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THE REFRIGERATION COMPRESSOR

- THE STEPS TO MATURITY

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Today we are likely to take the refrigeration compressor for granted just as we take for granted the way the uses of refrigeration have intertwined themselves into our everyday lives. Whether we think of food processing, transportation and marketing; accuracy in industrial processes; computer systems; or human comfort, all depend on refrigeration and the refrigeration compressor. In fact some southern locations owe their industrial development almost entirely to air conditioning in manufacturing plants, in offices, and in homes, to say nothing of the air conditioned car which gets people to work. Refrigeration in its many forms and applications has become a way of life, not only in the United States, but increasingly in many other places in the world. And heat pumps save important heating energy.

The compressor is the heart of any refrigeration system except for the very few which are directly operated by heat such as the absorption units. In 1865 to 1875 a few tens of refrigeration compressors were made each year. These were massive steam engine driven machines with their weight in tons considerably in excess of their capacity in tons of refrigeration.

Today the industry produces some 15,000,000 compressors per year, and one engine driven compressor used for automotive air conditioning can produce over three tons of refrigeration, yet it weighs only 14#, Fig. 1. In a great many ways the progress in refrigeration is more spectacular than in the automotive field. It is noteworthy that the ice man no longer cometh to our homes and groceries.

This paper will identify and discuss how some of these changes have been accomplished, and indeed what the changes were. If I have any qualifications to attempt this chronology it may be because I began to dedicate myself to the refrigeration industry in 1927 when still in college. I had tried to identify an area of technology not already flooded with engineers and one which should have rapid growth. The "reverse heat cycle" as refrigeration was sometimes called was not as broadly understood as the power cycles and seemed to offer the

opportunity of less competition. In a matter of three years the "great depression" was upon us, and I was to become thankful for having made such a choice. I have remained in the refrigeration and its directly related fields such as air conditioning ever since 1927.

For ease in discussion I have divided the past into four periods, that prior to 1900, the period from 1900 to 1925, that from 1925 to 1950, and from 1950 to 1975. I will also have a few comments about the post 1975 period. In each period the design of compressors was grossly influenced by which of the many refrigerants were readily available and understood, and in the last two periods the choice of refrigerants was based on perceived levels of safety for certain applications. Another major influence on compressor design has been the type of drive available and the source of power.

Before 1900

For refrigeration compressors this period begins about 1865. Factories were more like job shops then like the compressor factories we now know as seen by the 1876 photograph of Fig. 2. The office and factory management team typical of that factory is shown in Fig. 3. At that time the Corliss engine was in use for driving various forms of machinery, and piston type water pumps were in general use. The Corliss engine was a massive thing with a combined drive pulley and flywheel sometimes as large as 30' in diameter. But it was a natural thing to combine the concepts of pumps and the Corliss engine to provide refrigeration machines.

Since both the engine and the compressor had reciprocating components it was an obvious step to use a common shaft for the cranks of both components. And since engine rooms often had any required height the engine was often horizontal and the compressor cylinder was placed above the crankshaft in a vertical position. I recall one such compressor at Eastman Kodak which I was told had been in operation for 70 years. Fig. 4 shows a compound Corliss engine driving a multi-cylinder ammonia compressor.

The typical operating speed of 120 to 180 rpm allowed the use of poppet type valves of considerable mass. Since manual control was usually employed and the refrigerant flow to the evaporator was also controlled manually it was not at all unusual for large amounts of liquid to be returned to the compressor, and thus most compressors had safety heads which were spring loaded to remain in a sealed position for all normal operating pressures, but to open in the case liquid entered the cylinders. The valve location was usually in the cylinder head, or in the cylinder walls.

These early compressors used a cross-head and piston rod rigidly affixed to the piston. The piston rod entrance into the cylinder was packed to prevent the leakage of refrigerant. The piston rod, the piston, and the valves were the only moving parts exposed to the refrigerant, and it appears that lubrication processes were similar to those used in steam engines, using various types of feeders to introduce a small amount of oil needed. The external moving parts also used steam engine practices such as oil cups, or Manzel lubricators. With so little oil exposed to refrigerant it appears that its excursion to impede heat transfer in evaporators or condensers was not a major problem.

