



Yeast and fermentation

By Billy Mitchell

This is the fourth article in the series to support those studying for the IBD General Certificate in Distilling. This will look at some of the practical and theoretical aspects of the fermentation process employed in spirits production. We shall discuss how the raw materials, defined and specified in my first article, when processed as detailed in articles two and three to produce a sugary 'wort' solution, can then be fermented by the action of yeast to produce ethyl alcohol and numerous other flavour compounds. I will also cover the Health and Safety implications, general maintenance overview and plant cleaning processes which arise. Figure 1 gives a simple schematic of where fermentation fits into the overall production processes employed in spirits distilling.

General Principles

Before discussing the general principles around yeast and fermentation it is worth a few moments to reflect upon some of the terminology used throughout the spirits industry. The distillers refer to the sugary solution produced during mashing as 'wort'. The amount of sugar in an unfermented mash can be measured using a density meter or hydrometer.

The density of a substance is its mass per unit volume defined by the equation: $p = m/v$, where p is the density, m is the mass and v is the volume. To simplify comparisons of density within an industry such as spirits

production using different systems of units across the world, it has been replaced by the dimensionless quantity of 'relative density' or 'specific gravity'.

The gravity of a liquid, in the context of mashing and fermentation within the spirits industry, refers to the relative density or specific gravity compared with water. The specific gravity is the ratio of the density of a sample of process liquid to the density of water both measured at the same pressure and temperature. For the spirits industry this is generally at atmospheric pressure and 20 °C.

The density of wort is almost totally due to its sugar content. During alcohol

fermentation the action of yeast on sugars converts them into ethyl alcohol and other low concentration flavour compound or congeners. This decline in sugar content and the increasing concentration of ethyl alcohol results in a drop in density. Ethyl alcohol is significantly less dense than water.

The Original Gravity of a wort (OG) is the specific gravity before fermentation. This can range from 1040-1080 in the spirits industry and can also be referred to as Declared Gravity.

The Final Gravity (FG) is the specific gravity measured at the end of the fermentation process. In general this can range from 1005 to 996 – i.e. 5 over or 4 under water, dependent on fermentation efficiency and the Original Gravity of the wort.

Regular measurement of the OG of wort can indicate the efficiency and consistency of mashing while regular measurement of FG gives an indication of fermentation efficiency.

Measurement of specific gravity at regular intervals throughout the course of a fermentation can give an excellent indication of yeast performance and general fermentation efficiency and shows that fermentation is complete when the gravity stops falling.

Key inputs

Having now given an overview of some of the key terminologies used in mashing and fermentation we can now look at the general principles of yeast and fermentation. There are two key inputs to the fermentation process – fresh

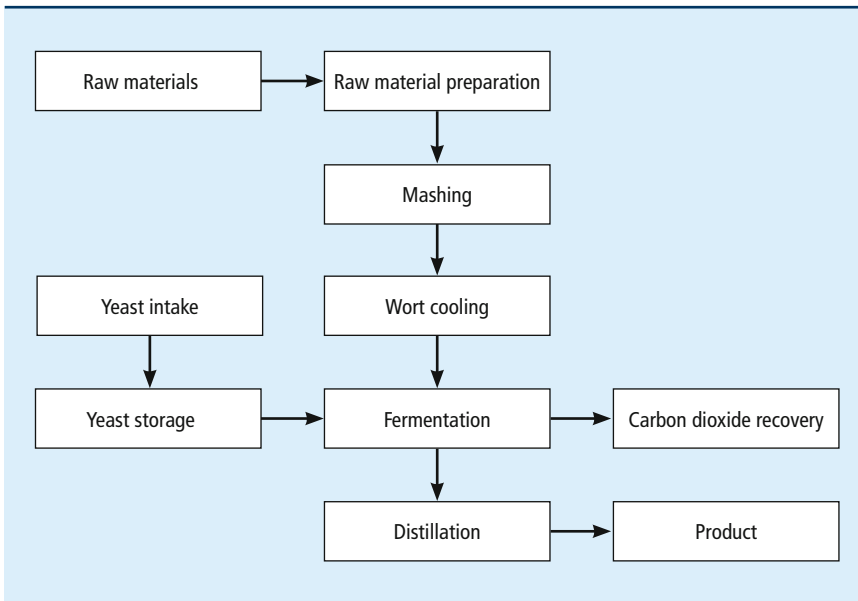
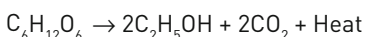


