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Japanese and American Competition in the Development of Scroll Compressors and Its Impact on the American Air Conditioning Industry

February 1990

Prepared by Energy International, Inc.
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JAPANESE AND AMERICAN COMPETITION IN THE DEVELOPMENT OF SCROLL COMPRESSORS AND ITS IMPACT ON THE AMERICAN AIR CONDITIONING INDUSTRY

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February 1990

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PREFACE

The development of Scroll compressor technology has been a major part of my professional career as a mechanical engineer for the past 17 years. I have participated in this development as a player rather than as a spectator; it has been a challenging and interesting adventure that happens perhaps once in a person's lifetime.

When the basic concept for a gas compression device using involute-walled chambers was brought to us, I was intrigued with the possibilities for such a machine which could have non-pulsating, quiet, efficient performance. A review of prior art indicated that little or no effort had been expended on designing the details of this type of compressor. Therefore, the opportunity to develop a patent position forming the basis for a technology-licensing effort was revealed. From the start, our efforts were focused on developing and refining the component parts of Scroll machines including, of course, suitable bearings and seals so that this machine would be competitive with alternative compressors. During this evolutionary period, we developed a healthy respect for existing gas compressor designs, which were in a mature state of development and manufacture, and which appeared difficult to equal.

The machining of compressor parts incorporating Scroll or involute contours is easily done with gear-driven generation techniques on conventional milling machines when producing parts one at a time. However, the best means for mass production is not obvious. The involute contours are simple to define mathematically, but the configuration of the complete Scroll path does not lend itself to normal high-speed production machining processes. As a result, it was difficult to interest production manufacturing engineers in suggesting possible ways to produce this type of compressor part in quantity. They seemed to be more interested in the possibility that Scroll technology would fail; therefore, they would not have to deal with the production problems. In partial defense of their position, it should be noted that this was near the end of the Wankel engine glorification period when several machine tool builders developed special production equipment, but the market for these machines did not materialize because of problems with the engine itself.

It was only after Japanese-produced Scroll compressors were sold in the U.S. that our industry began to respond to the challenge of manufacturing Scroll compressors in production quantities. Scroll technology was basically reduced to practice in the United States, but the Japanese were the first to make Scroll compressors in production. The fundamental reasons for this appear to be that Japanese manufacturers are better able to carry out long-range product development and the associated production machine tool development activities. Their focus on export products, coordinated economic activity, and a patent system supportive of Japanese industry provides a fertile environment for their industries.

By contrast, U.S. machine tool builders and product manufacturers seem more fragmented, making joint product development activities difficult. Also, the focus of U.S. industry on short-term financial return and distractions caused by merger or acquisition activities does not provide a fertile environment for long-term product development. Even in product development, the U.S. has focused on product rather than process innovation. That has certainly been my focus.

I hope that the events described in this document will be useful to others by bringing to light the necessity for resolving the inequities of the Japanese patent system, improving the cooperation between U.S. product and machine tool manufacturers, and reinforcing the need for U.S. industry to accept the challenges of manufacturing process innovation, as well as product innovation, with some enthusiasm.

John E. McCullough
Arthur D. Little, Inc.
Cambridge, Massachusetts

June 9, 1989

John E. McCullough is a Director of Technology and Product Development at Arthur D. Little, Inc. He is one of the leading inventors of modern scroll technology. At Arthur D. Little, Inc., Mr. McCullough is responsible for projects in all areas of specialized mechanical design, with emphasis on those where proprietary technology can be generated. He is now working on second-generation Scroll compressor designs to improve efficiency, reduce noise, and reduce manufacturing costs. Mr. McCullough holds twenty-four patents on Scroll equipment, and three in the field of commercial combustion equipment.

ABSTRACT

This report examines the technological development of scroll compressors and its impact on the air conditioning equipment industry. Scroll compressors, although considered to be the compressors of the future for energy-efficient residential heat pumps and possibly for many other applications, are difficult to manufacture on a volume-production base. The manufacturing process requires computer-aided, numerically controlled tools for high-precision fabrication of major parts.

Japan implemented a global strategy for dominating the technological world market in the 1970s, and scroll compressor technology benefited from the advent of new-generation machine tools. As a result, if American manufacturers of scroll compressors purchase or are essentially forced to purchase numerically controlled tools from Japan in the future, they will then become dependent on their own competitors because the same Japanese conglomerates that make numerically controlled tools also make scroll compressors.

This study illustrates the importance of the basic machine tool industry to the health of the U.S. economy. Without a strong machine tool industry, it is difficult for American manufacturers to put innovations, whether patented or not, into production. As we experience transformation in the air conditioning and refrigeration market, it will be critical to establish a consistent national policy to provide healthy competition among producers, to promote innovation within the industry, to enhance assimilation of new technology, and to eliminate practices that are incompatible with these goals.

SUMMARY

Scroll compressors, the latest development in energy-efficient compressors for residential heat pumps and air conditioners, are considered the compressors of the future for energy-efficient residential heat pumps and possibly for many other applications. Although an American company has some of the earliest patents on improved scroll compressor technology, it was a Japanese company, Sanden, that sold the world's first commercial scroll compressor for automobile air conditioners in 1981. Another Japanese company, Hitachi, sold the world's first scroll compressor for heat pumps. An American company (Copeland Corporation) began selling scroll compressors for heat pumps in 1987, and another American company (The Trane Company) entered the scroll compressor market in 1988.

