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Celebrating 150 years of ammonia compression

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Why you should attend

1. Find out about the history of the early development of ammonia refrigeration.
2. Understand the contribution of some early pioneers of ammonia refrigeration during the 1800s– including David Boyle.
3. Celebrate over 123 years of the Institute of Refrigeration and 150th anniversary of the world's first ammonia refrigeration system using vapour compression.

Introduction

Mechanical refrigeration using a vapour compression cycle was first demonstrated in London in 1834 and was very slow to develop into a viable commercial proposition but by the mid 1870s it started to take off. Over that initial period ammonia was suggested as a possible refrigerant several times but was not successfully demonstrated until the 1870s. It is reasonable to suggest that the successful adaptation of vapour compressors to the use of ammonia as the working fluid is linked to the commercial success of vapour compression as the preferred method of achieving mechanical refrigeration. There are several versions of the way in which ammonia was brought into the family of refrigerant working fluids. This paper aims to dig into the stories behind the superficial understanding of this development and give credit to some pioneers who may be less familiar to the modern audience.

Refrigerant expert Jim Calm has noted (Calm, 2012) that the history of refrigeration can be divided into four epochs and he characterises the first, from 1830 to 1930 as "whatever worked", meaning that the working fluids used in these systems were not developed for that purpose but were already available and could be readily applied to the refrigeration cycle. This rather underplays the significant technical developments that were required to make refrigeration systems safe, efficient and reliable. It might be more honest to describe most of the early developments as "whatever didn't work". Often progress was delayed because the mechanical difficulties of adapting existing available equipment to work in a refrigeration cycle. This appears to have been the case with ammonia, which was identified by William Cullen as the most favourable fluid for this purpose as early as 1755 and was listed as a possible refrigerant by many people. In his 400-page treatise "*Ammoniaque dans L'Industrie*", Charles Tellier wrote *"Les différentes applications industrielles de l'ammoniaque, dont j'ai signalé la possibilité, ont assez vivement excité l'attention. De divers côtes, des demandes de renseignements m'ont été adressées. C'est pour répondre à la plupart d'entre elles, satisfaire l'empressement qui a accueille mes vues, que je publie cet ouvrage."* [The different industrial applications of ammonia, the possibility of which I have pointed out, have excited much attention. Enquiries have been made to me from various quarters. It is to answer most of them, to satisfy the eagerness which welcomed my views, that I publish this work.] (Tellier, 1867)

At the conclusion of the book he wrote *"Ai-je énoncé toutes les applications qu'il est possible de faire de ce corps? Non, assurément! Quelles qui soient les recherches tentées en vue d'applications nouvelles, j'applaudirai à leur succès, comme aussi toutes mes sympathies seront pour les travaux, qui, en vulgarisant ce corps à tant d'égards intéressant, favoriseront son entrée dans la pratique industrielle."* [Have I stated all the applications that it is possible to make with this substance? Definitely not! Whatever will be attempted by researchers with a view to new applications, I will applaud their success, just as all my sympathies will be for their work which, by popularising this substance in so many interesting respects, will encourage its adoption in industrial practice.] He patented the use of ammonia for refrigeration in 1870 but there is no indication, despite his support for ammonia in industry in many diverse applications, that he commercialised the ammonia vapour compression system at that time.

A frequently repeated myth about ammonia refrigeration is that it was the brainchild of the German scientist Carl von Linde who built a machine in 1876 for a Trieste brewery and kick-started a successful industrial gases and engineering company which is still active, with sales of over $30 billion in 2021.

Linde was certainly an early adopter of ammonia but his first attempts at mechanical refrigeration, beginning in 1873 and following Charles Tellier's lead, were with dimethyl ether as the working fluid. Mikael Hård notes in his biography of Linde, "Machines are Frozen Spirit" (Hård, 1994), that he only switched to ammonia as a safer alternative when his prototype ether system exploded and completely demolished his laboratory. Linde's great contribution was, as Hård observes, that he was an unusual combination of scientist, engineer and businessman. He was able to address the academic challenges of the new science with sufficient technical skill to turn theory to practice and with the commercial acumen to make it a profitable venture.

Some other sources, for example Woolrich (1965), Thévenot (1977) and Lindborg (2007), cite the Scottish emigrant, David Boyle, as the first to patent an ammonia compressor for refrigeration, giving his US patent number 128,448 of 1872. However patent 128,448, "Improvement in Ice-Machines", although it contains several novel features, does not specify which refrigerant is to be used in the system. To assess the relative merits of these competing claims it is helpful to understand something of the contenders' life stories and to measure their achievements according to the statements made about them by their contemporaries and in their own words.

