REVIEW ARTICLE

***Dr S. Forbes Pearson** studied at Strathclyde and Glasgow Universities, taking the degrees of ARCST, BSc in Mechanical Engineering and a PhD for work on component losses in small compressors. During his training period, he worked with L. Sterne & Co. Ltd., Rolls Royce Ltd. and Tecumseh Products Michigan.*

After university, Dr Pearson accepted the post of Senior Scientific Officer at Torry Research Station, Aberdeen and was involved in the practical development of freezing fish at sea on trawlers. Dr Pearson left Torry Research Station after 3 years to take up a post with L. Sterne & Co. Ltd., Glasgow, for 11 years, during which he became a Divisional Director and Chief Engineer of the Industrial Refrigeration Division. On the closure of the Industrial Refrigeration Division by Prestcold Ltd., Dr Pearson and some colleagues founded Star Refrigeration Ltd. in 1970.

At Star Refrigeration, Dr Pearson was responsible for the development of a patented range of high-efficiency blast freezers, for the low-pressure receiver type of refrigeration system, giving evaporator overfeed without the use of pumps, for four-port ball type reversing valves for reversed cycle defrost and for the introduction of the patented thermosiphon system of cooling for main frame computers. He developed the first practical drop-in replacements for R-502 and R-12 and has also patented drop-ins for R-22, R-12 in centrifugal compressors and R-13B1. He is currently working on an enhanced-efficiency replacement for R-22. Dr Pearson is President of Star Refrigeration Ltd., is a past-President of the UK Institute of Refrigeration (IoR) and is currently Chairman of the Technical Committee of the IoR. He is a Past-Chairman of BSI Committee RHE/18 "Refrigeration Safety" and of the European TC 182 WG2, also on refrigeration safety. Dr Pearson was awarded the Hall Thermotank Gold Medal of the IoR in 1991 and has also been awarded the Lightfoot Medal on 6 occasions. He is the holder of many patents on subjects relating to refrigeration and is the author of many papers.

Dr Pearson is a visiting professor at the University of Strathclyde and was awarded the prestigious IIR Gustav Lorentzen Medal in 2003 at the 21st IIR International Congress of Refrigeration in Washington DC. He was awarded the UK Cooling Industry Gold Award in 2004 and became an Honorary Life Member of the International Institute of Ammonia Refrigeration in 2005.

Ammonia – Yesterday, Today and Forever

by

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I. INTRODUCTION

Ammonia is a unique substance by virtue of its excellent thermodynamic properties as a refrigerant and the benefits it brings to the environment.

All life depends on the nitrogen cycle in which the breakdown of natural material into ammonia is an essential part.

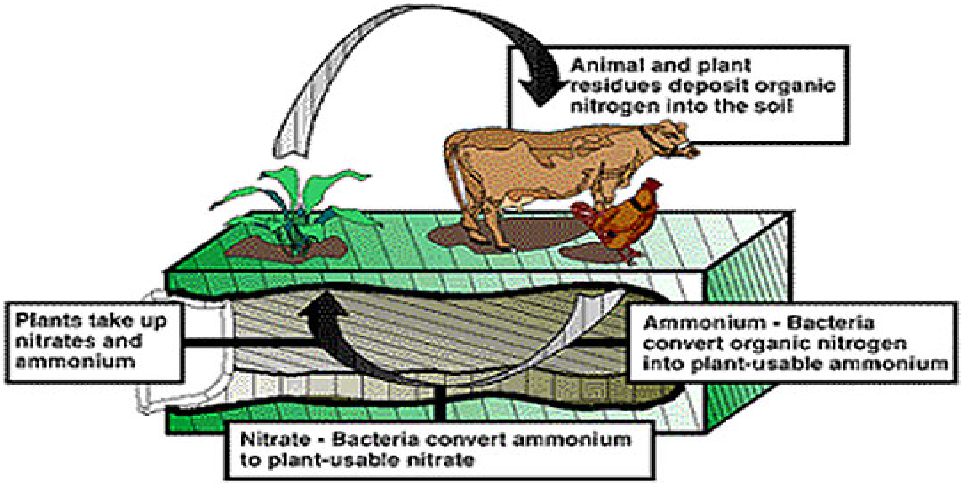

Figure 1. The nitrogen cycle
Le cycle d'azote

The amount of ammonia produced naturally has been estimated at 3 billion tonnes per annum but some writers consider the figure to be much higher. Industrial production of ammonia is of the order of 140 million tonnes per annum. By contrast the annual usage of ammonia for refrigeration purposes is of the order of 500 000 tonnes per annum. This is a negligible amount compared to the quantities of ammonia which are circulating naturally within the environment.