Refrigerants. Ammonia was the refrigerant of choice in a large portion of pre-1900 refrigeration plants. Ice making to supplement the ice cut from ponds and lakes was a growing industry. The benefits of cold storage for preservation of foods were appreciated, and cold storages began to emerge. Certain process cooling was early recognized as an important application of refrigeration, for example in the making of photographic film.

Carbon dioxide was used frequently as the refrigerant where ammonia would have been hazardous, but the principle of the supercritical "supercharged" cycle does not seem to have been used. High-side pressures in the range of 1200-1400 p.s.i. were experienced with CO₂ and hence these compressors were designed with closed crankcases and packing around the rotating crank shaft. Such systems were used by the Navy and in some other shipboard applications, but required high horsepower for a given cooling effect.

Air systems were also used quite extensively on shipboard in spite of their large power consumption. Even the dense air system, which used air under several atmospheres pressure, required massive machinery and made an expansion engine a part of the cycle as well as a compressor. Both would then be driven by a separate steam engine.

Capacity Control. Double-pipe heat ex-

changers were used for the cooling of liquids, Fig. 5., and bare pipe arrangements for cooling of cold storages. These evaporators had large internal volume and considerable mass. These factors together with the size and type of compressors and drives made it desirable to keep the equipment operating once it was started. Hence the need for capacity control soon developed.

Evaporator capacity could be accomplished by adjustment of hand expansion valves, or by valving off portions of the evaporator entirely. If this resulted in too low a suction pressure some means of reducing compressor capacity was needed and was usually accomplished by opening clearance pockets in the compressor cylinder walls. See Fig. 6. By the end of this period some compressors were equipped with cylinder bypass valves. See Fig. 7.

End of Period. By 1900 we see that refrigeration by mechanical means is well accepted. Equipment is large and bulky. Control is almost entirely by manual means with clearance pockets and some cylinder bypass in use. Steam engines drive most compressors, tho electric motor belted drives are starting to make their appearance. The common refrigerants are ammonia, carbon dioxide, air, with a smattering of sulphur dioxide. Compressors operate at low speeds, most require manual lubrication at reasonable intervals, valves must be seated or "ground" and are of the poppet type, but with maintenance they have extremely long life.

1900 to 1925

During this period the usage of refrigeration expanded rapidly. Many plants for manufacture of "artificial ice" were built. Reefer cars on railroads were developed for long distance shipment of perishable foods. Some very large cold storage installations were made, including at least one system in which ammonia was piped below city streets to numerous stores. Ice cream became popular in the corner drug store and in restaurants. See Fig. 8. Small compressors were available by the end of the period for soda fountains, but ice and salt were still used to pack lots of the ice cream. These same compressors were used in conversions of domestic ice boxes to "artificial" refrigeration with the unit remote, usually in the basement. A few industrial air conditioning installations were made and one theatre was cooled in 1914. See Fig. 8. These and other applications signified the growth of the refrigeration industry. Chilled brine distribution was applied to large systems.

Compressors. Compressors got smaller as their speeds were increased to a range of 300 to 600 rpm. Enclosed crankcases such as shown in Fig. 7 became more standard, and the packing was moved to the rotating shaft outside the crankshaft bearing. Steam driven units became smaller with side-by-side cylinder arrangements. See Fig. 9. Electric motors became the usual driver, and the big pulley of the compressor often required an outboard bearing to take the pull of the belt and the weight of the pulley. Towards the end of the period a few rotating seals were tried in small compressors.

The move to a packed crankshaft instead of a piston rod and crosshead meant that all the moving parts except the drive pulley were exposed to the refrigerant atmosphere. With refrigerants such as ammonia, sulphur dioxide, and carbon dioxide the solubility with oil was very low, and to some extent this was also true with methyl chloride. New oils had to be developed to avoid undesirable reactions with the refrigerants particularly if moisture was present. Crankcases were kept at or near the suction pressure.