Figure 1. Fermentation within the process steps employed in spirits distilling

cooled wort from the mashing process which provides the fermentable extract – and yeast which is the driving force in the conversion of this sugar solution into ethyl alcohol. The provision of ‘clear’ or ‘solids in’ wort will be dependent on the form of mashing employed upstream. The wort temperature leaving the mashing process will be too high for yeast to perform so some form of wort cooling will be employed after the mashing process to provide wort at a temperature consistent with the type of fermentation process employed. This will be explored in greater detail later.

Yeast will be added at the early stage of the fermenter or washback filling sequence and thereafter fermentation will proceed until all the available carbohydrate has been converted into ethyl alcohol. The stoichiometric equation showing the reaction of yeast on glucose to produce ethyl alcohol is:



Hence one molecule of glucose is converted to two molecules of ethyl alcohol, two molecules of carbon dioxide with the subsequent generation of heat. This exothermic reaction is an important feature of the fermentation process and must be controlled to ensure the maximum temperature does not exceed 35°C as yeast is then killed off. Figure 2 gives a simple schematic of a typical fermentation.

The X axis is the timeline from start to end of fermentation while the dual attributes on the Y axis of gravity and % vol (concentration of ethyl alcohol) of the fermenting wash are given.

This simple graphic shows the drop in gravity during fermentation with an almost mirror like increase in the ethyl alcohol concentration of the fermenting wash. The three phases of this typical fermentation will be discussed later. Three other analytes which can be easily measured at regular intervals during the fermentation process are pH, acidity and temperature. Modern fermentation process generally allows for automatic logging of temperature during fermentation. The significance of these will be also discussed later.

In the previous feature on mashing I explained the importance of mashing efficiency and its impact on the efficiency of the downstream fermentation and distillation processes. The fermentation process is equally important to the spirits producer – the key aim is to maximise the conversion of sugars produced during mashing to ethyl alcohol during fermentation. Wort produced in both malt and grain spirits mashing processes will have some residual amylase enzymatic activity; this is unlike the brewing process where the wort is boiled to ensure sterility prior to fermentation, so denaturing (inactivating) these enzymes. These enzymes will remain active in spirits production and continue to hydrolyse any residual larger carbohydrate molecules in the wort or fermenting wash into fermentable smaller sugars for yeast metabolism – resulting in significantly lower final gravities and higher alcohol yields when compared with brewery fermentations. This secondary conversion is said to represent anywhere between 10 – 20% of total conversion activity.

Grain and malt whisky producers



in Scotland are regulated by the Scotch Whisky Order which only permits the use of process aids in all the production processes. This is not applicable either in the Grain Neutral Spirit (GNS) or fuel alcohol businesses where addition of non-process aid chemistry and technology can be applied to stimulate yeast performance and fermentation efficiency.

Yeast

Yeast is a single-celled living micro-organism whose individual units are visible only when viewed through the microscope. They are found readily in all types of environment throughout the world.

The diagram below shows the basic structure of a typical yeast cell. As indicated above these features are only visible through a microscope at 100 x magnification.

The action of yeast in both the brewing and baking industries has been established by archaeologists, which show its use some 4,000 years ago and it is often regarded as the oldest cultivated micro-organism. In 1857 the French microbiologist Louis Pasteur proved that alcoholic fermentation

