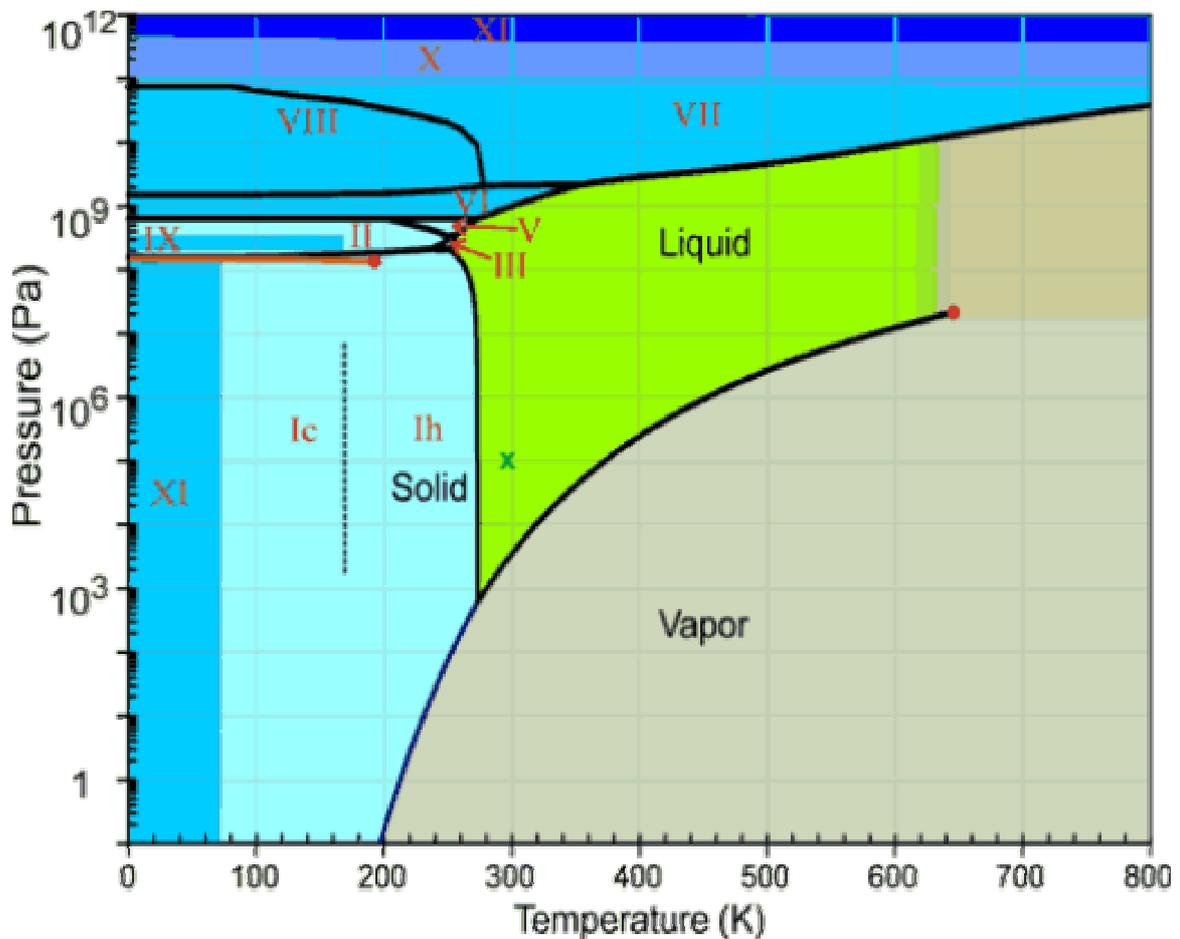


Scottish Curling-Ice Group

WATER IN A CURLING RINK

Water is the only material on earth commonly found as gas, liquid and solid. In a curling rink it is found as a gas in the air, as a liquid in fog or condensation and during flooding and pebbling, and as a solid in ice. From the phase diagram of water below, it is clear that water can exist as all three, or as any of these, around 0°C (273°K). There is also a fourth form of water, supercritical, that only exists under extreme pressure and temperature, which will not be further discussed here.