David Boyle

Boyle, Figure 1, was born in Johnstone, Scotland on October 31, 1837, the third of six children of David and Agness. The 1841 census lists four children (John, Mary, David and James) living with David, a grocer and his wife at an address on High Street, Johnstone. Ten years later two more children (Robert and Agnes) have been added to the family but the head of the household is described as a widower. Mary, by then aged 17, is listed as the housekeeper and the eldest son, John, is no longer resident with the family.

Figure 1 – David Boyle, 1837 - 1891

Fowler's Directory for Paisley and Johnstone in 1851 describes David Boyle senior as *"Grocer, Spirit Dealer and Cork Cutter"* with premises at 71 High Street, Figure 2. A John Boyle is listed in the 1851 directory as *"Butter and egg merchant"* in premises at 22 High Street.

Figure 2 - High Street, Johnstone, home of the Boyle family, as it was at the end of the 19th Century

The town of Johnstone, in the district of Renfrew, is unusual among Scottish towns because it was a planned community, created in the late 18th century to supply housing for workers in an industry that had not yet been established. It therefore has quite an American layout, with a main street (High Street) leading through a town square and with a grid pattern of side streets as shown in the early map from the 1850s in Figure 3. The population grew from 10 people in 1780 to 1,434 in 1792 and by 1811 it was 3,647. This planned growth was the work of George Houston, the 4th laird of Johnstone, who intended to develop cotton mills on the banks of the Black Cart river, which runs to the north-west of the town. Two mills were constructed in the early 1780s close to the Brig O' Johnstone using overshot waterwheels and the newly constructed town provided homes for many of the mill workers.

Figure 3 – Map of Johnstone 1782 and Ordnance Survey map, surveyed in 1857, 25 inch to the mile

The world's first machine tool factory, Craig and Donald, was opened in Johnstone in 1815, Figure 4, and the town was rapidly becoming known as a centre of excellence for machine tools, particularly related to millwork and shipbuilding. By 1837 when David Boyle was born, there were 11 mills in Johnstone, all powered by the Black Cart, producing mainly cotton and thread but also paper, leather goods and other fabrics (Scott, 1951).

Figure 4 – Memorial to Craig and Donald in William Street, Johnstone and a 1966 picture of the site

At the age of 15 Boyle was apprenticed as a grocer together with his brother, James, who was one year younger. It is suggested that they would both have preferred to train as mechanics but their father overruled them and so they followed in his trade. In 1859, when David was 22, he left Scotland, possibly with James, and emigrated to Mobile, Alabama, a port on the Gulf of Mexico. He set up business, hoping in time to earn enough to establish his own grocery store. At that time Mobile had a population of about 32,000 and was one of the main ports serving the south. The Civil War, which started in 1861, ravaged the southern states over the next four years and brought mixed fortunes for the Boyle family. Towards the end of the war, David had moved to Demopolis, a small town about 150 miles north of Mobile, and found that he could earn good money using imported natural ice to make lemonade. However the high cost of transporting ice from the north and uncertainty over the supply persuaded him that there would be a high demand for manufactured ice if an economic and reliable means of production could be found. This started a ten year mission to find an improved ice machine and took him and his family from Demopolis to New Orleans, then to San Francisco, then back to New Orleans, then to Jefferson, Texas (a town of about 4,000 people 150 miles east of Dallas, near the Louisiana border) and finally to Marshall, Texas (population about 2,000, 15 miles south of Jefferson). In New Orleans he learned about absorption ammonia machines but concluded that they were too expensive to build and too expensive to operate, so travelled to San Francisco seeking more information. There he ordered a Siebe machine from London, based on Harrison's ether machine and quite popular in England, but after waiting a year for it to be shipped he sued to get his money back. During his time in San Francisco he worked on better ways of making ice, resulting in his famous patent (Boyle, 1872) but his funds ran out, so the family moved back to New Orleans in November 1872 where he attempted unsuccessfully to licence the technology of his improved ice machine. In June the following year the Boyles relocated to Jefferson, with David perhaps anticipating the opportunity to build his own machine with the prospect of higher sales of ice there and he tried to get the machine to work reliably. By this stage, according to his own account of his developments (Rushton, 1896), he was working with his brother James who went on to patent an ice machine compressor in 1876 (Boyle, 1876). The work in Jefferson was painfully slow and difficult – the machine when constructed and charged with ammonia leaked "like a sieve" (Nickerson, 1891) and the summer passed without any sales of ice. They moved the prototype to Marshall, at that time a smaller town than Jefferson, but growing rapidly due to cotton trading. The ice machine finally ran reliably in April 1874 and sales picked up over the summer. In August that year a fire destroyed the ice plant and Boyle travelled to Quincy, Illinois, a city of about 25,000 people on the Missouri border, strategically located on the Mississippi river and the railroad, with the new Quincy Rail Bridge over the river providing valuable links to Chicago in the east and Kansas City in the west. Two ice plants were constructed there, funded by local businessman William Bushnell for installation in Texas. Boyle relocated temporarily to

Washington DC in October and November, returning to Quincy in the spring of 1875 before finally moving to Chicago in August 1875, where he set up in business as The Boyle Ice Machine Company. The Boyle Company and the Boyle family had finally found a home.