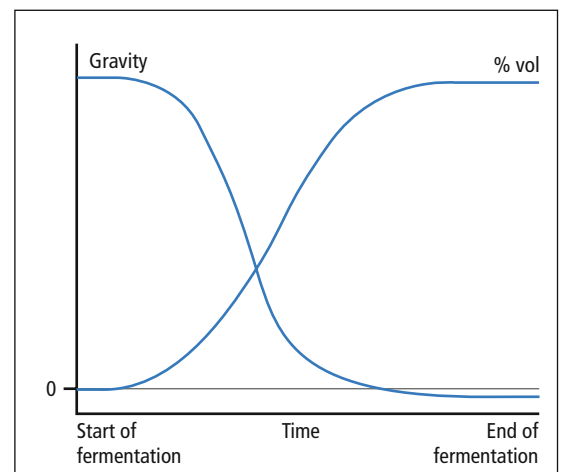
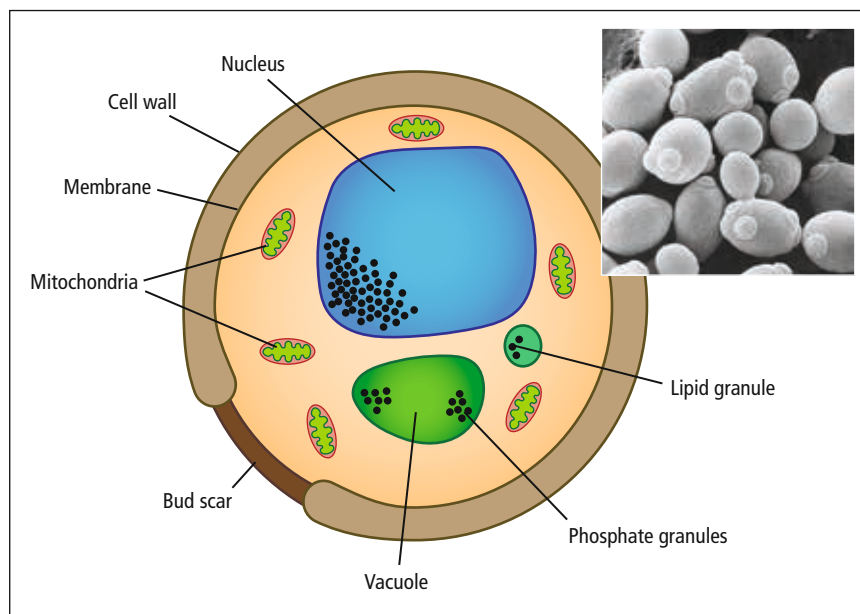


Figure 2: A typical fermentation profile



Yeast cells *Saccharomyces cerevisiae*

was conducted by living yeasts and not by any chemical catalyst.

Historically the selection of yeast for the spirits industry in Scotland was not seen as a high priority – most of the yeast came from locally-sourced brewing yeast. As with most processes in the spirits industry this has changed quite dramatically over the years and now a pure culture distilling yeast is the preferred choice. The brewers' yeast was not a single yeast but was likely to be a mixture of many different types and strains. With the development of the distilling yeast, all the yeast originates from a single cell and is defined as pure culture yeast. Pure distilling culture yeasts are now readily available from a number of commercial suppliers. Commercial yeast suppliers have huge collections of yeast strains which are stored under controlled conditions to maintain stability and which are uncontaminated with any other micro-organisms.

There is a worldwide convention for the naming of species of living things. As already mentioned yeast is a living organism and the one which is most suited to the distilling industry is *Saccharomyces cerevisiae*. There are many different strains and species – and their performance in the fermentation process may vary quite markedly from strain to strain.

In the commercial production of yeast, a single suitable yeast cell is isolated with the aid of a microscope and allowed to multiply under conditions of continuous aeration in a suitable growth medium containing the requisite food and energy. By transferring to larger and even larger quantities of food- and energy-ripe media, a large bulk of yeast

can be manufactured. This can then be transferred into huge fermenters of the requisite media where full-scale production is achieved; all this activity is undertaken under sterile conditions to avoid contamination from competing bacteria. Some of the key elements for successful production of yeast include a sterile supply of air [oxygen], suitable growth medium containing sugar, nitrogen, phosphate and various minerals and vitamins. It is important to note that this production of yeast bio-mass takes place under aerobic (in the presence of oxygen) conditions unlike the anaerobic conditions of the distillers' fermentation where the action of yeast on sugars produces ethyl alcohol, carbon dioxide, heat and numerous other flavour compounds.

Once the requisite mass of yeast has been grown it will be harvested and can then be supplied as dried yeast, compressed yeast or yeast cream – all of these different yeast supplies will be purchased on an agreed specification – this would likely include total solids, viability (95 %) and bacteria and wild yeasts ($< 1 \times 10^4$ total per gram). Dried yeast will have dry matter of ~ 95 % wt/wt, compressed yeast will have a dry matter ~ 25 % wt/wt while cream yeast will have a dry matter of ~18 % wt/wt.