If properly designed and manufactured, scroll compressors are believed to be more energy efficient than other compressors of their size, both as a fixed-speed and as a variable-speed compressor. It is also believed that they produce less vibration, and therefore, can be quieter, lighter, and smaller than other compressors. Because they contain a smaller number of moving parts, scroll compressors are also potentially more reliable.

One of the main reasons the scroll compressor was not commercialized more quickly after its invention in 1886 is that its design is a complex curve requiring precise fabrication if it is to be efficient. Such precise fabrication, based on a low-cost, high-volume production schedule, was impractical or impossible until the development of computer-aided, numerically controlled tools. Although numerically controlled machine tools were invented in the United States, in 1971 the Japanese government adopted a plan promoting them; and by the 1980s, Japan absolutely dominated the world market in machine tools.

A major conclusion of this report is that American technology is not far behind the Japanese in inventiveness and the advancement of a technology base for high-quality, long-life refrigerant compressors. It is important to note that the technological incubation time for high-precision, engineering-intensive products such as scroll compressors is significant. That two U.S. manufacturers are now competing effectively in the scroll compressor market indicates that the U.S. industry is keeping pace with international competition. What is important is whether the high-precision machine tool industry in the United States will be competitive.

In securing a leadership position in the world's heating, ventilation, and air conditioning (HVAC) industry, as well as other engineering-product markets, it is concluded that the U.S. machine tool industry must be resurrected. This report presents a consolidated view of the relationship between the machine tool industry and its impact on the basic manufacturing industry using the large domestic HVAC market as an example.

Present HVAC work implies that consistent national trade and industrial leadership are crucial for reviving the machine tool industry, which is the foundation of our industrial strength and national security. The successful introduction of scroll compressors in the early 1980s by Japanese manufacturers (before their U.S. competitors) was primarily the result of the U.S. machine tool industry's suffering great losses during the 1970s when technology for high-precision fabrication and assembly was needed. Scroll technology had to be developed by parallel advances in design engineering and integrated design fabrication technology, which unfortunately, was not occurring in the United States at that crucial time. However, future competition for the basic manufacturing industry in the United States by international conglomerates is now likely.

The sustained competitiveness of American scroll manufacturers is important because, in the future, scroll and other compressors could be important factors in the competitiveness of American manufacturers of heat pumps and air conditioners. If, in the future, American manufacturers of heat pumps and air conditioners purchase, or are essentially forced to purchase, their compressors from Japan, then they could become dependent on their own competition. This is because the Japanese conglomerates that make compressors also make heat pumps and air conditioners. Although Japanese conglomerates now concentrate on small-capacity heat pumps for the Japanese market, they conceivably could begin manufacturing larger-capacity heat pumps for the

mainstream American market, just as they began by selling small cars developed for the Japanese market and progressed to selling larger cars for the mainstream American market. In short, Japanese conglomerates who began by dominating the numerically controlled machine tool industry, are now making a strong bid for the compressor industry. These conglomerates could make a bid for the heat pump and air conditioner industry as well.

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CONTENTS

1.0 INTRODUCTION

Energy conservation in U.S. industrial and economic systems has received increasing attention since the 1970s energy crisis. For applications in the heating, ventilation, and air conditioning (HVAC) market, most energy consumption occurs in vapor compression work, which has developed a need for high-efficiency compressors within the U.S. market. Overseas, particularly in Japan, the need for low noise/vibration is more predominant than the need for an efficiency advantage. The scroll compressor, as explained in this report prepared for the Pacific Northwest Laboratory,[a] is an alternative compression mechanism that offers potential advantages for both markets.

Piston (or reciprocating-type) compressors, the workhorse of the air conditioning and refrigeration industry since the 1930s, offer good efficiency levels and, through proper design and application, work well for a variety of HVAC applications. These applications include air conditioning, refrigeration, and heat pumps. In addition, the design and operating parameters of piston compressors are well developed and understood; the technology presents no particular manufacturing problems.

However, industry requirements for final packages are changing, necessitating corresponding design changes and performance specifications for compressors. Competition, high energy costs, and increased government regulations are compelling domestic manufacturers to develop even more efficient systems, and attaining this goal cost effectively will require compressor efficiencies higher than piston technology can achieve. At the same time, end users are beginning to demand improved comfort characteristics from air conditioning and heat pump systems. System noise is also becoming a greater concern, with local regulations on system sound levels becoming more common. Japanese manufacturers, compelled by a need for quiet systems (appropriate for a high-density housing environment), have developed residential split systems with noise levels typically below those of comparable U.S. models (Copeland 1988).

(a) Pacific Northwest Laboratory (PNL) is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

The new market demands are leading the air conditioning industry away from piston technology to alternative designs. Scroll compressor technology offers many of the features required to meet the future needs of air conditioning heat pump systems, and interest in scroll technology has accelerated with the increasing competition for global market share.

Aiming to capture the bulk of the high-efficiency HVAC equipment market, five Japanese and two U.S. manufacturers are competing in the hermetic scroll compressor market for residential and commercial HVAC applications:

- Hitachi (Japan)
- Matsushita (Japan)
- Mitsubishi Electric (Japan)
- Daikin Industries (Japan)
- Toshiba (Japan)
- Copeland (U.S.)
- Trane (U.S.).