In the next few years, the Boyle Ice company grew steadily and by the end of the decade they had installed 7 ice machines in Texas, one in Atlanta and one in Adelaide, South Australia. They had also developed a water chiller for brewery applications, with a trial unit installed in a brewery in Chicago in July 1878.

Figure 5 - the offices at 10 N Jefferson St, Chicago of the Boyle Ice Machine Company

Boyle's security in Chicago was founded on the basis of having persuaded the Crane Brothers Company to act as his manufacturing base, so the Boyle Ice Machine Company and the Crane sales office shared the address at 10 N Jefferson St (now 156 N Jefferson St). Jacob Skinkle, Treasurer of Crane Bros, also acted as President of the Boyle Ice Machine Company, with William Bushnell as the company secretary. The original Crane Brothers office building is still intact (Figure 5), although the factory behind it has been replaced with apartments.

David Boyle's patent 128,448, titled *"Improvement in Ice Machines"*, which is often cited as the invention of the ammonia compressor, was filed while he was a resident of San Francisco and was granted on June 25th 1872. It is remarkable because it doesn't mention ammonia and is not concerned with the compressor used, although it does relate to ice machines, "particularly to that class in which the vaporization of a volatile fluid is used for producing the required degree of cold". Of course this does not mean that he wasn't contemplating the use of ammonia, or even already using ammonia, at that time although circumstantial evidence suggests that he didn't start those tests until he was back in Texas. The key elements that form the claims of patent 128,448 relate to the evaporator, which was configured to make plates of ice using direct expansion refrigerant fed through a combined expansion valve and distributor. The system included a method of reverse cycle defrost to release the ice plates and a glass level gauge on the outlet of the condenser to enable the manual expansion valve to be set accurately. The compressor is barely mentioned in the text and is only referred to as an *"exhaust and force pump"*. Note that the "exhaust" is what we would now call the suction of the compressor.

Boyle's other three patents were all also titled *"Improvement in Ice Machines"* and were granted consecutively on 11 May, 1875 although they were filed from various places at different times over the preceding six months. Patent number 163,142 describes a method of agitating the water to be frozen and the refrigerant to ensure clear ice is formed quickly and evenly (Boyle, 1875). It was filed from Washington DC in November 1874. Usually the two witnesses required are unknown names, presumably clerks in a legal office, but the witnesses to this invention were Boyle's financial backer and Company Secretary William Bushnell and an engineer called Thomas Rankin who went on to design many significant refrigeration systems over the following two decades, including the Ice Railway exhibit at the Chicago World's Fair in 1893 which showcased the De La Vergne compressor technology.

The other two patents granted on 11 May were 163,143 on further developments of the freezing plates, distributor and defrost mechanism and 163,144, which describes a single evaporator plate in more detail. The witnesses for these two patents were not recognised players in the ice making industry.

James Boyle

Much less has been written about James, David's younger brother, except that he is the one who patented the compressor (Boyle, 1876). This was filed on November 24, 1875 and notes James as resident of Houston, Texas. It was granted on March 21, 1876, almost a year after David's three patents on Improvements in Ice Machines and nearly four years after the original San Francisco patent, number 128,448. James' patent, number 175,020 is titled *"Improvements in gas-liquefying pumps"* and also doesn't mention ammonia although it is suggested by various sources writing around the time of David's death that James patented the design developed by the brothers for their successful ammonia system as constructed in Jefferson and operated in Marshall (Rushton, 1896 and Nickerson, 1891). Victor Becker provides some further detail in a series of articles written for Ice and Refrigeration in 1909. He mentions several visits to Houston to inspect *"the first single-acting ammonia compressor I had heard of"* which he describes as *"a crude piece of mechanism"* but admits that it *"contained pregnant germs and it really proved to be an epoch maker, for from this primary beginning grew the remarkably successful career of the Boyle Ice Machine Co."* Becker notes that "*the inventor's brother David achieved considerable distinction and profit with it after the early death of James."*(Becker, 1909b). James Boyle made a contract with Thomas Rankin to get his patent application funded and the papers were duly submitted on November 24, 1875. However James immediately suffered a short illness and died just five days later on 29 November. Rankin continued to fund the patent in accordance with his commitment and it was duly granted in March 1876. The valuable innovation in patent 175,020 was the design of the spring loaded poppet valves for the inlet and discharge. It seems that Thomas Rankin believed he had the rights to this valve design and developed compressors with the De la Vergne Company in the 1880s, but David Boyle, who had used the design in his original ice machine back in 1873, continued with this technique in his machines from 1876 onwards. The Boyle Ice Machine Company merged with the Empire Refrigerating Company of St Louis in 1884 to form the Consolidated Ice Machine Company and when they were declared bankrupt in 1890 a dispute flared between the De La Vergne Machine Company and John Featherstone's Sons who had purchased the rights to the Consolidated Ice Machine Company's range of products. This case fizzed for the next two years, ultimately reaching the US Supreme Court, and only petered out when the patent expired on 21 March 1893.