Trunk type pistons became almost standard with an upper and lower portion in contact with the cylinder and a central portion open in front of a suction port in the side of the cylinder. See Fig. 7. Valves were lighter in weight, often being diaphragm or finger type with the suction valves in the head of the piston and the discharge valve in the cylinder head. Such valves could be replaced instead of being re-ground.

Cold storages were found to need freezer space and other spaces above freezing. To accommodate such systems with one compressor, dual suction machines were designed in which the low temperature was in the usual position in the cylinder wall, but an additional port was provided to be uncovered by the piston at its lowest position. This additional port was then connected to the higher temperature suction, the gas from which entered through this port and in doing so raised the pressure of the lower pressure gas already in the cylinder to that of the higher pressure gas. The mixture was then compressed and discharged in the normal way. See Fig. 10 for a verticle compressor of this type with the low pressure suction valve in the piston head, and Fig. 11 for a horizontal compressor with the suction valve in the cylinder wall.

Another way of providing for two temperatures in storage was to use a booster compressor to take the refrigerant gas from the lower temperature system and discharge it into the compressor which receives the higher temperature gas directly. Booster systems

were, and are still, used to reach lower temperatures than can be efficiently handled by a single stage of compression.

It is during this period that the small condensing unit was developed with a more or less standardized combination of compressor, electric motor drive, and a water cooled condenser, all mounted together on a common base. See Fig. 12. This unit was widely used in cooling of ice cream cabinets, and towards the end of the period air cooled models appeared. They were used in the early domestic refrigerators, often by converting an existing ice box with an evaporator in the ice compartment. In many cases conversions or new installations were made in kitchens of apartment houses with the liquid refrigerant piped from a central condensing unit and a suction return from each refrigerator.

Refrigerants. The refrigerant of choice for cold storages and other fixed installations was ammonia, but smaller systems increasingly turned to SO_2 and to methyl chloride, particularly for air-cooled condensing units. Central units such as mentioned for apartment use used SO_2 , and I well remember the day the refrigerator in such an apartment we rented sprang a leak. We moved out in a hurry while repairs were made, and when we returned the plants had succumbed and some of the decorations were a new color!

The increasing use of air conditioning in theatres lead to development of larger CO_2 machines which became standard for most such applications since CO_2 was non-toxic and free of fire hazard. See Fig. 13. For the same reasons CO_2 became the usual refrigerant on shipboard. The "super-charged" cycle was soon worked out to relate the heat rejection temperature to liquid temperature and evaporator temperature.

Other refrigerants were used to some extent such as iso-butane, methyl chloride and methylene chloride in small systems, and propane in larger systems, but the use of these refrigerants did not have a major influence on compressor design.

Capacity Control. Many of the newer applications of refrigeration systems had wider and more frequent variations of load than ice plants or cold storages, so the need for better capacity control became evident. Smaller compressors were adapted to be started and stopped as a means of capacity control, and automatic temperature and pressure controls were developed for this purpose. This required the introduction of various methods to see that the oil did not leave the crankcase during the repeated starts.

For larger compressors the use of suction bypass became more prevalent. Ports could be placed at 1/3 or 2/3 of the piston travel, arranged so that when their control valves were closed there was negligible change in cylinder volume, but when these valves were opened, the port connected to suction and the piston was thus prevented from starting compression until it had passed the port. A variety of port arrangements could be provided on one or more cylinders to get as many steps of capacity as might be needed, the main precaution being to maintain enough refrigerant flow to prevent local over heating. The ports could be either manually or automatically controlled.