In addition, two Japanese companies have commercialized open-shaft-type scroll compressors for automobile air conditioning application:

- Sanden
- Mitsubishi Heavy Industries.

This research work assesses Japanese scroll compressor technology and its impact on the U.S. HVAC industry. The work builds upon a study previously performed by PNL, the U.S. Department of Energy (DOE), and Energy International, Inc., on Japanese technology for rotary compressors and variable-speed heat pumps for HVAC applications (Ushimaru 1987a, 1987b, and 1988). The previous work covered all types of rotary compressors, as well as reviewed how inverter technology served as a catalyst for industry-wide changes in the Japanese residential and commercial HVAC markets.

The objectives of the present work are as follows:

- to examine Japanese technology for scroll compressors
- to contribute to U.S. industrial competitiveness by facilitating access to the recent advances in these areas
- to analyze how the technical advances taking place in Japan may affect the U.S. HVAC industry.

The basic thesis of this work presents the development of scroll compressor technology not as a technical innovation, but as a successful result of a complex industry-government structure for promoting manufacturing excellence, including patent practice, machine tooling industry, air conditioning equipment industry, and a national policy for exporting manufactured goods.

There is evidence that a significant portion of Japan's machine industry growth in the 1970s was heavily subsidized, either publicly or cooperatively by the Japanese government and industry-banking conglomerates. The expansion of the machine tool industry and its high-precision, high-volume machining equipment was a precursor to the subsequent development of engineering products, which requires extremely high-precision machining. Some of the leading products include rolling piston compressors, scroll compressors, screw compressors, automotive turbo-chargers, and high-performance bearings.

A major conclusion of this report, however, is that Western technology is not far behind the Japanese in inventiveness and the advancement of a technology base for high-quality, long-life refrigerant compressors. In fact, two of the leading U.S. compressor manufacturers currently belong to the fraternity of "scroll manufacturers." It is important to note that the technological incubation time for high-precision, engineering-intensive products such as scroll compressors is significant. That two U.S. manufacturers are now competing effectively in the scroll compressor market indicates that the U.S. industry is keeping pace with international competition, at least in this area. What is important is whether the high-precision machine tool industry in the U.S. will be competitive.

To secure a leadership position in the world's HVAC industry (as well as other engineering product markets), the U.S. machine tool industry will have to be resurrected. This report presents a consolidated view of the relationship between the machine tool industry and its impact on the basic manufacturing industry by using the large domestic HVAC market as an example.

Over 80% of the global market for vapor compressors used for the HVAC industry is controlled by Japanese and U.S. manufacturers. The strength of the Japanese manufacturers is in the area of small-capacity (less than three tons), rotary-type compressors for residential room air conditioning units, refrigerators, and automotive air conditioning units. The strength of the U.S. manufacturers lies in the area of medium- to large-capacity (2.5 to 15 tons) reciprocating-type compressors. Aided by the large domestic market in the United States, several key domestic manufacturers are still quite successful in the compressor market. However, the impending enforcement date of the new efficiency standards for air conditioning and refrigeration equipment, as well as the change in the market demand for product specifications, may significantly reshape the U.S. HVAC industry in the 1990s.

Japan and the United States, the world's two great HVAC industry leaders, will be competing for the new-generation HVAC equipment market share based on the new compressor specifications. Because the scroll compressor concept is appropriate for the medium-size range (3 to 5 tons), the leading manufacturers of scroll compressors will first compete in the U.S. HVAC market where the greatest market demand is in that size range. This is, therefore, an opportune time to reevaluate the foundations of the U.S. basic manufacturing industry and its technological base and to develop a consistent national policy stance based on lessons learned during the 1980s. This will enable the U.S. to compete effectively in the technology-driven global market for the 1990s.

2.0 CONCEPT OF THE SCROLL COMPRESSOR CONCEPT

This section explains basic compressors: how they originated and how they evolved to today's modern scroll compressors. It further explains difficulties, such as potential leakage, in fabricating operational scroll compressors, and how these difficulties are resolved through research leading to new inventions. Japanese and U.S. scroll technology is compared.

2.1 CLASSIFICATION OF BASIC COMPRESSOR TYPES

The compressor is one of the six essential parts of the compression refrigeration system; the others are the condenser, the expansion device, the evaporator, the controls, and the interconnecting piping (American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE 1988). A positive displacement compressor is a machine that increases the pressure of the refrigerant vapor by reducing the volume of the compression chamber by a fixed amount through work applied to the mechanism. Such compressors include reciprocating, screw, rolling piston, and scroll.

These compressors can be further categorized into three major types, depending on the relative motion between the moving parts and the fixed parts of a machine needed to generate the change in the "positive displacement." The three types are as follows:

- reciprocating
- rotating
- orbiting.

In this section, a brief description of major compressor types are presented to illustrate the difference between the scroll compressor and other compressor types. More detailed explanations of each (and other) compressor types and their representative performance characteristics can be found in the ASHRAE Equipment Handbook (ASHRAE 1988).

2.1.1 Reciprocating Compressors

Most reciprocating compressors are single-acting, using pistons that are driven directly through a pin and connecting rod from the crankshaft. The basic structure of a reciprocating compressor is similar to an internal combustion engine. Pistons are enclosed in cylinders with suction and discharge valves. The reciprocating motion of pistons inside cylinders induce periodic change in the internal volume. Refrigerant vapor is introduced into each cylinder during the down stroke of a piston and compressed during the up stroke. The valve mechanism allows the suction and discharge valves to open and close in sequence.

