

1984

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Elson, J. P., "The Eccentric Cam: A New Compressor Technology" (1984). *International Compressor Engineering Conference*. Paper 497.  
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## THE ECCENTRIC CAM: A NEW COMPRESSOR TECHNOLOGY

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### ABSTRACT

A new compressor product is introduced which fulfills the market need for a low cost, high efficiency, durable air conditioning and heat pump compressor for the 1.5 to 2.0 ton capacity range. A review of compressor technologies has indicated the optimum compressor for this application would incorporate the durability and versatility of a piston compressor while employing the cost and noise advantage of a fixed vane rotary compressor. To serve this market need, a single cylinder piston compressor has been developed which utilizes both an eccentric cam drive mechanism and a unique assembly concept. Included below is a review of the product design features in terms of efficiency, durability, cost, and noise and vibration. Actual performance results are also given.

### INTRODUCTION

Marketing studies show an increasing use of 1.5 to 2.0 ton compressors for central air conditioning and heat pump systems. Where larger compressors have been utilized in the past, smaller homes, energy efficient construction materials, and increased system efficiency have reduced the size of the required compressor for many applications. Thus, the need was recognized for an improved compressor design to better serve the needs of the 1.5 to 2.0 ton central air conditioning and heat pump markets.

To help identify the optimum compressor design for this capacity range, a study was made of over ten generically different types of compressors and over forty distinct designs. The results of this evaluation indicated there was no single compressor design that is optimum for all applications, but two designs were superior to the others. These two designs are the reciprocating piston and the fixed vane rotary. Both designs have a potential for high energy efficiency with the piston

design being more reliable and versatile while the rotary is lowest in cost and noise.

To better understand and evaluate the differences between these existing technologies and any new compressor technology, design criteria were established for an optimum compressor for central air conditioning and heat pump applications, commercial refrigeration applications, and room air conditioning applications. The selected design criteria are: high durability, low cost, high efficiency, versatility, and acceptable sound and vibration level. Each of these criteria are discussed below.

The most important aspect of any compressor design is the ability to operate reliably over a wide range of applications and environments. Specifically, the optimum compressor must demonstrate potential for long life under such adverse conditions as high ambient temperature, high pressure ratio operation, liquid slugging during startup and heat pump defrost, and the presence of system contaminants. With the rotary compressor, both contaminants and liquid refrigerants can cause wear which increases carefully selected clearances vital to the efficiency and capacity of this machine. In contrast the piston machine handles liquid and contaminants well and generally maintains or improves performance under adverse conditions. This is due to the wearing in of the piston ring which is the only gas seal in a piston compressor. A similar comparison of the two machines could be made at high pressure ratio and high ambient operating conditions, but here the difference is less significant.

Inherent low cost is critical to the economic success of any compressor design. As compressors are designed today, cost studies show the rotary compressor is generally lower in cost than the reciprocating compressor. This cost

differential is largely due to the suspension and general packaging differences of the two designs. The reciprocating piston compressor is internally suspended which results in a larger shell and a more expensive mounting and discharge tube system than is required on the externally suspended rotary. Also, the smaller, more compact construction of the rotary compressor provides a stiffer structure to contain noise and minimize the necessity of internal gas mufflers.

High energy efficiency over a broad operating range was recognized as a key attribute of an optimum compressor design. For the low pressure ratios frequently experienced in air conditioning, the rotary compressor design is often better due to reduced flow losses and the relative unimportance of leakage related losses. For the higher pressure ratios of air conditioning and heat pump applications, the piston compressor is superior due to minimal leakage and the relative unimportance of flow losses. The optimum compressor design requirement would therefore incorporate the low pressure ratio efficiency of the rotary and the high pressure ratio efficiency of the piston. Figure 1 illustrates this ideal performance curve relative to existing technologies for air conditioning.