End of Period. By 1925 use of refrigeration has become widespread, and is an important part of many industries. Small equipment has been developed for automatic operation, but manual control remains on some larger jobs. Ammonia, carbon dioxide, sulphur dioxide, are the main refrigerants. Some use of iso-butane, methyl chloride, and methylene chloride is extant. Speeds have been increased until small compressors operate at speeds as high as 800 rpm. Electric motors drive most compressors with belt and pulley arrangements. While a few are direct driven by synchronous motors. See Fig. 14. Many alternating current motors in medium sizes are the repulsion-induction type. Domestic refrigeration has started by conversion of ice boxes, and by a few units designed as refrigerators with mechanical compressors, but the compressor is usually remotely located. Such compressors may be air cooled instead of water cooled. Mechanically refrigerated ice cream is in most soda fountains. Refrigeration is still used to make "artificial ice", and air conditioning has started in theatres and some factories which are sensitive to high humidity.

1925-1950

In this period refrigeration has become a must for many purposes. The decentralization of the equipment has caused the development of smaller compressors of relatively stable designs which can be mass produced. Manufacturer's shops became more modernized. See Fig. 15. The first hermetic compressors appear in domestic refrigerators, and are followed by semi-hermetics as air conditioning becomes available in small mass produced packages. Availability of electricity increases to most areas of the country and the household refrigerator is in most every home. Department stores followed theatres in comfort air conditioning, and soon office buildings followed suit. World War II lent great impetus to small, even isolated, refrigerators with specialized compressors and drives. War suppliers saw need for

more process refrigeration and for 100F temperatures, and the industry responded. Heat pumps were introduced, even some with capacity control, but the savings were not of sufficient interest to people at the going prices of other energy sources. Many experimental heat pumps were installed with ground source and well water sources, and they even made a major article in Readers Digest about 1950.

But without doubt the most important event during this period was the development of the Freon refrigerants by DuPont and General Motors. Without such a refrigerant series a large portion of the things just recited would not have occurred.

The increased use of refrigeration compressors and other components in many applications indicated the need for standards and better performance information of units. The American Society of Refrigerating Engineers developed the needed testing standards to bring order out of chaos, while the American Society of Heating & Ventilating Engineers provided technical background. (These societies merged in the late 50's to form ASHRAE). Trade associations such as ACRMA, REMA and NWAHA were also formed and contributed to useful standardization of equipment, just as the Air Conditioning and Refrigeration Institute is doing today by use of a broad consensus process.

Compressors. In the late 20's the General Electric Company introduced the first truly hermetic design of compressor in their domestic refrigerator line. This was the famous "Monitor Top" refrigerator in which the convection cooled condenser surrounded the compressor, and from which the evaporator depended into the cooled compartment. With a four pole motor directly driving the crank shaft the speed of 1750 rpm was considered to be venturesome. Initially the refrigerant was SO_2 , but before many years it was changed to R-12. It was about 1930 when Frigidaire introduced domestic refrigerators with R-12 refrigerant. Other manufacturers kept their open compressor designs for the first decade of this period with belt driven open drives and various forms of mechanical shaft seals.

By 1933-34 several designs of R-12 compressors were available. Large systems using R-12 employed modified ammonia compressors such as the 4 cylinder 14" x 10" unit of Fig. 16. For the first time compressors in tonnages of 1/2 to 15 tons could be placed in or immediately adjacent to living spaces without the inherent dangers of NH_3 or SO_2 . Several unusual compressors appeared and though used for a time, then faded out of the picture. Examples are the Savage Arms mercury driven "Archimedes Spiral" compressor (Fig. 17)

and the Zorzi design. (See Fig. 18) In the Zorzi design a single cylinder accomplished two compression strokes per revolution.

The safety of R-12 led to the introduction of self-contained room air conditioners. These units sat on the floor in front of a window and drew condenser air in and out through the window. Weight was 450# or so. Some had hermetic compressors as shown in figures 19 and 20, but many still had belt driven compressors using repulsion-induction motors for drives. By the end of the 30's capacitor start, induction motors, were more common as compressor drives, and often required some kind of equalizing orifice or valve to permit starting.