2.1.2 Rotating-Type Compressors

Rotating (or rotary) compressors are characterized by circular, rotating motion, as opposed to reciprocating motion. Their positive displacement compression process is nonreversing and is either continuous or cyclical, depending on the mechanism used. Figure 2.1 shows one common type of rotary compressor, the rolling piston. The rolling piston compressor uses a roller mounted on an eccentric shaft with a single vane or blade suitably positioned in the fixed cylindrical housing. This blade can reciprocate with the eccentrically moving roller.

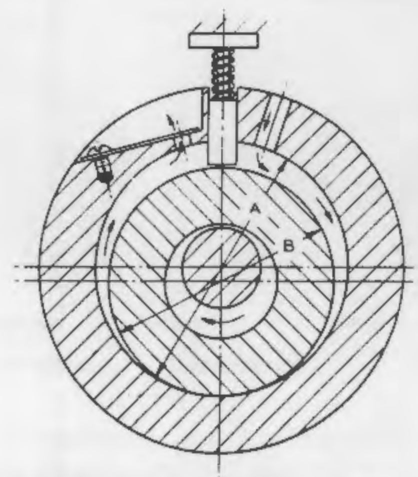

Figure 2.1. Fixed-Vane, Rolling-Piston Rotary Compressor (Reprinted by permission from the 1988 ASHRAE Handbook - Equipment.)

The blade is pressed against the internal wall of the cylindrical housing by a spring. The change in the gap between the rotating piston and the fixed enclosure allows the refrigerant gas to be compressed and discharged into the high-pressure refrigerant pipe. The fixed vane separates the suction chamber and the compression chamber, as shown in the figure.

The rotating screw compressor is a positive-displacement compressor consisting of two helically grooved rotors. The pair of rotors consist of a male (lobes) and a female (flutes or gullies). These are enclosed in a stationary housing with inlet and outlet gas ports (Figure 2.2). The flow of gas in the rotors is mainly in an axial direction. Frequently used lobe combinations are 4+6, 5+6, and 5+7 [male+female; (ASHRAE 1988)]. The screw-type compressor is often mistaken with the scroll-type compressor. However, fundamental differences exist in the compression mechanism, rotor geometry, and operating characteristics.

Compression in a screw compressor is obtained by direct volume reduction with pure rotary motion. For clarity, the following description of the three basic compression phases is limited to one male rotor lobe and one female rotor interlobe space [Figure 2.2; (ASHRAE 1988)].

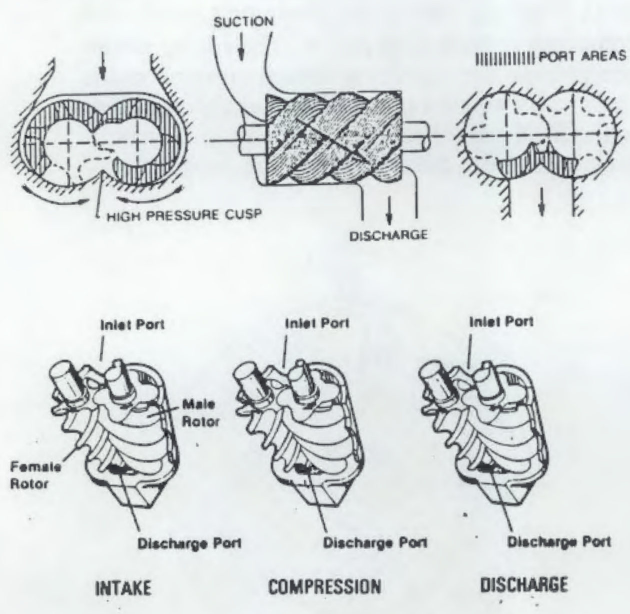

Figure 2.2. Compression Process (Reprinted by permission from the 1988 ASHRAE Handbook - Equipment.)

- **Suction** - As the rotors begin to unmesh, a void is created on both the male side and the female side, and gas is drawn in through the inlet port. As the rotors continue to turn, the interlobe space increases in size and gas flows continuously into the compressor. Just prior to the point at which the interlobe space leaves the inlet port, the entire length of the interlobe space is completely filled with refrigerant gas.
- **Compression** - Further rotation starts the meshing of another male lobe with another female interlobe space on the suction end and progressively compresses the gas in the direction of the discharge port. Thus, the occupied volume of the trapped gas within the interlobe space is decreased and the gas pressure is consequently increased.
- **Discharge** - At a point determined by the designed built-in volume ratio, the discharge port is uncovered and the compressed gas is discharged by further meshing of the lobe and interlobe space.

Rotating screw compressors have application in many air-conditioning, refrigeration, and heat-pump applications, typically in the industrial and commercial market. Machines can be designed to operate at high- or low-pressure levels and are often applied below 2:1 and above 20:1 compression ratios single stage. Commercially available compressors are suitable for application on all normally used high-pressure refrigerants (ASHRAE 1988).

2.1.3 Orbiting Compressor

The modern scroll compressor is an orbiting, positive-displacement compressor. It is a free-standing, involute spiral (scroll) bound on one side by a flat plate or base. In recent manufacturing engineering literature, the scroll is sometimes referred to as the "wrap." Although the scroll compressor is just now going into production, the basic scroll concept has existed since 1886 when an Italian patent was issued. The first American patent was issued in 1905 to Leon Cruex.