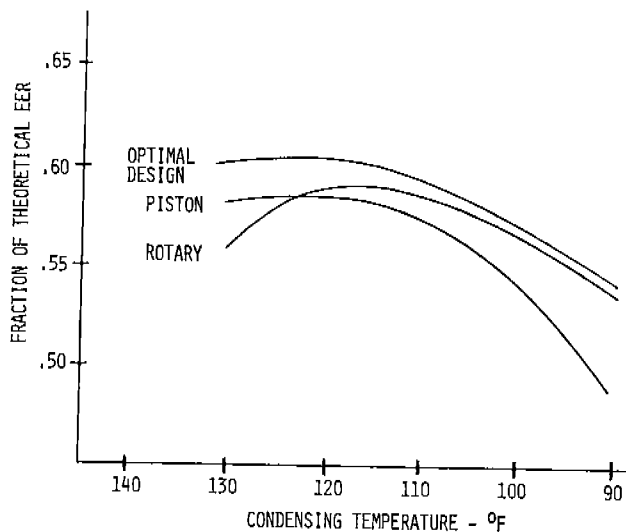


Figure 1. Compressor Efficiency Comparison

and commercial refrigeration pressure ratios of 10.2. For this wide range of pressure ratios, the piston compressor is a very good design due to the excellent sealing characteristics of the piston ring at both high and low pressure ratios. Reliability over a wide range of pressure ratios and applications requires proper cooling. The piston compressor, generally being a low side or suction gas cooled machine, maintains low motor and oil temperatures for the relatively high discharge temperatures caused by either high pressure ratios or high ambient applications. In comparison, the rotary compressor is a high side or discharge gas cooled machine, and may require supplementary cooling means such as liquid injection to control temperatures under the same conditions.

An acceptable sound level is also an important design criteria for compressors. Generally, the acceptable threshold level of compressor noise depends on both application and system size. Room air conditioning units, for example, require lower sound level compressors than central air conditioning units due to closer proximity to the end user. For larger units, where fan noise is significant, compressor sound levels can be somewhat greater than with smaller units. Figure 2 shows acceptable compressor sound level requirements for systems as determined from a survey of system designers.

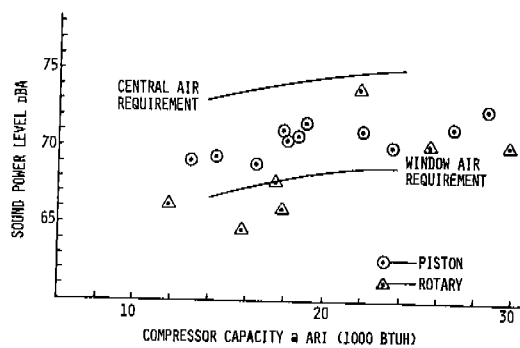


Figure 2. Compressor Sound Level Requirements

Closely related to the efficiency requirement is the need for a versatile compressor design, i.e., a design that has the ability to be both efficient and durable over a wide range of applications. Typically, the efficiency design requirement includes air conditioning pressure ratios of 3.4

Both rotary and piston compressor designs meet these requirements today for central air conditioning with the rotary having an inherently lower sound level. Vibration level is an additional aspect of the overall sound level requirement. Internally suspended piston compressors typically have low vibration while externally suspended rotary designs typically exhibit high vibration. The importance of this difference depends on the degree of vibration isolation incorporated in the system tubing and mounting design. Lower vibration compressors typically are applied with low

flexibility tubing and relatively stiff external mounting components while higher vibration compressors require high tubing flexibility and "soft" mounting components. These applied cost differences make the externally suspended compressor more expensive to apply. However, due to the inherent low cost of the externally suspended compressor, the overall compressor cost in the system is generally less for the externally suspended compressor.

Based on the above review of two existing compressor technologies relative to established criteria, each design appears to have distinct advantages and disadvantages. The piston compressor appears to be a more durable and versatile compressor with excellent contaminant tolerances, excellent liquid tolerance, excellent gas sealing at all pressure ratios, and high durability in all environments. The rotary compressor appears lower in cost and noise due to compact size, no internal suspension, fewer parts, and smoother gas flow. Both designs have potential for high energy efficiency with the rotary being better at low pressure ratios and the piston being better at higher pressure ratios.

An optimum compressor technology should combine the best features of the two designs summarized above. To maintain high reliability and versatility, a reciprocating piston with a ring seal is a fundamental requirement. Then, to minimize the traditional cost penalties generally coupled with the piston design, the internal suspension components must be eliminated. Finally to control noise with this concept, a compact, rigid construction must be employed to minimize noise radiation from the compressor case or shell.