The stability of these yeasts is directly proportional to the higher dry matter content. Dried yeast can be stored and used within twelve months; compressed yeast has shelf life of around two weeks if stored in a temperature-controlled cold store while yeast cream must be used within a seven days of receipt in temperature-controlled bulk storage tanks.

A sensitive organism

Commercial yeast supplied to the spirits industry will have been selected on a variety of different factors including :-

- The desired rate of fermentation
- The Original Gravity and maximum ethanol concentration of the wash
- Consistency of performance
- Plant capability and yeast process conditions.
- Whether any particular flavour compounds are required to be delivered during fermentation
- Reliability of performance throughout the supply chain

It is hopefully evident that yeast is a fairly sensitive organism and must be purchased, stored and used within specific timeframes to deliver optimum fermentation efficiency. Unfortunately it also has characteristics which make it sensitive to temperature tolerance, Osmotic pressure within the fermenter and the effect of pH within the fermentation process itself.

The key to successful and efficient fermentation will be determined by how the distiller maintains process conditions which are geared to support the strain of yeast selected. It should be noted that yeast used in distillers' fermentations is only ever used in one fermentation cycle – unlike the brewing industry where yeast is harvested and reused in many subsequent fermentations.

The selection criteria for yeast as laid out in this article will be relevant whether used in potable spirits, grain neutral alcohol or fuel alcohol production.

In Scotland only, the Scotch Whisky Regulations prohibit any chemical or bio-chemical treatments within the fermentation process while these restrictions are not in place within the GNS or fuel alcohol industries – these



Yeast storage tank at the John Fergus & Co.'s new InchDairnie Distillery in Scotland

technologies can be applied to support and drive fermentation efficiency within these non-regulated (or indeed, non-Scottish) industries.

There are spirits industries around the world which have the capability of growing their own yeasts from single cells – this reduces the input costs of this expensive raw material but has an initial costly capital input. Other distillers may employ a yeast optimisation process where fresh commercial yeast is allowed to grow on wort produced on site prior to seeding into subsequent fermenters – this can again significantly reduce input costs. The same principles apply to each and all of these different processes where provision of suitable substrate for efficient yeast propagation, plant and air sterility and temperature control are essential prerequisites for delivery of process efficiency.

Fermentation

The Concise Oxford Dictionary describes fermentation as: *the chemical breakdown of a substance by bacteria, yeasts or other micro-organisms, typically involving effervescence and the giving off of heat.*

It is also variously described as 'a metabolic process that converts sugars to acids, gases or alcohol' or 'a large scale microbial process occurring with or without air'. In this particular scenario 'fermentation' will be considered as the action of yeast on a sugar solution (wort) produced from cereal grains to produce ethyl alcohol, carbon dioxide and heat under primarily anaerobic conditions.

There is no need to here discuss the metabolic pathways followed during fermentation to produce ethyl alcohol and many low concentration congeners; this theory is well established and has been discussed in detail by many authors. I intend to focus on the plant and practical elements of fermentation within the spirits industry and the potential safety and health implications of the process.

Like most of the processes within the spirits industry there is no one design or scale of plant and processes employed, but the defining theory and principles apply to all of them.

Before discussing the fermentation process itself it is worth revisiting where this sits in the overall spirits production process (Figure 3).

Within the spirits industry (potable alcohol and fuel alcohol) there is a huge variation in the scale of the fer-