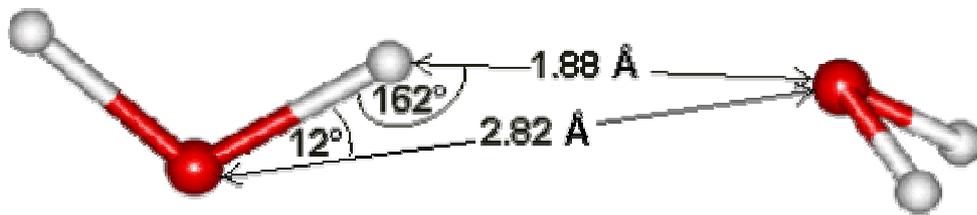


Phase diagram of water (Dr Martin Chaplin)

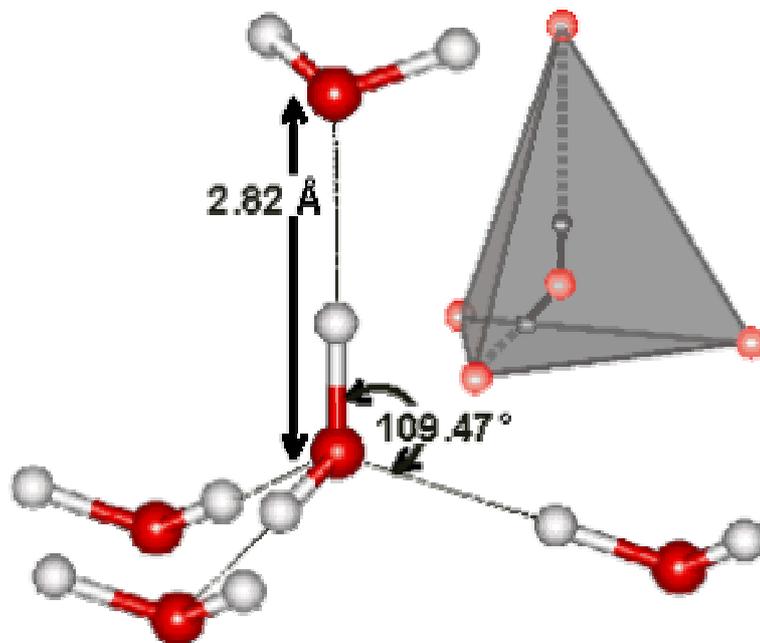
Water (H₂O) is the third most common molecule in the universe (after H₂ and CO), the most abundant substance on earth and the only naturally occurring inorganic liquid. A water molecule consists of two hydrogen atoms and one oxygen atom, as illustrated below.



In liquid water these molecules cluster together through hydrogen bonding in a very specific way.



Whilst the molecular movements within liquid water require the constant breaking and reorganisation of individual hydrogen bonds on a picosecond timescale, it is thought that the instantaneous degree of hydrogen-bonding is very high (>95%, at about 0°C to about 85% at 100°C) and gives rise to extensive networks, aided by bonding cooperativity.



In liquid water, the instantaneous hydrogen-bonded arrangement of most molecules is not as symmetrical as shown here.

It is fortunate that a full understanding of the complexities of water and ice is not required in order to understand what happens in a curling rink. These diagrams are included only as an aid to understanding the relative simplicity of its structure. What is however important is to understand that the properties of water and ice change with every change in temperature, pressure and environment. By understanding the significant changes it is possible to adjust them or adapt to them, and so control the most important component involved in a curling rink, the actual ice surface.

On the website presented by Dr Martin Chaplin on water (<http://www.lsbu.ac.uk/water/index.html>) there is a wealth of scientific information relevant to the subject. This includes the forty-one anomalous properties of water which, although complex and difficult for the uninformed to understand, clearly demonstrate that water is a very strange and unique substance. While not every anomaly will be a problem in a curling rink, there are many that will have an influence, and it is important to take note of these. The following observations, mostly from the website, are noted here as an abbreviated way to emphasise the complexities of dealing with water, omitting those not thought to have a significance within a curling rink.

- The large heat capacity of liquid water contributes to thermal regulation and prevents local temperature fluctuation, with water having over twice the specific heat capacity of ice or steam.
- The high latent heat of evaporation of water and ice gives resistance to dehydration and considerable evaporative cooling.
- Water is an excellent solvent due to its polarity, high dielectric constant and small size, particularly for polar and ionic compounds and salts, which have varying effects on properties such as density and viscosity.
- The density maximum at 4°C and low ice density results in the necessity that all of a body of water (not just its surface) is close to 0°C before any freezing can occur.
- Notable amongst the anomalies of water are the opposite properties of hot and cold water, with the anomalous behaviour more accentuated at low temperatures.
- Water has unusually high surface tension (under influence of temperature).
- Water has unusually high viscosity and shows an unusually large viscosity increase but diffusion decrease as the temperature is lowered.
- Hot water may effectively freeze faster than cold water, the Mpemba effect.

To these scientific observations we can easily add more simplistic ones.

- It can be anything from a gas to a solid at normal temperatures.
- In its purest form it only exists in a laboratory.
- It changes in its behaviour at every change in temperature, and under every external influence.
- It wants to dissolve everything it touches.
- It is indestructible.
- It wants to move and fill every space.
- It will always try to migrate to the driest part of its environment.
- Warm air holds considerably more water than cold air (when reaching 100% RH).