2.2 DEVELOPMENT OF SCROLL COMPRESSOR TECHNOLOGY

The basic compression unit consists of a set of two scrolls. One scroll is fixed in space and the other moves in a controlled orbit around a fixed point on the fixed scroll. The two scrolls are phased 180° apart (mirror image to each other). Figure 2.3 shows the principle of operation (ASHRAE 1988). The suction gas enters the scroll set on the outer periphery. The meshing of the involutes forms crescent-shaped pockets, which, starting from the outside, reduce in size, increasing the pressure of the trapped gas. The closed pockets move radially inward until a discharge port is uncovered, resulting in the discharge of high pressure gas. The scroll is unidirectional (ASHRAE 1988); it functions as a compressor when rotated in one direction and as an expander when rotated in the opposite direction.

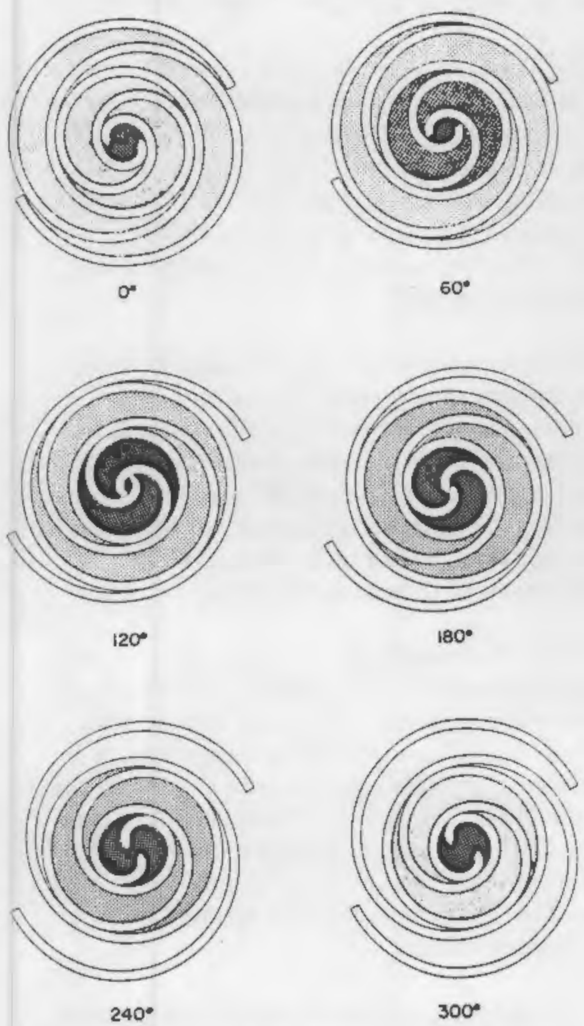

Figure 2.3. Sequence of Operation for the Scroll Compressor (Reprinted by permission from the 1988 ASHRAE Handbook - Equipment.)

The scroll compressor is a constant-volume ratio machine. As such, it has no valves to control the gas flow through the scroll set during normal operation. By controlling the number of wraps on the involute and the location of the discharge port, the optimum pressure ratio is established for a given compressor. Operating losses occur when the compressor is forced to operate at pressure ratios other than the optimum. These losses are small, however, for normal operating conditions (ASHRAE 1988). The performance levels for scroll compressors are generally high if leakage and other losses are controlled. Performance factors at the Air-Conditioning and Refrigeration Institute (ARI) rating point 45°F or (7.2°C) saturated suction temperature and 130° (54.4°C) compressor outlet temperature with 15°F (8.3°C) subcooling and 20°F (11.1°C) superheat can range from 10 to 11 Btu/watt-hour (2.9 to 3.2 watt/watt-hour) (ASHRAE 1988; Copeland 1988).

While the theoretical benefits of the scroll compressor concept, in terms of energy efficiency and the possibility for effective matching with HVAC systems and liquid chillers, were well known, early attempts at production of scroll compressors revealed significant technical challenges. Key difficulties in making an operational scroll compressor were the following:

1. Internal leakage must be controlled for good performance. Leakage sites have included the gaps on the flanks of the involutes and between the tips of the involute and the opposing scroll base plate.

2. The crank mechanism for the orbiting scroll required innovation. The moving or orbiting scroll is driven by a short-throw crank mechanism. The proper indexing of the orbiting scroll relative to the fixed scroll had to be maintained by a coupling that forces the orbiting scroll to translate rather than rotate as a result of the action of the crank.

Presently, flank leakage is controlled through the use of precisely machined scrolls or a linkage mechanism that holds the involute of the orbiting scroll in a flexible manner (the compliant design), against the involute of the fixed scroll. Tip leakage is controlled by a pressure balance that forces the pair of scrolls together axially or by the inclusion of a sealing element at the tip of the involute.

It is important to understand the key difference between a rotary compressor and a scroll compressor. In a rotary compressor, a rotor rotates inside its casing; but in a scroll compressor, an orbiting scroll does not "rotate" against a fixed scroll.