The *"crude piece of mechanism"* is shown in Figure 6. The cylinder is mounted vertically and the valves of the compression chamber are on the base with the suction gas flowing into the upper part of the compressor before passing to the compression chamber. The connecting rod protrudes from the top of the assembly unlike most subsequent designs, which were either driven from below or mounted horizontally.

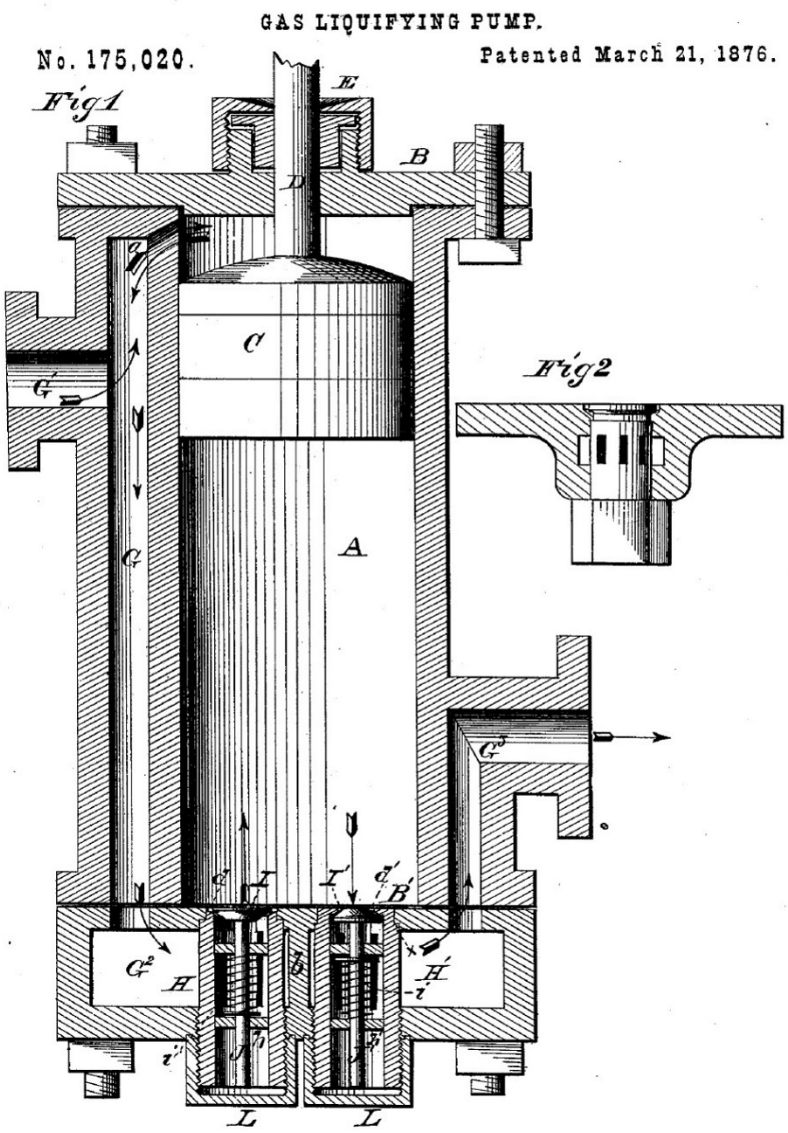

Figure 6 – James Boyle's compressor

The reason for the unusual suction gallery arrangement is unclear. It may have been to provide some cooling to the stuffing box on the connecting rod or to maintain it at low pressure to minimise leakage, which had been the major challenge that the Boyles had to overcome in 1872. It would have raised the temperature of the suction gas and hence reduced the effective mass flow of the compressor by reducing the suction gas density. This would not have mattered much initially, when there was no previous machine for comparison, but would have become a disadvantage as improved machines with better performance came to market. David Boyle apparently used this design for his first installation but once he was established with the Crane Brothers Company he did not persevere with it and the Boyle Ice Machine catalogue of 1879 drew the reader's attention to their *"improved apparatus for the manufacture of ice"* with an engraved plate as shown in Figure 7. This appears to show in the foreground on the left a steam engine fed with steam from the boiler at the back of the room and with an ammonia single acting, single cylinder compressor behind the steam engine. The belt and pulley arrangement drives the small condenser water pump at the back of the room and the ice is made in rectangular blocks on the right.