The environment

The environment of a curling rink is complex, and it is impractical – and unnecessary – to measure every aspect. In order to discuss and so develop control of the environment, the measurements have to be standardised. The following are the key parameters:

BT	Brine temperature (in and out)
FT	Floor temperature (usually beneath the ice, and displayed on the controller)
IST	Ice-surface temperature (taken either by infra-red laser, or fixed probe)
AT	Air temperature at 1.5m above the ice surface
RT	Roof temperature (of the air, just below the roof, say at 5m)
OT	Outside temperature at 1.5m
DPT	Dewpoint temperature at 1.5m above the ice surface
HR	Humidity ratio, g/kg at 1.5m above the ice surface
RH	Relative humidity at 1.5m above the ice surface
ORH	Outside relative humidity at 1.5m

The refrigeration equipment and conditions of all curling rinks will vary from place to place, as will the weather conditions even from hour to hour. Due to the many influencing factors the BT can be ignored here, and for the purpose of discussing water within a curling rink the only relevant readings will be the IST, AT, RT, DPT and RH. Consider now the following four scenarios, with the readings taken from the log of a standard four-sheet curling rink under real conditions.

	Conditions	IST	FT	AT	RT	DPT	HR	RH	ORH	OT
1	Ideal	– 4.5°C	– 6.4°C	+ 7°C	+ 20°C	– 3.7°C	2.77	45%	70%	+ 8°C
2	No heating, poor dehumidification	– 3.6°C	– 5.0°C	+ 6°C	+ 8°C	+ 4.2°C	5.1	90%	80%	+ 8°C
3	Heating, but no dehumidification	– 4.2°C	– 6.4°C	+ 7°C	+ 20°C	+ 3.8°C	4.9	80%	70%	+ 8°C
4	Normal full rink	– 3.8°C	– 6.9°C	+ 8°C	+ 25°C	– 1.6°C	3.3	50%	65%	+ 8°C

1. The important indicator here is that $IST = DPT$, or reasonably close to it, which is primarily achieved by controlling the RH through dehumidification, and with some heating to prevent condensation. There will be little frost to deal with, no condensation anywhere and good curling conditions.
2. Should the heating fail the RT will gradually reach the OT or even colder. If there is insufficient dehumidification and the surplus moisture in the air is not extracted, the RH will rise and eventually reach 100% and produce fog, and at 90% the DPT will already be at $+ 4.2^{\circ}\text{C}$. There will be massive amounts of condensation and uncontrollable frost on the ice surface. Because there is no surplus heat to extract, the FT can be raised by the steering system and so the IST, but this will not help to control the frost, and despite the technician's efforts to manipulate everything in his control the battle will soon be lost.
3. With no dehumidification the DPT can also rise to uncontrollable levels. Because the roof and walls are heated there will be little condensation, but frost will gradually form on the ice surface.
4. During a busy day with some 32 curlers nearly always on the ice, the FT has to be lowered to compensate for the additional heat introduced. The extra heat will initially lower the RH about 5%, but if no extra moisture is extracted it will gradually rise to 5% above the original value due to the extra moisture introduced by the curlers. The high IST reflects the additional heat load that needs to be extracted through the ice, while the DPT has risen a little to reflect the increase in AT but not enough to cause a frost problem.

All the changes and consequent problems are directly related to unseen water, under influence of changes in temperature and conditions within the rink. Although these readings were taken from an actual log and were based both on what the instruments say and an intelligent interpretation of the readings, they do illustrate the many changes that occur within a curling rink where conditions are either well controlled or beyond control.

The section on Humidity in *Curling Ice Explained* will help to clarify the problems of water in a curling environment.

Water in the air

The volume of air within the rink is 4000m^3 and the normal conditions in winter are as follows: $RT = 25^{\circ}\text{C}$, $AT = 10^{\circ}\text{C}$, $IST = - 4^{\circ}\text{C}$, $DPT = 0^{\circ}\text{C}$, $ORH = 60\%$, $OT = 8^{\circ}\text{C}$. Every day about 60 litres of water is extracted from the air through dehumidification to maintain the RH at 50%. If the outside RH should fall below 50%, this will not contribute to the load. However, should the outside RH rise to say 80%, there will be migration of gaseous water into the rink through whatever passage it can find to fill the drier environment, and so require a further 40 litres of water to be extracted. If this is not done, the RH will rise to 80% as in the third scenario above. Additional gaseous water will also be introduced by the breathing of curlers, evaporation of the pebble water when applied and, under the right (or wrong) conditions, sublimation of the ice surface.

In the same scenario as above, the moisture content at 1.5m will be 4 g/kg, while at 5m under the roof it will be around 10 g/kg. Some of the moisture held in the warmer air nearer the roof, in the absence of air movement, will migrate towards the drier and colder ice surface. As the moisture enters the colder air the gas will condense into droplets of liquid water as fog, and the fog will condense onto the ice surface as frost. Should there be some air movement and turbulence caused by the players, the air nearer the ice could be sufficiently warm to prevent the fog from forming, but the frost will still accumulate on the ice surface and be most obvious where the players have not brushed it aside or forced it into the ice. In this scenario, should the surface not be continuously played, the ice will become unplayable within two hours, and more so on the unplayed sides of the sheet.