It is interesting to note that the quantity of ammonia contained in refrigerating systems in the USA amounts to about 5% of the total USA inventory but the amount used is less than 0.5%. This usage would amount to about a 10% loss per annum, which is within the range of 5 to 15% annual loss for large ammonia systems given to me in a private communication by Anders Lindborg.

Ammonia was first used as a refrigerant in vapour compression systems in 1872 by David Boyle in Texas, USA. David Boyle was a Scot from Johnstone in Renfrewshire. Carl von Linde from Germany started production of ammonia compressors for refrigeration in 1876. Boyle was a practical engineer who does not appear to have published any theoretical basis for his designs. Linde, by contrast, was a methodical engineering scientist who gave a sound theoretical basis to the new industry of mechanical refrigeration.

Ammonia has remained in continuous use as a refrigerant since its introduction around 1870.

The reason ammonia has continued in use to the present day lies in its thermodynamic properties. It is instructive to compare the properties of ammonia with those of R-134a, the only single-component HFC in common use today, water, which is a theoretically ideal environmentally friendly refrigerant, and propane, which is a flammable hydrocarbon having properties otherwise rather similar to ammonia. From *Table 1* it can be seen that water is very difficult to use as a refrigerant because of the enormous swept volume required. R-134a is significantly worse than ammonia and propane in terms of required swept volume but is not impracticable. Coefficients of performance taken from the 1997 *ASHRAE Handbook, Fundamentals* show that there is not much to choose between the three practical refrigerants but ammonia is the best. Ammonia would tend to appear even better in a comparison of coefficients of system performance because its transport and heat transfer properties are better. The only refrigerant having significant global warming potential is R-134a.

Table 1. Some refrigerant properties at 0°C, unless otherwise stated

Refrigerant	**Formula**	**NBP**	**CT**	**Latent Heat**	$\frac{Vs}{L}$	**COP**	**ODP**	**GWP**
		°C	**°C**	**kJ/kg**	$\frac{m^3}{KJ}$	**+3/37°C**		
Ammonia	NH_3	-33.3	135.0	1262	2.29×10^{-4}	7.3	0	0
R-134a	$C_2H_2F_4$	-26.1	101.1	199	3.48×10^{-4}	7.0	0	1600
Water	H_2O	100.0	373.9	2501	823.6×10^{-4}	?	0	0
Propane	C_3H_8	-42.1	96.7	374	2.58×10^{-4}	7.1	0	20

II. AMMONIA YESTERDAY

The way in which ammonia was used as a refrigerant varied over time.

Original ammonia compressors were generally steam driven at less than 60 rpm. Often the compressor and steam engine shared a common crankshaft. Condensers were water-cooled using river water originally and then natural circulation "atmospheric" condensers in which mains water trickled down over an interlaced grid of pipes. Evaporators were generally plain pipe grids fed through a hand regulator valve. Such systems required constant attention from an experienced operator because the setting of the hand regulation valve was critical and the time constant of the system was long. Fortunately, these early compressors could tolerate a significant amount of wetness in the suction vapour. A very reliable range of ammonia compressors was manufactured by the DeLaVergne company of New York. These compressors were unique in that the cylinder clearance volume was filled with oil at the end of each stroke. The company believed that filling the clearance volume with oil would reduce re-expansion of ammonia at the start of suction stroke and improve volumetric efficiency. The oil injection was beneficial in that wear in these slow-running machines was negligible but the expected improvements in efficiency did not materialize. This was because ammonia dissolved in the oil at high pressure tended to flash off during the suction stroke, producing volumetric efficiencies significantly worse than those that could be obtained from "dry" compressors. A famous comparative trial was performed at the Eastman Kodak Company. The refrigerating performance of a DeLaVergne compressor and a York compressor were carefully compared. It was shown that the fuel consumption required for the DeLaVergne compressor was significantly greater than that of the York compressor. The DeLaVergne design faded from the picture in the years following the trial. However, oil injection made a comeback much later in the form of the oil-injected screw compressor which does not suffer from re-expansion effects.

