified risk, you will need to develop procedures to reduce the likelihood of any potential injury to an acceptable minimum. This can be through the use of personal protective equipment, staff training detailed working practices, etc. Finally, you will need to ensure there are procedures in place to make sure that all the instructions are followed by all staff. For example, once you have prepared risk assessments and procedures for storing, transporting and using cryogens, you should make sure that all staff who may come into contact with cryogens have read and are fully aware of these. It is also advisable to make sure they are checked and revised as necessary, at least annually if not more often.
As cryogens can be dangerous if not handled correctly, you should display appropriate signage in the areas where they are used along with copies of the risk assessments.

REFERENCES


Marshall AB. 1901. The Table. 24 August 1901.