To accomplish these objectives, a unique eccentric cam drive mechanism was identified which allows the entire mechanical section of the compressor to have the same diameter as motors typically used for this size compressor. This mechanism is a variation of the reciprocating piston design where the traditional connecting rod and wrist pin is replaced by a round eccentric cam part. Figure 3 illustrates the three basic parts of the eccentric cam mechanism. The bottom part is an eccentric crankshaft, the part on the left is the eccentric cam, and at the right is the piston which actually wraps around the eccentric cam. The eccentric cam may be viewed as a short connecting rod in which the wrist pin diameter is enlarged so that it encompasses the crank pin diameter.

A kinematic model of the eccentric cam drive is shown in Figure 4. The eccentric arm of the crankshaft is shown as the distance from the bearing center to point A

which is the center of the crank pin bearing. Point B is the center of the wristpin bearing and the line AB is the kinematically equivalent connecting rod for this mechanism. As motion occurs, the eccentric cam translates and oscillates as may be seen by visualizing the motion of line AB.

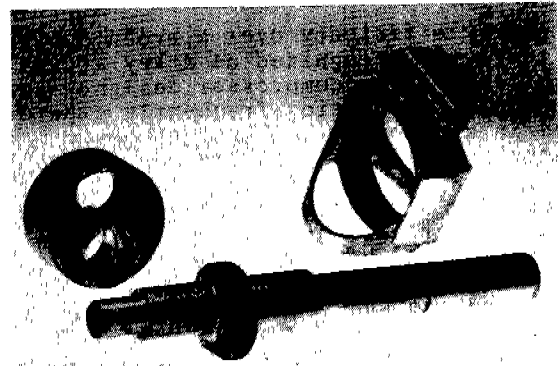


Figure 3. Eccentric Cam Components

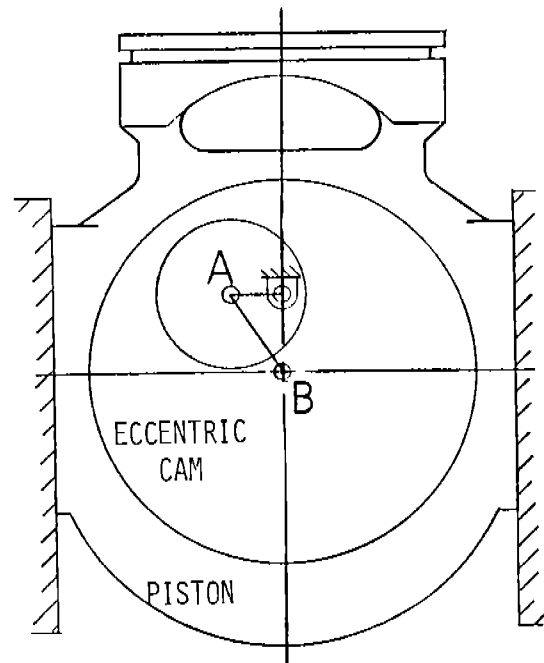


Figure 4. Eccentric Cam Kinematics

Using the eccentric cam mechanism as a basic starting point, a single cylinder compressor design was conceived to satisfy design requirements for a compact, low cost, high efficiency, and durable compressor. The cross section of this design, Figure 5, illustrates the unique assembly feature in which both mechanical and electrical sections are pressed into the shell with the shell serving to replace the bolted fasteners typically used with piston compressors. Specifically, cylinder head bolts and stator to body bolts have been totally eliminated with this design. Design features of this compressor concept are reviewed below in terms of durability, cost, efficiency, and noise and vibration.

#### DURABILITY FEATURES

- No internal suspension
- No flexible internal discharge tube
- Low temperature motor operation
- High contaminant tolerance
- Gas free oil pump
- High flooded start liquid tolerance
- High defrost liquid tolerance
- Low stress valving

The first two features result from the removal of internal components which can influence the failure rate of conventional piston compressors. Low motor temperatures are a result of suction gas or low side motor cooling which is sufficient to maintain low motor temperatures over a wide range of operating conditions and high temperature environments. High contaminant tolerance is the result of sufficient bearing clearance and optimum bearing materials to minimize bearing damage due to foreign materials. Also, in the event contaminants reach the compression chamber, the inherent imbedability of the aluminum piston allows the containment of debris which may become trapped in the cylinder. Both contaminant control features are typical of many piston compressors with normal bearing clearances.