One can imagine that if a compass is placed on a rotor of a rotary compressor (with the compass card fixed to the rotor), the marker needle will always point to the north, whereas the compass card will rotate with the rotor. Thus, the needle and the compass card coincide, pointing to the north only once during their travel around the rotor. If a compass is placed on an orbiting scroll of a scroll compressor, however, the needle and the compass card will always point to the north throughout the compression process. "Orbiting" or "translating" without "rotating" is accomplished by a special crank mechanism.

Prior to the 1970s, the lack of precision fabrication technology (such as numerical control fabrication machines), prevented the development of working scroll compressors (Etemad and Nieter 1988, pp. 56-64). Little was accomplished until the 1960s and 1970s, when scroll development work was undertaken in France and Germany (Beseler 1987). The scroll mechanism was tried in a variety of applications ranging from vacuum pumps to a Brayton cycle expansion engine. In 1972, Arthur D. Little, Inc. (ADL) was introduced to the scroll concept. ADL further developed the concept, obtained several patents, and then marketed this technology via license agreements in a variety of industries (Beseler 1987). Potential uses included vacuum pumps, liquid pumps for various liquid types, gas expanders, engine blowers, and other applications.

The bulk of the development funds for ADL's efforts came from the Office of Naval Research (ONR), whose application opportunity was a naval ship propulsion (quiet ship propulsion) system using a superconducting electric motor cooled by liquid helium. The scroll concept was to be applied in a cryogenic helium refrigerator (Moore 1973). This research work resulted in the production of a two-stage scroll compressor with a compression ratio of 16:1, mass flow rate of 90 cfm, with forced oil lubrication in the compression chamber. Shaft horsepower was 13.2 hp per stage, and orbiting scrolls had an outside diameter of 464 mm in the first stage and 292 mm for the second stage. The unit was quite large in terms of capacity compared with the subsequent application in the residential HVAC market.

Joint development of a commercial scroll air conditioning compressor by ADL and The Trane Company began in the early 1970s (Beseler 1987). The two firms initiated a joint development program resulting in the construction of the first operating hermetic compressor in 1977, followed by evaluation and testing. Trane made several significant improvements, resulting in the second-generation design introduced in October, 1978 (Beseler 1987). A third generation compressor was developed and operated in October, 1981. At this stage, Trane's concept included various sizes (up to 15 tons). From this work, 10- and 15-ton designs evolved.

The Trane/ADL development resulted in several key patents, including a tip seal and other compliant features that will be discussed later. Today, Trane holds the exclusive license from ADL for manufacturing air conditioning scroll compressors with ADL patents larger than 1.5 tons for use in building comfort systems, excluding automotive air conditioning (Beseler 1987).

Daikin Industries received a manufacturing license for scroll compressors in air conditioning equipment from Trane/ADL (JARN 1988). Daikin made its own technical improvements based on Trane's technology. However, the manufacturing license from The Trane Company specifically prohibits use or sale of Daikin scroll products in the United States or Canada (JARN 1988).

Although detailed license agreements for scroll compressor technology are difficult to determine, it has been reported that ADL successfully entered into manufacturing and sales license agreements with several Japanese manufacturers (Morishita and Sugihara 1985a). In addition to Daikin's license in air conditioning equipment, Sanden (Sankyo Electric prior to 1982) has a license for manufacture and sales of scroll compressors in the automotive air conditioning market.

Over 100 years of technological evolution was required to produce commercial-grade scroll compressors. In the following section, the developmental history from the early days of invention to today's race for commercialization is presented.

2.3 EARLY HISTORY OF THE SCROLL COMPRESSOR

The original U.S. patent granted to Leon Cruex (1905) contained a set of ideas making possible today's commercial production. For example, Cruex's invention included the following:

- compensation of the thrust force exerted on the base plate of the fixed scroll in the axial direction by proposing a fixed scroll with involute shape on both sides of the base plate and matching orbiting scrolls that are mated in the opposing direction

- a spring-loaded seal on the tip of the orbiting wrap

- proper movement of the scroll pair by fixing one scroll and allowing the other to orbit, or allowing both scrolls to orbit in the opposite direction of each other.

Cruex proposed these ideas as part of scroll expanders (engine) rather than a compression device. Other later inventors and their work in developing the scroll compressor are explained below.

Rolkerr (1921) was granted a patent for a scroll compressor. He proposed a driving mechanism for the pair of serolls joined in an eccentric fashion by using several connection pins and a gear mechanism to coordinate the proper motion. He also proposed an idea for joining the pair of scroll members by fabricating a groove in the fixed scroll.

Johnson's patent (1932) proposed a connection mechanism for the eccentric alignment of the scroll members using a ball joint. Today, this mechanism is used in some commercial products.

Ekelof (1933) focused on the leakage problem and reliability by suggesting the use of a tip and flank seal. Furthermore, Ekelof suggested using an eccentric bushing to support the thrust force generated by the compression work and centrifugal force of the orbiting scroll. The eccentric bushing has a vibration control mechanism, and the flank seal was proposed with either spring loading or back-pressure loading by intermediate gas pressure. Ekelof's suggestions are an integral part of modern scroll compressor technology.

Although the idea was not complete, Mikulasek's 1949 patent proposed a spring-loaded flank seal as well as the use of an Oldham ring for the driving connection of the orbiting scroll. His proposal for using an eccentric ring joint actually did not provide proper translation from suction to discharge, especially the geometrical constraints near the discharge port location. However, his suggestions for seals and the Oldham ring are still considered practical today.