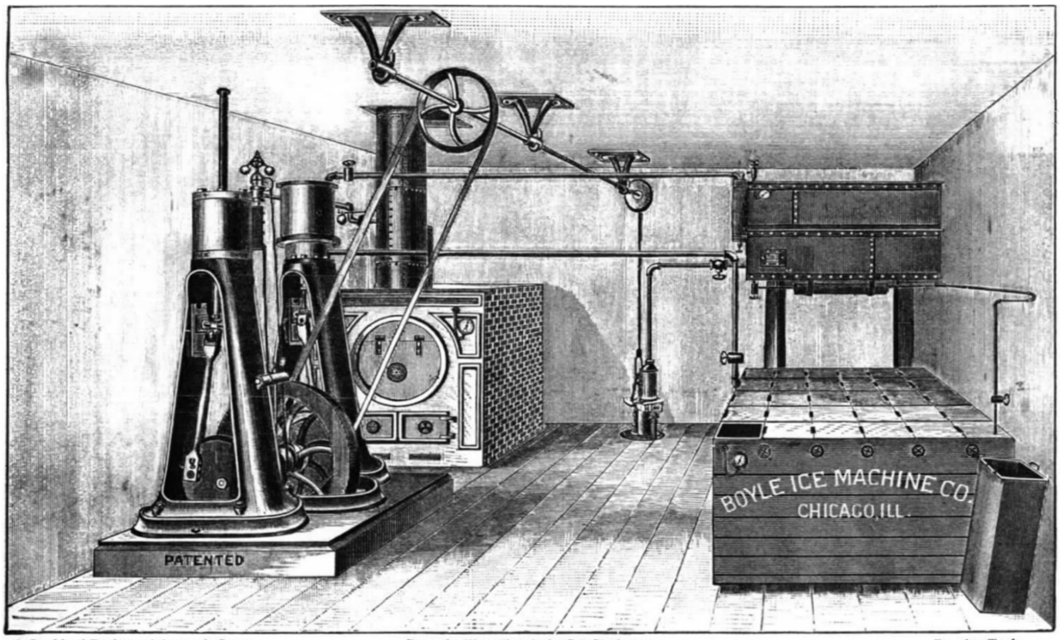

Figure 7 – The Boyle Ice Machine of 1879

The Boyle Ice Machine Company is rightly regarded to be the first successful venture constructing ice making plants on a large scale. Woolrich (1965) described the company as *"the principal builder of ammonia compression machines from 1876 to 1884"* and said of David Boyle that he *"contributed more to the early machine development of commercial ammonia compressors than any other one man".* However several other innovative engineers were active in the field at the same time.

Francis de Coppet

De Coppet was a resident of New Orleans in the 1860s and worked on early cooling experiments at the Louisiana Ice Company and the Merz brewery. Some of his experiences are detailed in an article he wrote for Ice and Refrigeration (De Coppet, 1892). He had been a draughtsman at the US Patent office in Washington DC and served in the US Army as Assistant Engineer before moving to New Orleans (Becker, 1909a). At that time the Louisiana Ice Company ran the largest ice making plant in the world at Gretna, Louisiana (now a suburb of New Orleans on the opposite bank of the Mississippi from the downtown district), equipped with six 10-ton Carré absorption machines imported from France in 1868. The success of the ice company encouraged many other local businesses to try to make their own ice, including George Merz, a brewery owner in New Orleans. He took delivery of a small compressor purchased from Charles Tellier in 1869 and supplied by Leopold Bouvier, Tellier's agent in the United States. This machine had been designed to work on methyl ether and an attempt was made, unsuccessfully, to operate it on anhydrous ammonia. The high pressure required and the relatively high speed for the time of 350 revolutions per minute resulted in frequent breakdowns so in the autumn of 1869 Merz invited De Coppet, who had been involved in the Louisiana Ice Company trials, to design an improved ammonia compressor. This first compressor was a single cylinder horizontal double acting machine and was used to chill air which was forced through tubes in a flooded shell and tube evaporator to chill a beer cellar in the brewery (De Coppet, 1892)

The compressor worked well but to maintain the beer cellar at the desired temperature of 40°F (4.5°C) the air had to be chilled to 32°F (0°C) which caused frequent blockages of the horizontal tubes due to ice build up.