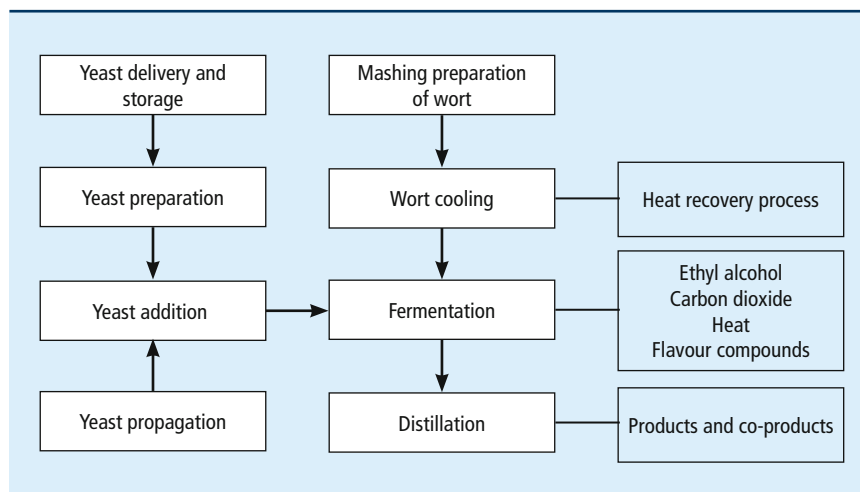


Figure 3: Fermentation within the spirits production process

mentation processes where the small malt distillers may only ferment from as little as 10 tonnes of wort to the huge scale of the fuel alcohol industry where it could ferment hundreds of tonnes of material per fermenter and many other scales of operation between these two extremes.

Some of the key elements of fermentation design may include some if not all of the following: method and materials of construction, pipe-work and valve configurations, capacity including agreed vacuity (or spare capacity), sterilisation processes, wort filling procedures, fermented wash removal procedures, provision of steam and air, anti-vacuum facilities, stirrers, switchers, anti-foam addition, carbon dioxide removal or recovery, internal or external location, yeast addition procedures, temperature control process (jackets or external coolers), and general isolation and potential maintenance operations.

Key to the design and build phase would be to ensure there are no dead legs in pipework or valve arrangements and to ensure complete removal of all wastes after fermentation.

I use the term process deliberately because there are several types of fermentation process – they can be variously described as the batch process where a defined mass is fermented in a single fermenter for a specific time, continuous fermentation where fermenting wash is fed forward into a number of fermentation vessels over time and a combination of batch and continuous fermentation. In general batch fermentation is the preferred methodology within the potable spirits industry as it avoids the potential catastrophic impact of contamination within the continuous process with potential impact on yield and quality of final product.

Various shapes and sizes

The actual fermenter design, build and location also does not follow one standard pattern. Wood-constructed larch or pine, stainless steel or the older weathering (COR-TEN) steel fermenters each of various shapes and sizes – together with concrete vessels can all be found within the spirits industry.

Fermenters can be installed internally within a process building or externally situated with full exposure to all of the vagaries of the localised weather patterns. These effects must be considered when establishing design fermentation temperature profiles.

The more modern stainless-steel fermenters can also be fitted with temperature controlled cooling jackets or temperature control for all builds can be facilitated by the use of external heat-exchangers. Some producers favour no temperature control of the fermenter and allow adiabatic fermentation to proceed efficiently by ensuring that declaration temperatures and original gravities are such that a maximum tem-



New Douglas fir fermenters at Diageo's Teaninich distillery, Scotland



Stainless-steel fermenters at the Chivas Bros. Dalmunach distillery

perature of 35°C is not exceeded. Other distillers control fermentation temperature by the use of cooling jackets or external coolers while others employ a combination of adiabatic and temperature controlled conditions.

These fermentation processes can be controlled totally manually, totally automatically or a combination of manual and automatic. Wort can be added to the fermenter through a top or bottom filling process and yeast addition can either be manually or automated. Some distillers prefer the ability to top fill their fermenters as this gives added aeration of the yeast enriched wort at the start of fermentation although it does add the additional costs of filling and emptying pipe work and valve arrangements.

Filling and emptying from the same pipe work and valve arrangements on the base of the fermenter reduces the capital outlay on plant and also reduces the amount of kit that needs flushed and sterilised. The spirits industry has historically aligned

itself with the top filling process.

The fermentation process sits between mashing and distillation in spirits production and takes considerably longer than both these upstream and downstream processes and to this end fermentation times can be anywhere between ~forty hours and well in excess of one hundred hours. This requires a significant fermentation footprint both in the batch and continuous mode to ensure there is a continuous availability of fermentation capacity to accept wort from the mashing process while at the same time providing a continuous supply of fermented wash for distillation. In any distillery you will find the fermentation footprint is the biggest process area – with between six and thirty fermenters of all shapes and capacities being available depending on the output of the distillery.