With the dewpoint temperature very close to the actual ice surface temperature change can happen very quickly, without warning and without immediate remedy. The more humidity in the air, the larger the danger and the more obvious the change.

The formula used to calculate the amount of frost on the ice surface is as follows:

$$M = \alpha/P_c * (X_{air} - X_{ice})$$

M = + means added and – means evaporation of the amount of water on the surface (kg/sec) per m²
 α = heat conversion factor (1.5 if no air movement; 3.0 if small air movement)
 P_c = the heat content in the air (joule/kg and °K), normal factor is 1000
 X_{air} = water content in the air by air temperature and air RH (kg/kg) – use IX-diagram
 X_{ice} = water content in the air by ice-surface temperature and 100%RH (kg/kg) – use IX-diagram

Average calculations using this formula indicate an increase of water onto the ice surface of 0.1mm per day under good conditions and over 1.0mm under really bad conditions. Not all this increase can be removed through cutting the ice. To understand the quantity of moisture involved in the third scenario, consider that it needs only 6 litres of water to pebble the entire ice surface once. The 100 litres of surplus moisture in this case equates to 1 litre of water as frost for every 10m² of ice surface. Under every condition where the DPT is much higher than the IST, much of the water in the air will find its way to the ice surface.

This is not the only problem. While it is obvious that air turbulence will cause some transfer of heat from higher in the air down towards the colder ice surface, this is not very significant. There is a more significant transfer of heat due to the condensation or evaporation of water. At the dew point this will be effectively zero. If the IST is above the DPT of the air, then water molecules will evaporate from the ice, cooling it down. If the IST is below the DPT of the air, then gaseous water will condense onto the ice (e.g. frost), warming the ice up. Under conditions of high humidity such as scenarios two and three above, changes to the IST of a full degree Celsius have been observed, even where there has been no air turbulence. An ice surface at – 3.5°C is too warm for curling – it will not only be very slippery underfoot, but there will be excessive curl and very soon a flat pebble. This change in temperature due to condensation can occur within a few seconds and last for a few minutes, until refrigeration has extracted the heat.

The first instinct would be that such rapid and significant changes cannot happen in the controlled environment of a curling rink. However, these observations were made in two curling rinks using the same methods. The readings were taken from a probe 1mm beneath the ice surface and not the surface itself, with no turbulence and no other possible cause in evidence, and to be sure many readings were taken first thing in the morning before the lights were switched on. It happens often during games when the humidity is too high, causing curlers to lose their footing a little and then wonder what has changed, yet it doesn't really seem to affect the behaviour of stones too much as the effects are soon equalised when the temperatures stabilise.

Under the second scenario the IST could be kept much higher because there was little surplus heat to extract. However, it was also noted on the log that there was a reduction of 20% in the compressor hours per day when the RH was lowered to 60%, a clear indicator that surplus moisture introduced heat through condensation in significant amounts, when there were no other changes in temperatures to account for the reduction.

Clearly the air temperature and humidity should be controlled so that the IST is always equal or close to the DPT of the air. Perhaps the DPT should be controlled to be a few points of a degree colder than the IST as evaporation (keeping the floor colder) is preferred to condensation (which warms the floor), but uneven evaporation/sublimation here could destroy the level of the ice surface. Also, a DPT a little higher than the IST is not necessarily a bad thing for curling, as the increase in amorphous ice (see later) will be helpful to the behaviour of the stones – it is only when the DPT remains too high for too long that frost becomes a problem.

Note also that any condensed water would not necessarily be the first molecules to evaporate, so equal but significant amounts of evaporation and condensation would also lead to "frost" formation, something readily observed where desiccant dehumidification is used. The ice surface acquires a very fine dust-like layer of frost that looks much thicker than it actually is.

The scientific side of it is as follows. The key parameters are the specific heat of ice (38 J/mol/K), the enthalpy of fusion of water at 0°C, 6009.5 J/mol, and the enthalpy of vaporisation at 0°C, 45054 J/mol. Therefore 1g of water condensing from gaseous water to form ice will raise 1344g of ice by 1°C and 1g of liquid water fog forming ice will raise 158g of ice by 1°C. However, the gaseous water has to give up its heat to become a fog or frost, and this heat must mostly go into the ice.