De Coppet applied for a patent for his compressor in 1871, also under the title *"Improvement in Ice Machines"* and it was granted, number 148,675 on March 17, 1874. The novelty in De Coppet's design, and the focus of his claims in the patent, is the use of glycerine, or propylic alcohol as De Coppet calls it, to improve the shaft seal arrangement. De Coppet describes this in the patent text as follows:

"A quantity of glycerine – say several gallons at one operation – is put in the cup S; then screw on the cover of the cup;then open the small cock between the cup and the induction pipe G; the glycerine will then flow by gravity through the receiving side pipe and valves in the pump, and the movement of the pump-piston forces the glycerine around the piston-packing, filling the receptacles or grooves in the packing rings and the valve and their seats with glycerine, and any surplus glycerine is forced on through the delivery side pipe, in and through pipe H in trap E, where it falls by gravity to the bottom of the trap, the ammoniacal vapor continuing on to the compression-coil for compression to liquefaction."

This is illustrated in Figure 8, taken from Patent 148,675

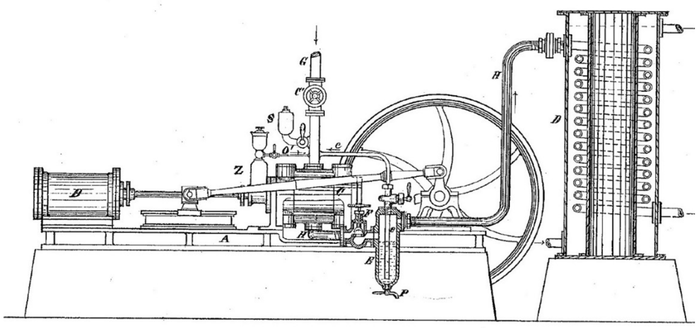

Figure 8 – De Coppet's glycerine sealed ammonia compressor from his 1871 patent application

This is a significantly more sophisticated device than James Boyle's *"crude piece of mechanism"* although it predates Boyle by at least a couple of years. Becker (1909a) noted that De Coppet, having worked in the Patent Office as a draughtsman, *"was a much better draughtsman than he was a specification writer"* and goes on to say *"the drawings of his patent therefore better illustrate his invention than does the description embodied in the specification; together they describe the invention in accordance with the rules of practice of the U.S. Patent Office then in force, but through having been indifferently prepared the claims did not give him all he was entitled to at the time"*. This seems a rather harsh assessment. De Coppet followed the "problem-solution" approach to patent claims where a problem with the current state of the art is described, a solution is explained (or "taught" as the patent lawyers would say) and the details of the solution are then claimed. The claims are the only part of the full patent text that provides the legal status and a common mistake is to claim too much of previous devices, leading to rejection of the application on grounds of insufficient novelty. De Coppet neatly avoided this pitfall by concentrating on the problems of sealing leaks on the piston rod stuffing box.

It can be concluded that this was probably a large part of the problem encountered at the Merz Brewery with the Tellier machine operating on ammonia and although Becker describes the De Coppet compressor as *"the first ammonia compressor ever built"* (Becker, 1909a) this is clearly not the case, as the Tellier machine on trial at the Merz Brewery in 1869 predated it. It could however perhaps be described as "the first purpose-built ammonia compressor".

De Coppet licenced manufacturing rights to his patent to the Fred Wolf Company of Chicago and the De La Vergne Company of New York. Wolf later adopted the Linde compressor design and manufactured compressors in Chicago on behalf of Linde from 1881 onwards. De La Vergne built a trial machine on the glycerine sealed principle in 1878 for his New York brewery and spent the next four years refining the design before entering the market as a compressor manufacturer in 1882. Over the next eight years the De La Vergne company delivered over 250 compressors and established sub-licenses in several countries, including L Sterne and Co in the UK. De La Vergne machines were installed in that first 8 year spell in England, Scotland, Canada, Argentina, Ecuador, Brazil, Italy and the Philippines as well as all across the United States, all with De Coppet's glycerine system although it is not given credit in the De La Vergne company literature (De La Vergne, 1891).