New forms and shapes of compressors came into being. One firm introduced a line of 3, 5 or 7 cylinder compressors, direct driven at 1150 rpm, with each cylinder sized for about 5 tons capacity at air conditioning conditions. By use of a double shaft motor units from 15 to 70 tons capacity could be furnished from a single set of parts for cylinders, valves and pistons. Another company folded the radial system used by the foregoing design into a "W" configuration to reduce space requirements, and still others introduced "Vee" designs. Coincident with these developments was the introduction of numerous "semi-hermetic" designs with motors in the refrigerant directly driving radial piston arrangements. One such line had cylinder dimensions to give 1-ton of capacity per cylinder, and was earlier used in 3 and 5 ton air conditioners of the water cooled type, for use as "store coolers". Such lines expanded rapidly to some 15 tons capacity by use of multiple compressors in a single unit.

Some early designs of open compressors for R-12 used new versions of shaft seals with very flat nose surfaces, often made of materials designed for the lowest possible friction. Particular attention had to be given to the cooling of the shaft seal, usually by circuiting of refrigerant, or by a spray of lubricating oil. One compressor manufacturer developed a "balanced seal" by mounting the nose on a diaphragm so supported as to reduce the force of the seal contact as crankcase pressure increased. See Fig. 21.

Most compressors went to thin plate type valves. Some retained the trunk type piston with the suction valve in the piston head, while others began to place both valves in the cylinder head. Some used ring type valves to gain more flow area, and reed valves began to appear. At this time valves seem to have been empirically designed, and valve breakage was a rather frequent service problem.

Because of the solubility of the R-12 refrigerant in oil, new problems in start-up were encountered, and the major oil companies endeavored to provide non-foaming oils. The solubility also meant that oil could be carried with the liquid refrigerant into the evaporator to a greater extent than with the previous refrigerants in which oil was not soluble. Oil separators were introduced, and various means within compressors were developed to separate the oil which did return through the suction and assure that it entered the crankcase. Until understood and planned for, this change to solubility of oil in the refrigerant was perceived as a major problem.

The large numbers of portable storage boxes used by the armed services during World War II put new demands on the industry and justified more rapid development of compressor refinements. Air conditioning became important to better use of ship-board spaces, and were employed in some army quarters. So the refrigeration industry remained quite active in its normal equipment fields during the war.

The post war period saw a resurgence of air conditioning and commercial uses. Window air conditioners proliferated, and whole house air conditioning began to take hold. Through-out the latter half of the period specialized companies developed for the manufacture of compressors, so that many companies who did not have their own compressor designs entered the field of air conditioning. These were "mass production" enterprises, and the level of tooling involved served to reduce the cost of compressors and to make the increase of usage proceed at a more rapid rate. By the close of the period the usual compressor speed for sizes under 15 tons capacity was 1750 rpm with a few smaller designs operating with 2-pole motors at 3500 rpm.

Refrigerants. Such refrigerants as CO_2 , SO_2 , methyl chloride and iso-butane were almost completely phased out during this period. Yet early in the period SO_2 had been the refrigerant of choice for domestic and small commercial refrigerators. The 1934 Refrigerating Data Book states on page 138, "The small machine in capacity of 1/20 to 3 h. p. models added by a few firms since their invasion of the comfort cooling field use most of the common refrigerants with SO_2 predominating in the smaller, and CH_3Cl in the larger sizes." The change from these refrigerants came as R-12, and some others of the Freon series became widely available.

By the end of the period, R-11, R-114 were prevalent on some rotary compressors and R-22 was the subject of experiment.

Capacity Control. The need for capacity control, at least in intermediate and larger sized machines, increased with the air conditioning usages wherein loads typically pass through zero at some time of the day, and reach a maximum on relatively few days during the year. Small units have been generally controlled in an on-off manner. Several lines of compressor provided cylinder unloaders as a standard or optional feature during the last half of the period. Most of these systems lifted the suction valve to form a sort of internal bypass and much attention was placed on achieving a low intercept of the "zero capacity" point on the capacity vs. power plot. Fairly rapid operation of the individual cylinder capacity controls, with the resulting short time constant as to compressor capacity, and the long time constants of the refrigeration system caused these systems to act as though continuously modulated. See Fig. 22.