The science apart, it is clear that excess moisture in the air should be removed and the DPT controlled, or the entire exercise of creating a perfectly level and consistent ice surface could be wasted. Surplus moisture is not only difficult to work with, it is expensive on running costs and labour costs and makes for poor curling. On the other hand a rink could be in an area of very low humidity, such as areas of Canada or Scandinavia, where the ORH could be as low as 10-20% and temperatures often at -25°C , and conditions within the rink will reflect this. Dehumidification will not be needed and heating will help to hold more moisture, but now the moisture will want to find its way to the drier environment outside. Unless the moisture is replaced, it will be drawn from the ice pad through sublimation and soon the level of the pad will be ruined.

Water on the ice

When flooding, the water used will come from a tap and through a hose. What happened to the water before it reached the premises will be largely unknown and at best educated guesswork. On its passage from rain to tap it will have absorbed countless gases in the air, minerals from rocks, organic debris and no doubt chemicals from a variety of sources. It could have filtered through rock into a well, or it could have been filtered by the supplier and cleaned through many modern processes to remove those impurities considered to be harmful to man or beast. The supplier might even have added a number of chemicals to the water to improve its qualities, and the expenses involved will be passed on to the customer who will no doubt believe that he has clean water. The water will not be clean, yet it is now accepted that the ice surface that is played on has to be as clean as possible, or the game itself will suffer.

Historically the game of curling was played on the frozen surface of outdoor ponds and lakes, with few options available to improve the surface. Now the game is usually played in an indoor arena or curling rink, where a level floor is flooded with water and the heat extracted to freeze the water solid. The purpose of using water is two-fold: to use the unique properties of water to create a perfectly level surface, and to use the properties of frozen water to slide a heavy lump of granite some 40m to the other end of the rink. However, the floor itself will not be perfectly level, therefore the water will not freeze level. Water might well find its own level if there is a sufficient quantity to cover all the high areas, but as water expands some 9% when it freezes it will expand more where the water is deeper, and therefore will not freeze level until the surface that is flooded is already level.

In order to use water for the purpose of playing a game of curling, the surface has to be perfectly level and clean, which at the outset will not be the case. All the positive aspects of the properties of water have to be harnessed, while all the negative aspects will have to be overcome, or the result will be less than ideal.

Salts, gases, minerals and impurities

- The ideal solution for a curling rink is to install a cleaning system for the water, such as reverse osmosis and/or deionisation. The water will freeze better and harder and will be suitable for curling. Although the water will not be perfectly clean, it will have a very low conductivity indicating a very low content of salts or minerals.
- Water containing salts will not be the same as clean water, and will not behave the same. Salts will require the water to be colder before it will freeze (a 2% salt content will need an extra 1°C to freeze), and the ice pad will have to be kept colder for the pebble to last a full game. The stones will behave differently on this surface because the ice will be softer, and by lowering the temperature more to compensate the friction between stones and ice will be less. When applying the pebble the salts will be lifted into the tops of the pebbles, aggravating the problem, and the pebble will not be strong enough to last a game.
The answer is to cut the surface of the ice as soon as the floods are sufficiently level and remove the salt on the surface. By then pebbling the cut surface more salts are lifted, and by cutting off the pebble these are removed. By pebbling the surface with hot water more salts can be lifted, as the pebble will melt more ice on contact with the ice. By warming the surface to about -3.5°C the ice will be softer and the cutting easier, and larger drops of water can be used. The cutting between floods will also help to level the surface and lessen the effects of expansion.
- Water containing salts will have a higher surface tension that will cause it to freeze at the leading edges. The water will take longer to freeze and, if the salts are not removed during the flooding process, the surface will become increasingly greasy with unfrozen salts and take ever longer to freeze.

- Water containing oxygen or other gases will also take longer to freeze and the structure of the ice crystals will be more open. By heating the water to 40°C the bulk of free oxygen can be removed, and heating pebble water to 30°C is often sufficient to ensure strong pebbles. With less oxygen in the water the resulting ice will have a higher density, less insulation properties and better heat transfer, all resulting in lower costs to create and maintain the ice floor.
- The heated flooding water, when it is being applied, will have lower viscosity and lower surface tension, both helping the water to flow more evenly and settle more level than otherwise. The many advantages of using heated water certainly outweighs the cost of heating, especially if a heat-exchange system is used. The main disadvantages of heated water are that it will melt more of the ice where there are hollows in the surface, creating problems for the levelling process, and the hose will have to be carried above the ice pad during flooding to prevent it from burning into the ice.

Achieving a level, strong surface

Several unseen problems can easily develop to affect the final result. It is best and quickest to fill the lower areas first with layers of successive floods, and then to flood the entire floor once it is sufficiently level, also with relatively thin successive floods.