Prior to the 1950s, simple solutions to the difficult problems of sealing, thrust compensation, driving mechanism, and discharge port location had already been invented. For two decades (in the 1950s and 1960s), patent inventions appeared to be centered around elaborate solutions to identical technical difficulties. In fact, most of the elaborate solutions proposed during that time are not used today. For example, complex driving mechanisms were proposed by Mikulasek (1950), two patents by Girvin (1957, 1958), Jones (1958), and Audemar (1961).

Mikulasek's (1950) proposal was to use a set of three pairs of discontinuous scroll members driven by three separate crank shafts. A balance weight was suggested to compensate for the centrifugal force. Girvin (1957,1958) proposed the use of several eccentric cranks, but possible leakage problems and the thrust-loading compensation were not addressed. Jones' (1958) invention used a scroll member of at least 360° involute for a pump application. His invention disclosing a crank driving mechanism resembles the system in use today. However, the geometrical description of the scroll alignment and flank leakage control mechanism were neglected in the disclosure. Audemar (1961) was concerned with the axial thrust compensation and proposed a set of scroll pairs mated in an opposing fashion. The system used several complex cranks using elaborate gear units. However, this design is not practical.

An extensive body of knowledge and invention was accumulated during the 1970s. Many ideas developed during this time were actually a practical extension of previous inventions. Engineering development and fabrication technology improved dramatically, and some scroll expanders and compressors were fabricated and tested, thereby further revealing the source of technical difficulties and possible engineering solutions.

Based on his experience with the side seal used in the Wankel engine, Moriyama (1970) suggested a spring-loaded tip seal that was to fit in a groove at the tip of the orbiting scroll. This idea correctly addressed the tip leakage problem and that tight fitting of the based plate (of the fixed scroll) and the tip involute (of the orbiting scroll) does not guarantee long-term reliability due to uneven wear caused by nonuniform thrust distribution. His proposal of the pressure-loaded tip seal is used in a practical design.

Dovorak and Lepsi (1971) proposed not only a scroll pump concept, but also a technique for fabrication. The proposed fabrication technique combined linear machining and rotating machining. This method has been tried in early versions of scroll machining at Mitsubishi Electric Corporation (Morishita and Sugihara 1985b). Dovorak and Lepsi (1971) also addressed the axial thrust compensation method using intermediate pressure pockets, as well as an idea for flank seal material.

Vulliez (1974) proposed using a scroll compressor in conjunction with a diaphragm separator to prevent lubricating oil from entering the compression chambers. Because the idea was to build an oil-free (dry) compressor, flank and tip contact between the fixed scroll and the orbiting scroll was not circumvented in the design (i.e., the precise contact remained an important manufacturing task). Sealing problems, however, were not addressed. Though a radical design, this idea is being reconsidered for developing an oil-free compressor (Coffin 1982).

Bennett and Hatfield (1974) suggested a combination of Oldham ring, tip seal, flank seal, and using intermediate pressure pockets for better leakage control. They also projected that given a good leakage control mechanism, using the natural pressure cycle available in the compression process of the scroll compressor, the wear on the wrap and the base plate actually improves over time; i.e., the idea of a scroll compressor that "wears in" over time was introduced.

2.4 RESEARCH WORK AT ARTHUR D. LITTLE, INC.

Significant contributions were made by the researchers at Arthur D. Little, Inc. in scroll compressor design, fabrication, and engineering solutions to the traditional difficulties associated with scroll technology.

Young's patent (1975) pointed out the fundamental difficulty in practical production of scroll compressors. He addressed the problems of leakage control, wear, and discharge port positioning. He clearly determined that flank leakage must be controlled, not only by high-precision fabrication of the wrap section, but also by high-precision assembly. Furthermore, he advocated the idea of seals that will "wear in" rather than "wear out" as the only practical means of maintaining high operational efficiency over time. Several key inventions were disclosed in this patent, including a method to maintain the alignment angle of the orbiting scroll, flank seal, tip seal, dynamic balancing of the moving parts, and the use of back pressure to improve tip leakage control. Young's proposal was based on the application of scroll compressor technology in automotive air conditioning.

Further patent improvements were made by Young and McCullough (1975), seven by McCullough (1975, 1976a, 1976b, 1977, 1978a, 1978b, and 1978c), Shaffer (1976), Hidden and McCullough (1979), and Armstrong and McCullough (1980). All these inventions made many fundamental proposals for practical solutions used by manufacturers today, including the following:

Young and McCullough (1975)

- flank seal
- crank design
- tip leakage control by gas pressure
- technique for maintaining proper alignment angle of the orbiting scroll
- design procedure for high-pressure ratio with a shorter involute wrap.

McCullough (1975, 1976a, 1976b, 1977, 1978a, 1978b, and 1978c)

- crank arm design
- improved flank seal due to the centrifugal force

- improved tip leakage control by intermediate gas pressure
- fine adjustment of scroll matching after assembly
- scroll-cooling method (to reduce thermal expansion of the fine-tuned wraps)
- Teflon®-coated tip seal
- thrust-bearing design
- spring- and gas-load thrust compensation and tip leak prevention mechanism
- new design for the Oldham ring and its connection mechanism with the crank.

Shaffer (1976)

- spring-loaded tip seal
- use of pressure to improve tip sealing
- use of intermediate gas cooling to improve compression efficiency.

Hidden and McCullough (1979)

- scroll liquid (fuel) pump
- suggestions for a scroll pump design suitable for volume production.