Some open drive compressors were fitted with two or three speed motors to better adapt to load changes, but since demand charges were not prevalent, and efficiency was not as great a concern as later, few were sold.

End of Period. By 1950 small compressors are mass produced in quantity. Frozen foods have entered the market, and storage and transport received a large impetus from World War II usages. Air conditioning of public buildings has become a must. Many residences are centrally air conditioned, but mostly as retrofits since builders do not yet consider it needed or especially salable. Railway air conditioning has improved the comfort and cleanliness in travel. Some buses are air conditioned. Packard even offered an air conditioned automobile.

Methods of rating compressors were well defined, and they could be placed into a system of other components with known ratings to produce required results. Most equipment, except in the fractional horse power sizes was water cooled, using once through flow from city water or cooling towers. Some evaporative condensers were in use. Compressor designs were quite stable during the last decade of this period, but usage was increasing rapidly.

1950 - 1975

We enter this period with a well developed market for frozen foods which could be kept in freezers in the average food store or in homes, and with adequate means of transportation in the frozen state. Room air conditioners are being installed in great numbers in offices and homes, while whole house air conditioning equipment is widely available for homes also. Larger units are available for stores and offices, for rest-

aurants, for process needs. For larger systems engineers understand design and most every building planned also plans its air conditioning system.

There is demand for larger factory assembled units for air conditioning, and in some cases for refrigeration. So many units have been installed that cities are beginning to refuse the use or disposal of more water from water cooled refrigeration and air conditioning equipment. The resulting move to air cooled condensing will place more demands on the compressor.

Automotive air conditioning is just becoming available. A large portion of the installations are made after the car leaves the factory, but this will soon change to a predominance of factory installations.

Compressors. A number of major changes were immediately ahead for the refrigeration compressor. The demand was heavy for lighter weight equipment, for physically smaller size, and for change to welded hermetic constructions. A change from R-22 began as it was realized that a given displacement could produce about 60% more capacity after such a change. Some changes in parts were needed because of the higher pressures, and some new problems developed in oil control because of the multi-phase solubility regimes of oil in R-22. Motor developments were needed to provide the newly required increased power at acceptable efficiency. To make matters even more complicated this change came at the time when air conditioning equipment went to air cooled condensers. This meant still higher pressures on the discharge side, and resulted as well in higher temperatures. But soon the 3-horse power R-12 compressor for water cooled applications became a 5-horse power R-22 compressor suitable for use in air cooled equipment.

By 1960, a further move to increase the performance of a given size and weight compressor came about with the change from 4-pole motors to 2-pole motors, thus nearly doubling the refrigeration capacity of a given frame. A given bore and stroke then produced about three times the amount of refrigeration it did some eight or ten years previously!

Almost concurrently a number of air source heat pumps were introduced for residential use with the result that more hours per year of operation was imposed on compressors and portions of the time a considerably higher compression ratio existed. Furthermore, heat pumps of this type go through frequent changeover from heating to cooling and back again, and have numerous defrost periods, both of which impose greater stress on the compressor.

Perhaps the compressor component to suffer most from these changes in use was the valve system. While plate and reed valves had been used for several decades the technology to determine valve stresses and to optimize valve designs did not exist. One of the many contributions of the Herrick Laboratories here at Purdue University has been their research and understanding of the compressor valve. Herrick has achieved worldwide recognition of the work done, and valve designs now survive their 60 operations per second for thousands of hours, and their operation at very high pressure ratios, and high pressure levels. I consider this one of the major contributions to the continued survival of the refrigeration compressor.