A gas-free, fast priming oil pump is obtained through the use of a positive flow gas vent connected to the crankcase area. With the single cylinder design and the use of a high impedance crankcase venting system, dynamic pressure variations occur in the crankcase with low pressure being realized near the top dead center position of the piston. Using the eccentric bearing of the eccentric cam as a rotary valve, a gas vent connected to the oil pump eccentric arm is exposed to the crankcase only during the low pressure part of the crankcase pressure cycle. This feature serves to quickly remove any refrigerant gas in the lubrication system, and also siphons oil into the pump eccentric arm for rapid oil pump priming.

High liquid tolerance during both flooded start and heat pump defrost are obtained with this design. During flooded start, where liquid refrigerant can fill the entire internal shell volume prior to startup, cylinder pressures can instantaneously reach 2000 psi and inflict high loads on internal mechanical components. The eccentric cam drive and associated bearing systems have proven to be extremely durable under these conditions and have been developed to survive flooded starts with the compressor completely full of liquid refrigerant. During defrost testing, where liquid refrigerant is injected into the suction inlet of the compressor, the degree of liquid slugging with this compressor design is much less than for the flooded start tests. This is primarily due to the tendency for liquid refrigerant not to collect in the oil sump, but rather be pumped immediately through the compressor. Conventional piston and rotary compressors may collect liquid refrigerant in the oil sump during defrost and, as a result, suffer slugging stress and/or some oil loss as the high temperature liquid is boiled from the compressor. The ability of a compressor to maintain sufficient oil charge during liquid slugging can be a more important liquid tolerance parameter than the design strength of the mechanical components. Both high liquid tolerance durability and the ability to retain oil charge are key advantages of the eccentric cam design. Consequently, this compressor has been developed to operate reliably without the use of such protective devices as crankcase heaters and suction line accumulators typically used with heat pump systems.

Low reed valve stress is inherent with the simple strip reed concept used in the eccentric cam compressor design. For both liquid slugging and the dynamic operation of the reeds, safe valve stress levels are obtained.

#### COST FEATURES

- No internal suspension
- No flexible internal discharge tube
- Fewer parts
- Compact size
- Integral mufflers

A low cost design was achieved primarily through the elimination of internal suspension components and the resulting compact design with fewer parts. As discussed earlier, rotary compressors today utilize these same features to achieve lower inherent cost than comparable piston compressors. Additional cost advantage is obtained through the use of integral mufflers which use existing shell structures rather than separate muffler components.