The action of yeast

Wort produced in 100% malted barley, the grain distillery, the grain neutral alcohol or fuel alcohol industries is a complex matrix including fermentable carbohydrate, dextrin, proteins, fatty acids, solids and minerals from the processed cereals. These are all essential for efficient ethyl alcohol and other congener production and yeast performance.

The action of yeast when added to wort can be divided into several phases – I will highlight the main three:

- The 'lag' phase – this is seen during the early hours of the fermentation process when there is very little production of alcohol as the yeast is adapting itself and growing in its new surroundings. The yeast will have

been added during the early transfer of fresh wort to the clean fermenter and may also have been aerated at this time. This early stage of fermentation is when any contaminating bacteria may cause significant damage with resultant efficiency and quality problems later in the process.

- The 'log' phase – this is the period of rapid fermentation and yeast growth when fermentation is at its most vigorous – with a corresponding rapid increase in the release of heat and rise in temperature of the fermenter if no cooling is employed. This is also the time of vigorous production of carbon dioxide. Within the malt distilling process this is when switchers or anti-foam may be used to avoid excessive frothing and foaming – this is generally not an issue for fermentations with high cereal solids concentrations.

- The 'decline' phase – this is the last few hours of fermentation when the yeast activity is falling off, fermentation slows down and eventually stops. This is a time when bacterial growth can be rapid as pH and temperature are ideal for such growth. It is essential the fermented wash is removed to distillation without any undue delay thus avoiding any unnecessary contamination. Balanced and well thought through production planning is key to achieving this.

There are several key steps in the process which must be routinely achieved to ensure the spirits producer delivers the goal of producing the volume and quality of alcohol in the most efficient manner, safely – and on time. These will include the declared gravity of the wort, the declared (setting) temperature of the fermenter and/or associated cooling processes, the use of the correct yeast, the use of the correct quantity of yeast, safe and clean yeast handling, storage, preparation and addition of the yeast, the cleanliness of all the associated plant pipe work and valve arrangements, the fermentation time and the removal or recovery of the carbon dioxide evolved during fermentation.

Carbon dioxide is an inert gas, it is heavier than air and will tend to fall into enclosed areas if not collected or vented efficiently and can cause death even after very short exposure times. Small spirits producers tend to vent the evolved gas to the atmosphere during fermentation while some of the larger producers will recover this evolved gas in a very capital-intensive scrubbing, compressing and liquefaction process. Others may only scrub



Active fermentation in a Kentucky bourbon distillery

the gas prior to venting either through its own or some other chimney in the process. Carbon dioxide evolved during fermentation does contain small concentrations of ethyl alcohol, which when water scrubbed and concentrated can be added back into the process stream just prior to distillation.

There are several important process analyses which, if followed during the course of fermentation, can give a real time overview of the efficiency of this process.. These will include:

- The gravity of the wash
- The alcoholic strength (% vol) of the wash
- The pH of the wash
- The acidity of the wash
- The temperature of the wash
- Total yeast counts
- Total yeast viability

The gravity, strength and temperature should follow a standard pattern if all the previous process control conditions are met – and should be readily repeatable for each fermenter. A rapid drop in pH below ~ 4.0 with corresponding rise in acidity can indicate bacterial contamination caused by poor cleaning, poor yeast efficiency and general dirty plant. The yeast counts give an indication of yeast health. Using all of these parameters and other process control data will allow you to establish the general health and cleanliness of your plant.

As has been explained throughout the article the action of yeast on wort is a living process and generally takes place at a temperature range anywhere between ~18°-34°C. At temperatures greater than 35°C the yeast is killed off and fermentation efficiency is adversely affected. Many other competing organisms and bacteria also flourish in this temperature range and it is essential that plant, process pipe work and valve arrangements are thoroughly cleaned and sterilised to avoid the proliferation of these competing effects. These cleaning processes can include water flushing, use of weak hypochlorite solution, use of live steam and hot and cold caustic solutions – again these can be manual processes or fully automatically delivered through cleaning in place (CIP) processes.