- Freezing the floods fast could produce smaller crystals. These crystals will be surrounded by a microscopic layer of "amorphous" (non-crystalline) ice containing impurities, and as the crystals are smaller the amorphous surface per unit volume will be higher. This will trap more salts, preventing them from reaching the surface during freezing, and gradually reducing thermal conductivity as the layers proceed. One solution is to flood with warm water that will take longer to freeze; another is to freeze the flood slower either by removing refrigeration during flooding, or by reducing the freezing capacity.
- The humidity within the rink can also affect the level, especially during the earlier floods. Should the RH be too high, the areas that freeze first (usually the higher areas) will collect more frost and become even higher. Should the RH be too low, the areas that freeze slower (usually the lower areas) will evaporate more before freezing and become even lower. An RH of 50-60% will control these problems.
- Temperatures of the ice surface before and after flooding are important too. The ideal is to create an ice pad that is consistent in quality, meaning crystals of similar size and a controlled surface tension. Apply floods of uneven thickness, freeze the surface colder than it had been before or freezing it too fast can all lead to cracks. Good flooding, once level, should freeze evenly and uniformly to achieve the desired consistency .
- Once the flooding is complete the surface is cut to remove salts. It is then pebbled and cut, many times, to melt more salts out of the surface and to fill the irregularities in level created by surface tension. If the cutting is not even and consistent the surface will be ruined, and if the pebble is not even this too will gradually ruin the level. Pebble and cut until there is a smooth, even, consistent surface with the snow as white as can be, and the pad will be ready for curling. Yet even then it will be a few days before the pad has settled down, free of tension and harder than concrete.

Pebble

There are many theories concerning pebble, because it is very difficult to measure the changes during a game or the effects of small changes in temperature and humidity. The focus here must be on what is known, or can be reasonably assumed, about the properties of water that are used to create the pebble.

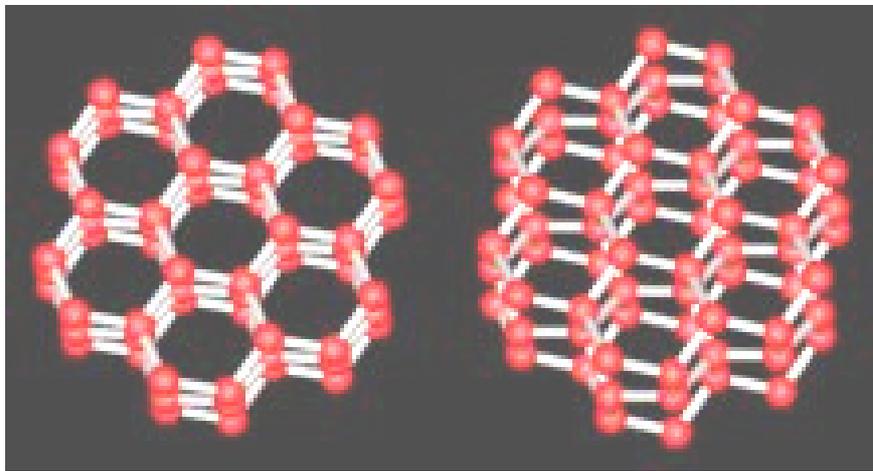
- Pebble water should be clean. The cleaner the water, the stronger the pebble. Whether deionisation, reverse osmosis or distillation is used does not appear to matter, provided it has very low conductivity and contains as few impurities as possible. Any suspended matter will block the holes of the pebble head and must be filtered out, and any salts will have deleterious effects. It is not clear if this clean water, being free of salts and "hungry" to dissolve anything it touches, will corrode the small holes of the pebble head, but in time it is assumed that it does, therefore the holes will gradually become larger.
- The water should be warm, to hold less oxygen and so provide less viscosity and less tension, with a higher density. Again there are many theories regarding the exact temperature as conditions and requirements vary from rink to rink, but the norm is 30-50°C in the urn and this should be sufficient.
- The water should have a consistent head of pressure to ensure a consistent size of pebble (see the report on Pebble Can Tests). If there is an obstruction in the pipe or fittings to restrict the flow, or the pipe is too small, the first few litres will be at a different flow rate to the last few litres. A good flow rate

(without the pebble head) will be higher than 0.3 litres per second, while 0.2 litres per second will prove insufficient towards the end. The delivery should be smooth, rhythmic and relaxed, and much practice will be needed before accurate distribution can be achieved with different pebble heads.

- If the water is too warm the pebble will flatten more on impact with the ice, and if it is too cold the pebble will sit up too high. If the pebble is small it will freeze faster and be stronger, while a larger pebble will freeze slower and not be as strong. Humidity in the air can also have an effect – if the RH is too low the size of the drop could well change in the air through evaporation.