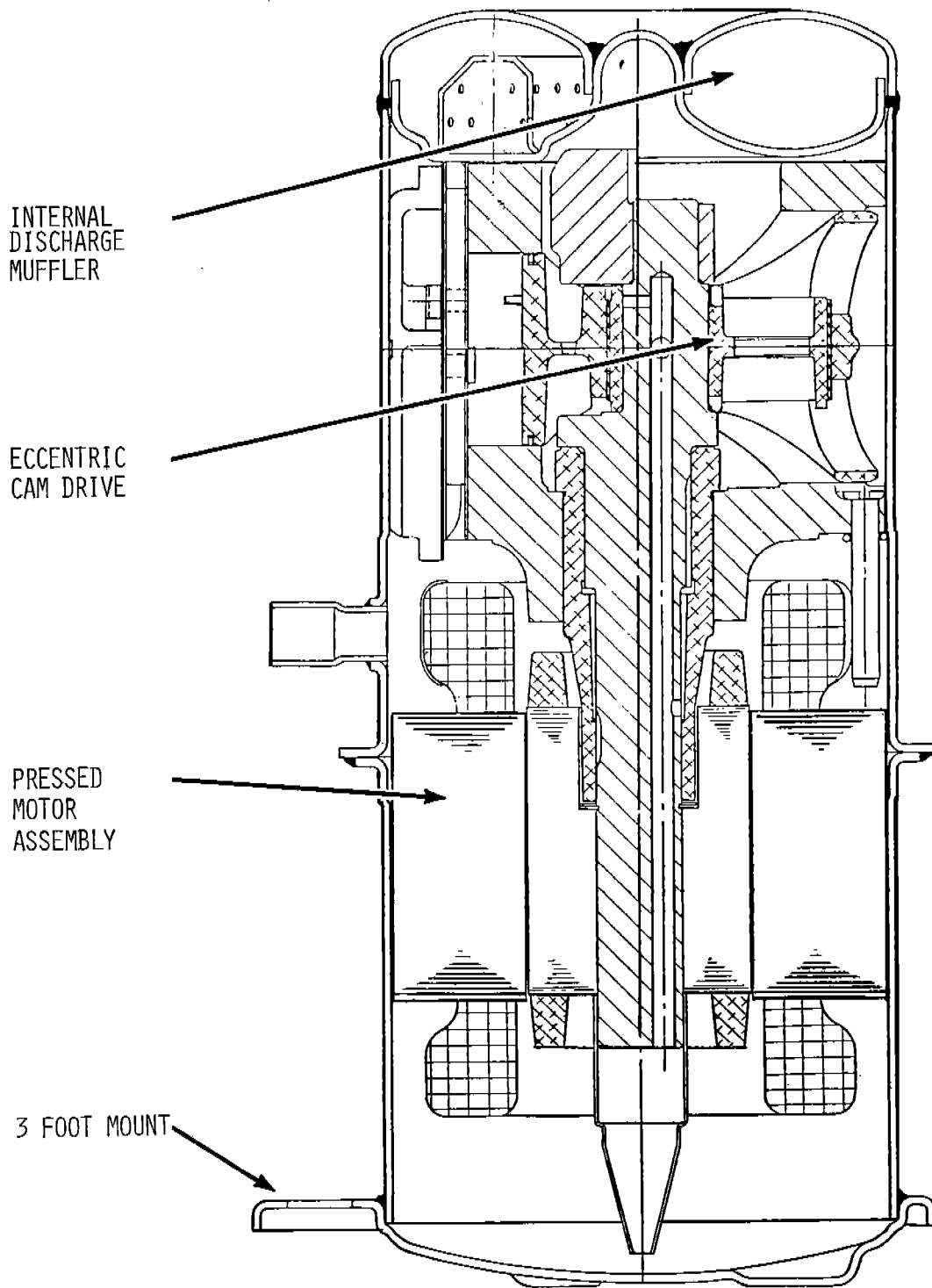


FIGURE 5. COMPRESSOR CROSS SECTION

Conventional piston compressors, for example, typically require suction mufflers to prevent suction gas noise from exciting the shell. With the eccentric cam compressor, the suction muffler is the natural cavity between the mechanical and electrical sections of the compressor. Suction gas noise does not excite the rigid shell structure of this design. Cost effective discharge muffling is achieved through a large volume at the top of the compressor. One-half of this muffler also serves as the outer shell structure.

#### EFFICIENCY FEATURES

- Long discharge period
- High bore-stroke ratio
- Large volume discharge and suction manifolds
- Reduced suction gas heating
- Low temperature motor operation

High efficiency compressor design requires minimal flow loss or pressure drop across the suction and discharge valves. For piston compressors, the flow loss from the discharge valving can be difficult to minimize due to the relatively short duration for the discharge process. For a typical piston-rod design at standard air conditioning rating conditions, the discharge duration is approximately 70° of crank rotation compared to 130° of crank rotation for the suction process. The kinematics of the eccentric cam drive mechanism increases discharge valve open duration by 30% so that nearly 90° of crank rotation is used for the discharge process. Figure 6 illustrates this difference by comparing the eccentric cam displacement characteristic with those of piston-rod and harmonic motion mechanisms.

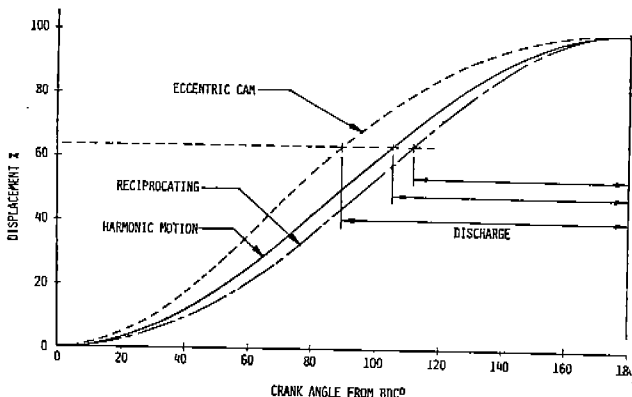


Figure 6. Compressor Displacement Versus Crank Angle

Additional features utilized to minimize flow losses are high bore to stroke ratios and minimal restriction suction and discharge manifolds. Valve port flow losses are reduced by the larger porting area obtained from high bore stroke ratios such as the 2.5 to 3.5 used with the eccentric cam design. Large volume manifolds reduce gas pulsations to the system with a minimal loss of efficiency due to restrictive gas flow.