Inherent dangers

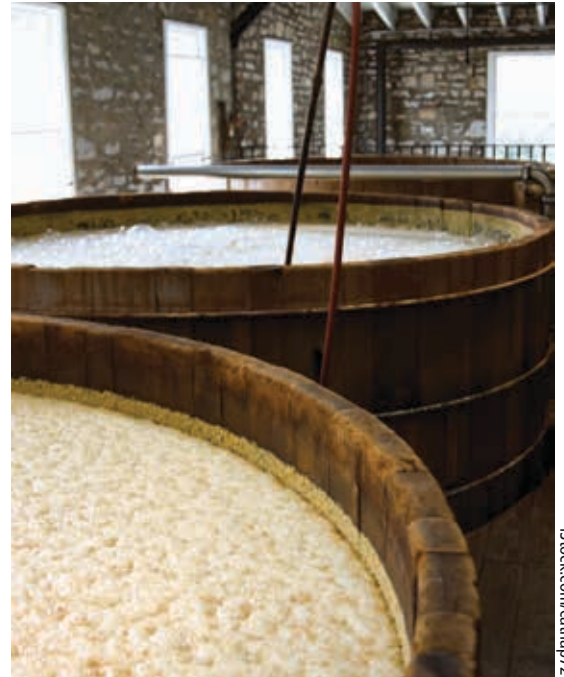
As with much of the other plant installed throughout the spirits production process there is an absolute requirement to deliver safe systems of work – this can be aided by the delivery

of a well thought through and actioned planned maintenance system with isolation procedures and work instructions all fully risk assessed. Fermentation vessels are inherently dangerous pieces of plant, due to the potential of residual carbon dioxide, live steam sterilisation systems and general complex valve, stirrer and pipe work systems. Entry into these dangerous confined spaces should be avoided at all costs and should only ever be considered after very careful assessment of all the risks involved and relevant control measures actioned including air purging and regular gas testing of the vessel (s) involved.

It is the intention of every distiller to produce a quality product with optimum efficiency and costs – a thorough knowledge and deep understanding of the plant and processes is required – even accepting all of the above things can and invariable do go wrong. Here are some examples:-

- Failure of some kind in the mashing process to produce the optimum wort – this could be the result of poor process control or input of poor quality raw materials resulting in poor fermentation efficiency and loss of yield.
- Overfilling of fermenter with wort thus compromising the available headspace resulting in overflow of materials, a potential environmental issues and certainly loss of overall efficiency.
- The use of the incorrect amount or type of yeast. Incorrect quantity could lead to loss of yield through poor and slow fermentation while wrong type could lead to wrong quality of product.
- Failure to adequately keep all your plant clean – could increase the potential for infection with subsequent quality and efficiency issues.
- Excessive fermentation temperature due to failure of wort or fermenter cooling or general ambient conditions could lead to poor yeast performance and incomplete fermentation with resultant loss of yield
- Early removal of fermenting wash to distillation prior to the actual completion of fermentation could result in distillation issues and again loss of yield.

Further reading on yeast and fermentation can be found in the second edition of *Whisky, Technology, Production and Marketing*, edited by Inge Russell and Graham Stewart – this is a book that should feature on the bookshelf of any serious student of the spirits industry. There is also excellent background information contained in the Learning Material and Syllabus for the



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General Certificate in Distilling.

There is no one size or design of plant fits all producer's requirements – here are some follow-up pointers to help embed your learning around your yeast and fermentation processes :-

- Talk with your procurement or quality people to get a detailed knowledge of your own yeast specification. Where is your yeast manufactured, how is it delivered, stored and processed?
- What is your standard yeast seed rate – what are any follow-up procedures if you fail to add the correct quantity of yeast – can you recover this process failure?
- Fully understand the capacities and capabilities of all the plant associated with yeast and fermentation.
- How are the risks associated with carbon dioxide release managed – both controlled and uncontrolled releases.
- What conditions deliver an optimum fermentation in your operation – temperature, time, sterilisation, analytical measurements etc.
- How do you recover if you encounter any or all of 'the things that go wrong in fermentation'. What are your recovery options?
- How is your overall production plan influenced by the fermentation capacity of your plant. Do you have any bottlenecks?

Answering these questions and posing a few more of your own will ensure you will have a more detailed understanding of how and where yeast and fermentation fit in your overall production processes. I wish you well in your endeavours.