One of the other notable compressor developments during this period is that of the automotive air conditioning compressor. Driven at a speed somewhat greater than that of the engine, and forced to operate at the highest road speeds, and even during forced downshifts at high speeds, the compressor survives short periods of 8000 rpm operation, long term operation at 3000 to 4000 rpm, and still cools the car at 800 rpm. To match its capacity to that of the evaporator and the condenser, it is usually cycled on and off at unusually frequent intervals. Shaft seals, valve systems, and oil management have all been developed to achieve the 3000 hours of operation typical of the life of the automobile. The weight of these unusual, but mass produced compressors, ranges from 14# to 40#. See Fig. 1.

Refrigerants. Reciprocating compressors now use either R-12 or R-22 in a very large percentage of applications. Some cold storage systems still use ammonia, but in such applications R-22 and some other Freon type refrigerants are the most common. Special low temperature applications may use some non-Freon refrigerants, but they are in the large minority.

Capacity Control. The 1950's and early 1960's may have been the period of the greatest consideration to different means of capacity control. The improvements in operation and in efficiency which could be achieved by applying capacity control had been recognized. In one case experimental heat pumps operated with capacity control, and equipped with condenser and evaporator heat transfer systems which maintained good heat transfer even at low capacity had demonstrated a seasonal COP of 4.1 as compared to the operation of the same units without capacity control showing a COP of 2.2 for a season's operation. Yet, the artificially low cost of electricity during most of this period did not encourage the full development and manufacture of such units.

Even though many types of capacity control

were tested in early development phases, none went into production. Even the already accepted cylinder unloading systems, though still used, were not further developed to give low intercepts at no-load for 2-pole R-22 compressors such as had been achieved with 4-pole R-12 machines.

Some further use of multi-speed drives was made during this period. However the ever decreasing size of standard motor frame sizes for a given output has reduced the gains since motor efficiency suffered.

Since 1972, the energy shortages have given new impetus to the potential improvements in efficiency from variable capacity. However, by 1975, the end of this period no significant changes had been observed.

End of Period. Once again compressors have become physically smaller by use of R-22 to replace R-12, and the change to 2-pole motors. Special compressors are mass produced for automotive air conditioning and a large percentage of all cars manufactured are air conditioned. Most new homes in large areas of the country are air conditioned, and many of the older ones have been retrofitted. It is unusual to build any large building without full air conditioning. Aircraft have their own on-board air conditioning systems for use on the ground and in the air. Most cross-country buses and many city buses are air conditioned.

The frozen food counters in supermarkets take as much as 20% of the display space. Refrigerated cases take another 20% at above freezing temperature. We in the east eat California lettuce throughout most of the winter, and enjoy many other benefits of refrigerated transport. Cooked foods are frozen in "TV" portions, and are an important portion of the food market. Hospitals enjoy better recovery records because of the air conditioning in critical areas, and in patient rooms.

In short refrigeration and air conditioning have become the very basis for our so called life style. And at the heart of each refrigeration system or each air conditioning system is one or more refrigeration compressors.

Post 1975

The four years since 1975 are the start of a new era when reductions of energy usage will be paramount. It is also the start of an era when another shift in refrigerants might occur due to environmental concerns, but that is too early to predict at this time. Many of the larger manufacturers now purchase their compressors from specialized manufacturers and thus find it more difficult to make innovative changes

which they by themselves could put into their products. But a brief look at what might be before us may be enlightening.

Compressors. In many ways the design of the refrigeration compressor is a mature technology. In addition to understanding valves due to the work here at the Herrick Laboratory, the mathematical modeling of other functions within the compressor is most helpful. Purdue's models have enabled manufacturers to develop their own models so that compressors are more easily designed for special characteristics such as higher efficiency. Motor design and frame choice are an integral part of the compressor design, and may be considered in the effort to save energy.

Solid state electronics has brought the possibility of efficient speed change over any desired range into the realm of accomplishment. Thus compressors which can adapt to any load by changing their capacity can be expected.