The advent of electric motor drive resulted in a new generation of ammonia compressors which ran at unheard-of speeds that could exceed 300 rpm. Compressor valves changed from the original poppet type to spring-loaded ring plate valves of a type that is still used today. High acoustic velocity of ammonia allowed the use of long-stroke machines that were efficient compared to modern high-speed compressors. Induced draught and forced draught evaporative condensers were introduced, as were fan-assisted evaporators with plain or finned piping. Float valves were used to control expansion of liquid refrigerant. Circulation of refrigerant was by gravity or by positive displacement pump. The low density of liquid ammonia makes it much more suitable for natural circulation than is R-134a.

Further development of ammonia systems was influenced by the adoption of standardized alternating current electrical supply and by the advent of synthetic refrigerants, starting with R-40 (methyl chloride).

Ammonia compressors were successively designed for 8-pole, 6-pole and then 4-pole motor speeds. These high-speed designs were arranged so that they could run either on ammonia or on the new synthetic refrigerants that were being introduced. The new refrigerants were non-toxic, non-flammable and had low indices of compression compared to ammonia. This meant that the compressors tended to run much cooler on the new refrigerants than on ammonia. The new designs of compressor, having short strokes to accommodate the larger valve area required by the new refrigerants, were not really suitable for ammonia and it seemed only a matter of time before ammonia would become obsolete as a refrigerant. The only range of compressors designed primarily for ammonia was that produced by Grasso using welded steel construction, which gave very good cooling of the cylinders. All the other cast compressors were difficult to cool and would rapidly overheat if the cooling system failed or a discharge valve broke.

Ammonia was saved as a refrigerant by two unrelated events, which bring us into the area of ammonia today.

III. AMMONIA TODAY

The first event that extended life of ammonia as a refrigerant into the indefinite future was development of the oil-injected screw compressor.

Screw compressors are positive-displacement machines but are rotary rather than reciprocating. They are thus capable of perfect balance and running at high speed.

The screw compressor was designed in the 1930s in Sweden as a super-charger for gas turbines. The James Howden company of Glasgow took up a licence for these machines in 1937 but did not use them for refrigeration till after World War II (1939-1945). In its original form, the screw compressor had to be run at very high speed and was intolerably noisy. Duncan Laing of James Howden discovered that, if oil were injected into the compressor, it sealed leakage paths past the rotors, allowing the machine to be run at reduced speeds with tolerable levels of noise. In addition, the injected oil could be circulated through a cooler, thus overcoming the high discharge temperatures associated with reciprocating ammonia compressors. From the moment that the first oil-injected screws ran successfully on ammonia, the future of ammonia as a refrigerant was assured. Ammonia still faced severe competition from synthetic refrigerants, which seemed safer and easier to apply. For a time it seemed that ammonia would be restricted to large industrial installations and that the vast majority of applications would be carried out using synthetic refrigerants. Large ammonia installations used forced draught evaporative condensers and plate finned coolers for cold stores and blast freezers. Sealed centrifugal pumps for liquid ammonia circulation were developed. Electronic control of refrigerant systems was introduced.

The second event that influenced the use of ammonia as a refrigerant was the discovery that chlorine-containing refrigerants were damaging the ozone layer in the stratosphere. The ozone layer protects the surface of Earth from ultra-violet radiation that would be harmful to life in excess. By a series of International agreements following a meeting in Montreal, it was agreed that all chlorine-containing refrigerants would be phased out. These chlorine-containing refrigerants are being replaced by synthetic refrigerants that do not contain chlorine but, for a variety of reasons, the replacement refrigerants are more expensive than the original synthetics and in other respects less satisfactory. As a result, ammonia is returning to applications from which it had been displaced by synthetic refrigerants. It is not clear how far the trend to apply ammonia to smaller systems will go. Ammonia is not suitable for hermetic systems though it would be possible to use compressors with canned rotors as is already done in ammonia pumps.