High thermal efficiency is essential to a high efficiency design. With the eccentric cam design, suction gas enters the upper motor cavity, cools the motor through pulsating flow, and reaches the valving through a hole in the bottom of the cylinder head. This direct suction process minimizes suction gas heating while providing sufficient cooling to the motor to allow optimum motor efficiency.

A final efficiency aspect of the eccentric cam design is the minimal leakage achieved with the piston ring seal. Other piston compressors have this same feature which results in consistent efficiency and capacity over the life of the product.

#### NOISE AND VIBRATION FEATURES

- Rigid assembly
- High piston elevation
- Large volume mufflers

Compressor designs without internal suspension systems must be designed with high rigidity to raise structural resonant frequencies above the level where significant compressor sound energy is present. In this way, sound energy must drive the structure as a rigid body and in the process be greatly attenuated. With the eccentric cam design, both the mechanical and electrical sections of the compressor have contact with the shell which provides both stiffness and damping to minimize sound transmission.

A high elevation piston design was selected to minimize vibration transmission at the base. With the eccentric cam design, vibration levels at the base are comparable to internally suspended compressors; whereas vibration levels at the top end are greater. Other externally suspended compressors such as the rotary design also have some areas of high vibration and as with the eccentric cam design must be controlled through careful installation of the compressor in the system.

Large muffler volumes facilitate the control of gas pulsations while minimizing efficiency loss. The eccentric cam design has significant volumes available to prevent gas pulsation excitation of the system.

## ECCENTRIC CAM SPECIFICATIONS

The first family of compressors of the eccentric cam design was selected to have a capacity range of from 15,000 to 24,500 BTUH at ARI test conditions with R-22 refrigerant. Development specifications for this product were selected to primarily satisfy the market needs for an extremely durable, low cost central air conditioning and heat pump compressor. Key specifications are listed below:

- Energy efficiency
  - 9.5 BTUH/W @ (45°F, 130°F, 65°F, 115°F, 95°F)
  - 15.0 BTUH/W @ (45°F, 100°F, 65°F, 90°F, 82°F)
- Capacity
  - 15,000 BTUH - 24,500 BTUH
- Flooded start tolerance
  - Full shell liquid charge
- Defrost tolerance
  - Full system charge
- Steady state operation
  - High durability over a wide range of heat pump and air conditioning operating conditions
- Discharge and suction gas pressure pulsation
  - 5 psi peak-to-peak maximum
- Vibration
  - 3 mils peak-to-peak maximum at mounting
  - 8 mils peak-to-peak maximum elsewhere
- Noise
  - 73 dBA sound power
- Oil carryover
  - Less than 0.5% by weight
- Cooling
  - Refrigerant only, no air flow required

A nominal energy efficiency level of 9.5 BTUH/W was selected based on the high volume market need for a low cost compressor with sufficient efficiency to meet

cost effective system requirements. Future system requirements may justify eccentric cam products with efficiency increased by 10% to 15%. A second efficiency test condition is included in the specification to emphasize the importance of compressor efficiency at low condenser temperatures.

Durability related test specifications represent extreme conditions but provide an excellent means for rapidly evaluating compressor designs for high durability. Noise and vibration specifications represent threshold levels or upper limits for which a compressor can be applied with acceptable noise and vibration in a typical central air conditioning or heat pump system. The oil carryover specification is typical for most piston compressors and the cooling specification is intended to require the compressor to operate successfully in high ambients with no significant air circulation.

## SUMMARY

A new compressor technology based on the eccentric cam drive mechanism has been introduced to satisfy the 1.5 to 2 ton air conditioning and heat pump market needs. Compressor design features have been outlined and development specifications given. These specifications are being met today and final qualification tests are being completed to verify important durability aspects of this product. Future development of this product concept will be focused on both higher efficiency designs and commercial refrigeration.