To improve efficiency of devices such as heat pumps which operate over a very wide range of suction and discharge pressure, compressors are needed which under one condition can tolerate the very high suction pressures from heat taken from a storage at temperatures as high as 100F or possibly 110F, and deliver it at only 20 to 40 degrees F higher. Possibly the speed control is the answer since mass flow through the valves would be reduced so that they might survive the high density involved as the gas flows through them. At the same time the same compressor must operate at all the pressures and pressure ratios we now impose on it. Here is a whole new field which the ability to efficiently control speed opens up for the industry, and I wonder if the compressor models we have built can be extended to predict the results and the needed changes.

To a large extent such future thoughts are speculations, but the need is sufficient to justify consideration in depth for such improvements.

Refrigerants. It is doubtful if any new refrigerants are needed for operating reasons. The Freon family covers as wide a range of boiling points as is likely to be needed. The question of environmental effects is still before us, and could cause changes in either the basic refrigerant, or in the methods of handling to avoid any large fraction of production escaping into the atmosphere.

Capacity Control. Presently there seems to be an examination of many of the means of capacity control on which experiments were run in the 1950's. It is of interest that many of the patents then issued are now

suddenly out of print and available only as photo copies.

The most powerful new tool for capacity control is speed control for positive displacement compressors. Solid state inverters can be used to change the 60 cycle or 50 cycle current used in most of the world's power supplies to any desired frequency and voltage. The frequency determines the rotating speed of the compressor motor while the voltage is chosen to give proper operation at the new frequency. Not only can the frequency and hence the speed be reduced from the usual 3500 rpm, but it can also be increased to a speed such as 4500 rpm so that a small compressor can handle short time demands for higher capacity. Induction motors operate well under these variable power supply conditions, the only important loss in efficiency being due to the fact that the same slip is needed, whatever the rpm, to produce the same torque. See Fig. 23. Very likely this loss can be eliminated by use of permanent magnet rotors which would then operate at synchronous speed and avoid slip loss even at full load.

While the possibility of these controlled speed drives is great indeed, the full realization of their energy saving potential will require much greater attention to the design of the heat transfer components of the refrigeration system. New designs will be needed which maintain a high refrigerant side heat transfer coefficient even at low velocity. So perhaps the compressor is leading other components in maturity!

Toward the Future. While we may think that the refrigeration compressor design and utilization has reached maturity, we should note that within the last few months such new features as speed control have been introduced and applied to reciprocating compressors. While little was said herein regarding such other forms of compressors as rotary designs or screw compressors, they may be considered to have reached a similar stage of maturity as to design. We can feel sure that conferences such as this in which we are engaged at Purdue's Herrick Laboratory, and the individual efforts of the various design teams throughout the world will produce further improvements in compressor design. Perhaps the concept of maturity is really the ability to make new designs based on a wide base of experience, and thus expect the results to produce the effects sought. We have come a long way from the 120 rpm massive compressors of a century ago.

Fig. 1 Modern Automotive Air Conditioning Compressor

Fig. 2 1865 Compressor Manufacturing Shop

Fig. 3 1865 Office and management team for compressor manufacturer

Fig. 4 Vertical compressor driven by compound Corliss engine

Fig. 5 Open type water cooler

Fig. 6 Clearance pockets in cylinder wall

Fig. 7 Compressor with manual cylinder by-pass

Fig. 8 First theatre to be air-conditioned, 1914

Fig. 9 Side-by-side engine and compressor operated at 140 rpm

Fig. 10 Vertical compressor used for dual suction pressure

Fig. 11 Double acting horizontal dual suction compressor

Fig. 12 Methyl chloride soda fountain condensing unit

Fig. 13 CO₂ compressor for Navy driven by DC motor

Fig. 14 Synchro motor direct driven compressors

Fig. 15 Compressor shop of the late 1920's

Fig. 16 4 cylinder 14" x 10" Freon-12 compressor made from ammonia unit operated at 180 rpm

Fig. 17 Fig. 17 "Archimedes Spiral" compressor, used mercury liquid