Present applications of ammonia refrigeration include low-temperature cold stores, chill stores, freezing and process plants, plate freezing systems and water and glycol chillers. In almost every case, ammonia out-performs other refrigerants in terms of system efficiency. However, there is one respect in which ammonia is deficient as a refrigerant. Its relatively high atmospheric boiling point of -33^{o}C means that most low temperature applications require evaporation of refrigerant at pressures lower than atmospheric. Under these conditions, ammonia has a very high specific volume, requiring the use of large and expensive machines. System reliability is also compromised by the possibility of drawing moisture and non-condensables into the refrigerating system through leaks on the low-pressure side.

Another challenge to the use of ammonia is increasingly stringent safety legislation, which makes the refrigerant difficult and expensive to apply where members of the public are present.

The twin challenges of safety and low evaporating pressures can be overcome by using ammonia in cascade systems with the non-toxic, high-pressure refrigerant, carbon dioxide. This provides an elegant solution improving efficiency of low-temperature systems, reducing overall cost by virtue of reduced component and pipeline size and removing toxic ammonia refrigerant from the vicinity of the public.

Return to use of the classical refrigerant carbon dioxide in conjunction with ammonia is a third development that has ensured continuous use of ammonia into the future.

IV. AMMONIA TOMORROW

It seems clear that ammonia will continue to be used as a refrigerant for the foreseeable future. Future applications of ammonia and the scale of its use compared to other refrigerants are not so clear. For small, fully-sealed systems there would seem to be no point in using ammonia, which is not a good electrical insulator and which, by reason of its relatively low mass flow, would not provide good motor cooling. Such systems will probably use hydrocarbons where national and local regulations permit and halocarbons where they do not.

There would appear to be no place for ammonia in window or split air-conditioning systems. These systems will probably continue to use halocarbons for as long as it is legal and practicable to do so. There is no technical reason why such sealed systems should not use flammable hydrocarbons but there is an understandable reluctance to do so. In the long term, it may be possible to use transcritical carbon dioxide systems for air conditioning but such systems are not available at present.

For large-scale industrial systems at evaporating temperatures above -33^{o}C where the public and non-specialist workers are excluded, there would seem to be no doubt that ammonia is the best choice of refrigerant. Where non-specialist workers are required to be in close proximity to the refrigerating system, it will be more appropriate to choose a secondary refrigerant, probably carbon dioxide, being refrigerated by a primary refrigerant, probably ammonia.

For evaporating temperatures below -33^{o}C I would recommend the use of an ammonia/carbon-dioxide cascade system. The lower the evaporating temperature, the more competitive the cascade system becomes when compared to an economized or a two-stage ammonia system. The lower limit of use of simple carbon dioxide systems is around -55^{o}C because of the triple point.

For large air-conditioning systems using a secondary refrigerant, it is now well understood that using carbon dioxide as a volatile secondary refrigerant (i.e. no carbon-dioxide compressor) in conjunction with ammonia or another primary refrigerant will be much more efficient and probably not more expensive than circulating a non-volatile secondary refrigerant through much larger pipes.

The main area of doubt concerning future use of ammonia is in the commercial sector. It is possible to use ammonia down to systems of only a few kilowatts capacity and it has been done in the past. However, it is probably more convenient to use non-toxic, miscible halocarbons.

Large commercial systems, such as supermarkets, have successfully used carbon dioxide either as a volatile secondary or in cascade with a primary refrigerant, not necessarily ammonia.

It will never be acceptable to use widely distributed ammonia systems in supermarkets, but small ammonia systems in locations remote from the public are quite practicable. However, they would be much easier to use if miscible oils were employed. Another technique to provide benefits of miscibility is to blend ammonia with a substance miscible with the lubricant. Tests have been carried out using an azeotropic blend of ammonia and dimethylether (E170). It remains to be seen whether the benefits of such a blend will overcome the disadvantages of making ammonia more flammable but scarcely less toxic.

V. CONCLUSION

Unless some completely new method of refrigeration is developed, ammonia will continue to be used as long as refrigeration is required.

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