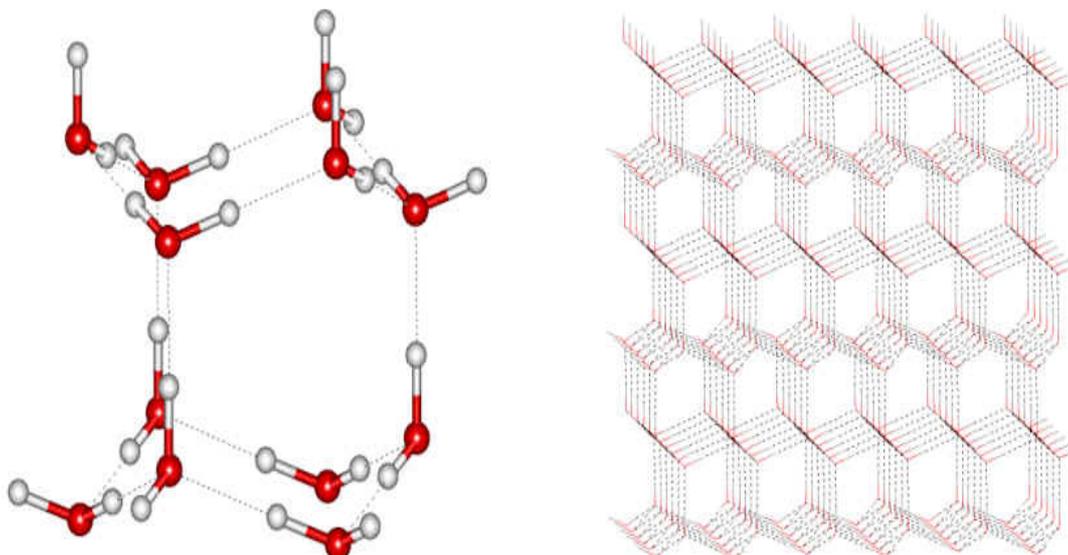
Water as solid ice

In all the solid phases of ice the water molecules are hydrogen bonded to four neighbouring water molecules. Hydrogen bonding occurs when an atom of hydrogen is attracted by rather strong forces to two atoms instead of only one, so that it may be considered to be acting as a bond between them. Typically this occurs where the partially positively charged hydrogen atom lies between partially negatively charged oxygen atoms.



From www.snowcrystals.com

In ice it is possible to represent the structures along scientific rules, to illustrate the different structures that occur. One such result is represented below, here that of hexagonal ice (ice 1h). Hexagonal ice is the normal form of ice and snow, as evidenced in the six-fold symmetry in ice crystals grown from water vapour (i.e. snow flakes).



A crystal is a material which has its molecules arranged into a crystal lattice. The crystals may be thought of as consisting of sheets lying on top of each other. The basic structure consists of a hexameric box where planes consist of chair-form hexamers (the two horizontal planes, above) or boat-form hexamers (the three vertical planes, above). The water molecules have a staggered arrangement of hydrogen bonding with respect to three of their neighbours, in the plane of the chair-form hexamers. The fourth neighbour (shown as vertical links above) has an eclipsed arrangement of hydrogen bonding.

As the temperature of the liquid water is lowered, the hydrogen bonding strengthens and becomes fixed, and until the ice melts again this bonding can be considered permanent for the purpose of curling ice. All the solid phases of ice involve the water molecules being hydrogen bonded to four neighbouring water molecules. In all cases the two hydrogen atoms are equivalent, with the water molecules retaining their symmetry, and they all obey the "ice" rules: two hydrogen atoms near each oxygen, one hydrogen atom on each O...O bond. The H-O-H angle in any ice phase is not very different from that in the isolated water molecule.

The introduction of salts into the water will obviously have an effect, as all the above information relates to clean water. The molecules will not be of water but of some different chemical, with different bonding and usually a weaker structure. This will give softer ice at the same relative temperature, and this will behave differently in a game of curling. Once the surplus salts that can be removed by pebbling and cutting have been removed, the contents of the ice pad can fortunately be largely ignored, because the water was only used to create a perfectly level surface. On the other hand, had deionised or clean water been used to install the ice pad, the whole pad will be more consistent and stronger than in the case of dirty water. In either case it is now the playing pebble that has to be addressed, because that is what the stones and players will be sliding on for the game of curling.