John Beath

Beath was a millwright who worked on machinery in gold and silver mines in California and Nevada. He realised in the late 1860s that the high price of ice in San Francisco and Los Angeles, up to 5 cents per pound, was an opportunity to develop an ice manufacturing industry on the West Coast. With a financial partner, Samuel Martin, he developed and patented a novel form of evaporator, relying on the two-phase flow of volatile refrigerant through the inside of horizontal tubes. Patent no 127,180 was granted on May 28, 1872 (Martin and Beath, 1872) and suggests that vapour compression was the means of cooling the refrigerant tubes. The patent states *"At present we prefer this fluid to be ammonia, which we obtain from the aqua ammonia of commerce by distillation, usually drying the gas as it goes over by passing it through quicklime. We introduce it to our machine by connecting a pipe with our distributor, allowing the gas to drive the air before it and out through a cock in the receiver".*

Beath erected a small machine in Los Angeles in 1869 and then, with Martin, applied for the patent mentioned above on the design of the evaporator. According to Beath's account (Beath, 1912) the pair applied for a second patent but then, when they moved to San Francisco to build a larger machine, Martin announced that he had no more funds due to recent losses in his mining operations. Beath managed to find other backers for the San Francisco project and it was successfully completed. Hearing of high ice prices in Portland, Oregon, Beath then moved there to construct another larger ice machine. However shortly before completion the plant was destroyed in a large fire. This might have been the devastating blaze of August 1873, which razed 22 city blocks in the centre of Portland, but was probably an earlier blaze in December 1872 or even earlier. Beath had been able to study the behaviour of the evaporating ammonia in the tubes and constructed a second machine on the site of the first but with further improvements in the evaporator design. He then travelled to Chattanooga, Tennessee and built an ice plant based on absorption but with his new evaporator design before returning to San Francisco to upgrade the plant there with his improved system. In 1874 he was drawn into a patent dispute with his former partner Samuel Martin. Martin was successful although Beath maintained that the claims of Martin's patent were stolen, and Beath noted of Martin that this *"was the turning point in his career; he lost his money, took to heavy drinking and died in an insane asylum"* (Beath, 1912). Despite his early experiments with ammonia compressors, all of Beath's successes seemed to be with absorption systems and following his Chattanooga installation he noted that *"my plan is now largely used all over the world".*

Two other eminent engineers are worth mentioning at this point. Alexander Twining, a civil engineer from New Haven, Connecticut worked on artificial ice manufacture from about 1850 onwards and was granted a patent, number 10,221 in 1853 on a vapour compression system using *"a volatile liquid, as alcohol, ether, sulfuret of carbon etc, of which at present I find ether the most available"*. Twining constructed a machine in Cleveland Ohio using diethyl ether and it ran successfully for many years. He suggested several improvements over the next few years, including the addition of an ammonia compressor to a Carré absorption system, Patent number 121, 975 dated December 9, 1871. The French engineer, Charles Tellier is credited with being the first to equip a ship with refrigeration equipment for the transportation of meat over long distances. Tellier favoured ether for this purpose, and according to Thévenot (1977) installed his first ether compressor in a chocolate factory near Paris in 1868 and attempted a shipment of meat from the Americas but this was unsuccessful. It was 1876 before he made a successful shipment from Buenos Aires to Rouen. From the beginning of his investigation of refrigeration systems Tellier was interested in the opportunities offered by ammonia in vapour compression although his early machines all used ether. At a paper presented to the Society of Arts in London in 1868 the speaker, Dr B Paul, identified three methods of artificial freezing; vapour compression of a volatile liquid, absorption of ammonia and compression and expansion of air (Paul, 1868). In the paper the only volatile fluid mentioned in connection with vapour compression was ether but the discussion afterwards centred largely on the various schemes being tried by Charles Tellier, including his investigation into the storage of meat. In this discussion a Mr Shand said that he had visited Tellier and seen his equipment in operation, using ammonia as the refrigerant. This statement was later repeated by the speaker who stated that Tellier *"used anhydrous liquid ammonia in the same way as ether was used for the reduction of the temperature by evaporation and then re-condensed the ammonia by means of mechanical power".* Tellier was a well known fan of ammonia. His major work, Ammoniaque Dans L'Industrie was published in 1867 (Tellier, 1867) and included a vast array of possible uses for this remarkable substance, including as a safer alternative to hydrogen in lighter than air balloons, as a fuel for motor vehicles, as a refrigerant in absorption systems and as a refrigerant in what he called *"mechanical compression apparatus".* The applications for refrigeration that he described include cooling of air in theatres, desalination of sea water and the manufacture of copies of marble statues as well as ice making, food preservation by chilling in warehouses and comfort cooling for passengers at sea.