The frozen pebble

- When applying pebble to the ice surface, the IST will immediately rise by about 0.1°C per layer of pebble, and for a double layer it will take a few minutes for the temperature of the pebble to equalise to that of the ice surface. During this time the pebble will be soft and easily worn, and should be left alone.
- The ice-surface temperature should be in the range of – 3.8°C to – 4.5°C if the pebble is to last for the duration of a game, usually at least two hours but often more than three. In the ideal scenario given above, the IST will be – 4.5°C before the pebble rising to – 4.3°C, and towards the end of the game could well be as warm as – 3.8°C due to heat introduced by curlers, turbulence, etc.
- For consistency from game to game the ideal is to remove the pebble by cutting and provide a fresh pebble for the next game. With the IST at – 3.8°C the ice is sufficiently soft to cut easily without adjustment to the controls, and if done efficiently it only takes ten minutes to fully prepare a sheet of ice. This is not always practical, but it is certainly possible and many technicians are able to do it as a matter of routine.
- The temperature of the pebble does not remain the same through a game, and some of the changes are extremely subtle. As shown above, too high humidity and DPT will have a serious effect on the surface through condensation as frost, where vapour turns into ice. Even under good conditions a microscopic layer of amorphous ice forms on the surface, within which the molecules are less organised and not yet crystalline. This is in fact what is played on, and not the drops of pebble themselves. It will be more fluid (but not liquid) and sticky at higher temperatures, providing more friction to the stone and therefore less speed and more curl. Yet, at the higher temperature some of the molecules could evaporate and cool down the surface, restoring the balance, or more vapour can condense and warm it up. A very careful balance must be found where the evaporation and condensation can be kept to a minimum, and only careful control of all the parameters can achieve this.
- Fluctuating temperatures are also likely to cause "recrystallisation" of the ice (small crystals changing into large crystals). This may cause some migration of salt to the surface and an increase in thermal conductivity, but both may be insignificant. However, should salt gather in the amorphous (frozen) water on the ice surface, it will make it more extensive, softer and more easily melted. A surface containing salts would have a lower vapour pressure, causing it to accumulate condensing water (frost) to a greater extent. A clean pad should have less frost, another reason for removing the salts and working only with clean water.
- Dust from the air will become wet (initially by interacting with the surface amorphous frozen water), then the water hydrogen-bonding network will not let it back into the air. The dust becomes trapped, and this too will have an effect on the friction between the surface and the stones.

- Then there are the players, brooms, brushes and stones, all determined to wear the pebble down. The amorphous layer is swept aside, forced into the ice, the molecules knocked about until they're in the right shape. Hands and knees melt small areas, sharp edges of plastic or teflon cut lines through the surface, some areas are played harder than others, some games sweep more than others. It is small wonder that many technicians resort to freezing the ice colder to contain at least the obvious damage, yet immediately changing the behaviour of the stones to straight and fast.
- There are many well prepared theories of why curling stones curl, and fortunately the subject here is ice. How do stones affect the ice, or interact with the ice. If the stone is too warm it will melt and freeze into its hole so solidly that it would be difficult to remove. Leave a cold stone in one place for long and it "sticks" to the ice, because it has melted enough of the surface to freeze to it. Is this due to the stone being too warm, or transferring too much heat from air to ice surface? It is due to the pressure on the ice from the weight of the stone that it warms up a fraction and a sufficient quantity of moisture is formed. Is this why stones curl, because they lose momentum and travel slower, so having more time to apply pressure to warm the amorphous layer, for higher friction and more curl? Had this been so surely the sweeping would make stones curl more and travel slower, because the sweeping warms the ice surface too!
- A stone weighs 20kg, which is distributed through its running edge over an area of 0.5cm². Although this can and does raise the melting point of the ice very slightly, it is insufficient to completely explain the curl.
However, the frictional heat required to form a thin (micron or so thick) melted layer would be about consistent with the energy lost during the stone's progress. The sweeping will clear any weak amorphous material ahead of the stone, and as much frost as is possible, to enable the stone to travel on different, stronger, harder ice, with less friction, while the stone's momentum and weight will do the rest. This is a grey area in the very finite world of curling ice, but full understanding comes ever closer.
- What is clear, though difficult to prove, is that the IST should be controlled as accurately as possible during a game, even when all the other parameters are close to the ideal. The stone is in contact with amorphous ice when it is not swept, and the very nature of this amorphous ice is very sensitive to change in temperature – had this not been the case the stone would not curl much at all. The IST has to be warm enough for the stone to be able to warm it another fraction and acquire the friction it needs to draw, yet cold enough not to become too warm. Every rink will be different and so will the IST, and this is the challenge that all curling-ice technicians face in search of the ideal. To date, under the ideal parameters given in the first scenario above, it appears that an IST of -3.8°C is as warm and -4.5°C is as cold as it is wise to go.

Compaction

During most games of curling the emphasis is down the middle of a sheet, roughly over the centreline. Here the pebble and the amorphous ice will be attacked by stones and players to force the molecules tighter into each other, creating a dense, compacted area. This will gradually rise by fractions of a millimetre and become so hard that it is almost impossible to cut with a blade. It is one of the challenges of maintaining curling ice to keep this damage down by cutting the centreline a little harder with extra passes in the cutting routine.

Summary

Without the unique properties – and the many anomalies – of water, the game of curling would not have become the precision sport it is today. Without understanding and harnessing the behaviour of water, whether as a gas, a liquid or a solid, and the interactions of all three in a curling rink, it will not be possible to create and maintain a surface that will remain at the right temperature and behave as required for the duration of a game. The more perfect the ice technician becomes, the more obvious his mistakes, and the easier to learn about them and improve.

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