Despite the views of the London audience on Tellier's use of ammonia in his compressors it seems that his machines were not well adapted for this purpose. When the installation at the Merz Brewery in New Orleans was modified to run on ammonia it was a singular failure, suffering regular breakdown of the connecting rod owing to the high forces involved in compressing ammonia compared to dimethyl ether and apparently also leaking profusely from the shaft seal. All of Tellier's marine installations used dimethyl ether and his original patent didn't mention ammonia. The received wisdom at the time was that ammonia was an excellent refrigerant but could only be used in Carré's absorption system and when the trial at Merz suggested that compression of ammonia was feasible, Leopold Bouvier quickly persuaded Tellier to apply for patent protection for this development. US Patent number 100,689 was issued on March 8, 1870 claiming

1. *"The use or application, for the purpose of generating artificial cold, of pure ammoniacal gas liquefied by means of mechanical compression, substantially as described,*
2. *The use or application, for the purpose of liquefying ammoniacal gas, of the pump and condenser, forming part of the machines or apparatus fully described in Letters Patent No 85,719 issued to me January 5, 1869, substantially in the manner and for the purpose above set forth."*

In the teaching of Patent 100,689 Tellier wrote *"Liquefied ammonia, prepared and used as herein described, possesses great advantages over the various substances heretofore employed for cooling or refrigerating."* These substances, according to Tellier, were sulphuric ether, hydrocarbons and carbonic acid.

Discussion

Assessing the achievements of engineers of so long ago is difficult. Some clues are given by what they wrote about themselves, but these accounts always only give one side of a story, particularly over a point of contention. Other hints are found in the patents that were granted to them, but it must be remembered that not everything that a person does is claimed in a patent and not everything claimed in a patent has actually been done in practice. It is interesting to note that the compressors described in the various patents studied here seem to fall into two sorts – practical machines, like those of Alexander Twining, Charles Tellier, Francis De Coppet and James Boyle and gross oversimplifications like the "exhaust pumps" described by Beath, Martin and even that shown in David Boyle's patent 128,448. A more accurate picture can be gained from the things that colleagues and acquaintances wrote about these pioneers although this too can be patchy and misleading. Some mistakes and half truths get picked up and repeated over and over and some people are forgotten and slip out of the narrative over time.

David Boyle was described in an 1885 article in The Western Brewer as *"a man of sterling integrity, quick, sensitive and eager to succeed. His every thought is towards the advancement of the world's knowledge of the science of artificial refrigeration."* His obituary in Ice and Refrigeration in 1891 said *"few have obtained as thorough a knowledge of the science of artificial ice making and refrigeration"* and a reminiscence written in 1896 described him as *"the father of successful artificial refrigeration and ice making: for although many had spent years of toil and vast sums of money in experiments in the art before he entered the field, yet to David Boyle is due the honour of having accomplished more in the advancement of the science than the combined results of the efforts of all of his predecessors".*

Others were described in less flattering terms. John Beath noted that Samuel Martin, his former business partner died in an insane asylum and Victor Becker described Leopold Bouvier as "the Casanova of mechanical refrigeration", not intended as a compliment. Becker also noted that Bouvier *"decamped with the proceeds of a draft for the last payment"* on a project in Newark in 1877 and *"after several other adventures finally hung himself with his suspenders in a prison cell".*

Conclusions

A number of notable "firsts" have been identified in this study. All of them are prefixed here with the word "probably".

Alexander Twining was probably the first person to use vapour compression to manufacture ice in North America.

Charles Tellier was probably the first person, together with his associates to run an ammonia compressor for this purpose. This may have been around 1867 in Paris or perhaps around 1869 in New Orleans.

Charles Tellier was probably the first person to patent an ammonia compressor with the granting of Patent number 100,689 on March 8, 1870.

Francis de Coppet was probably the first person to build a reliable, leak-tight, robust ammonia compressor with his glycerine-based adaptation of the Tellier machine as shown in Patent number 148,675, granted on March 17, 1874.

James Boyle was probably the inventor of the spring loaded compressor valve, as shown in Patent number 175,020 of March 1876

David Boyle was probably the first person to make the construction of ice machines based on the compression of ammonia vapour a commercial success.

Acknowledgements

Bernard Nagengast, co-contributor for this paper, who has been interested in refrigeration history for 55 years, provided much of the basic research that led to the conclusions offered here. Andy Pearson sifted through that material and added some observations and insights. The authors would like to thank Iain Murray and his colleagues at the Johnstone History Museum for a wealth of information about 19th Century Johnstone and the directors of Star Refrigeration Ltd and ASHRAE for their ongoing support. Both of the authors are very grateful to Tracy Boyle Abrusci, great-great-granddaughter of David Boyle, and John Boyle, great-great-grandson of James Boyle for their additional information and insights, which helped to clear up several long-standing and persistent mysteries.

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Figure 6: Boyle, J., 1876

Figure 7: Boyle Ice Machine Co, 1879

Figure 8: De Coppet, F., 1874

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