Armstrong and McCullough (1980)

- eccentric bushing to form zero-tolerance flank contact
- use of discharge gas pressure to minimize the deformation of the base plate at the center
- applications of a scroll device as compressor, expander, and engine.

2.5 PATENT TREND IN JAPAN

Many patents have been granted to Japanese manufacturers on inventions related to scroll compressor technology. Hitachi, Ltd., alone claims to have over 270 patents on scroll compressor technology as of 1987. However, crucial differences exist between U.S. and Japanese patent law, and these differences may have impacted the scroll compressor development.

As of 1981, 129 countries had patent laws that protected inventors of new ideas from noninventors during the patent process period and allowed a financial benefit through the eventual manufacture and sale of inventions after the patent was granted. Both Japan and the United States have a set of patent laws and penalties associated with infringement of patents.

Also, in addition to invention patents, Japan is one of twelve countries who have "application patents" that provide similar protection to the original proposers of new applications. The application patent, also known as the "utility model" in Japan and in several other countries (Kirk),[a] relates to the shape or construction of articles having industrial application. To be eligible for registration, the utility model must be novel (original) and not obvious, although a lesser degree of inventiveness is required than for patents. In Japan, utility models have a 10-year term from filing, whereas patents have a 20-year term from filing or 15 years from publication for opposition, whichever is shorter. Countries that have "application patents" are Korea, the Philippines, Morocco, West Germany, Italy, Poland, Portugal, Spain, Mexico, Chile, and Brazil. Other countries only give legal protection to inventors of original ideas and not to those who implement original inventions for financial gain.

The difference between the Japanese patent law and its enforcement and that of the United States is creating a great deal of controversy in the international business arena. For example, during the 25th Japan-U.S. Business Conference (held in Tokyo July 10-12, 1988), Japanese and U.S. business and government leaders agreed to harmonize their laws to afford better protection for patents and intellectual property (*The Japan Economic Journal* 1988). The frustration of the international business and scientific community is expected to continue, even

® Teflon is a registered trademark of E. I. duPont de Nemours and Company, Wilmington, Delaware.

(a) Private communication with Michael K. Kirk, Assistant Commissioner for External Affairs, United States Department of Commerce Patent and Trademark Office, April 1989.

though Japan expressed a plan to bring its patent laws up to the international standard.

Part of the difficulty stems from the fact that while most Japanese participants understand that Japanese and U.S. patent procedures differ, they are unaware that the practical implementation of the laws is drawing complaints from the United States. Many U.S. practitioners believe that Japanese courts have been less than friendly in providing a fair measure of protection to patented inventions (Kirk 1989). A comparison of some key differences between the Japanese and the U.S. patent system are as follows:

- U.S. patent applicants must include exhibits of similar inventions to help the patent attorneys determine the originality of the invention. However, in Japan, even mild alterations to an existing technology can be awarded patents.
- The length of time required for patent review is 2 years (average) in the United States and as much as 6 years in Japan. This allows a window for Japanese companies to slightly improve or genuinely innovate on U.S. patents already in the works and basically flood the patent office with similar applications for the same technology (*The Japan Economic Journal* 1988).

The time lag for applications is especially crucial because applications in the United States are not made public until the patent is granted, while in Japan they are made public 1-1/2 years after submission. According to the Japanese Patent Office spokesperson, they make the applications available to the public to keep others from reinventing something that is in the process of being patented (*The Japan Economic Journal* 1988).

Many other countries have early publication and deferred examination systems. For example, the European Patent Office also publishes applications 18 months after filing, and allows examination to be deferred until a request is made within 6 months after publication. However, Japan's systems of deferred examination, i.e., permitting a request for examination to be made up to 7 years from filing an application, has been criticized by the U.S. government (Kirk).[a] In fact, the deferred examination system in Japan has a major disadvantage confronting applicants, especially foreign applicants who have difficulties with the Japanese language. With more than 2.5 million pending Japanese patent applications (yet to be examined), the system could conceivably be the subject of a request for reexamination and subsequent patenting (Kirk 1989). With the existing law, Japanese inventors, driven by the need to have the earliest postmark, are inclined to rush even minor, insignificant inventions to the Patent Office. Only later do they begin to seriously consider whether they want the application to be further examined. Furthermore, each Japanese patent application claim has a very narrow definition of invention (i.e., protecting only the specific part of a mechanical system). This is because prior to 1987, the patent law limited an applicant to one claim per application in Japan. The practice continues despite the 1987 amendment that authorized multiple claims in an application (Kirk).[a]

According to *The Japan Economic Journal* (1988), as many as 540,000 inventions were submitted to Japan's Patent Office in 1987. Only about half, 256,000 cases, went on for further examination. Of those, about 107,000 were granted patent rights, or only 20% of the original applications. A Japanese Patent Office spokesperson indicated that the Philippines and the United States are the only two countries in the world using "first-to-invent" patent laws, while Japan follows the rest of the world with "first-to-file" laws (*The Japan Economic Journal* 1988).

Today, Japan claims to be the world's leading innovator of technology; this is an attempt to shed its image as the world's leading copier of original inventions. In 1979, 174,569 patent applications were filed (an increase of 104.8% from the previous year). During the same time period, there were 185,455 filings for application (an increase of 100.9% over 1978). The total number of "inventions" supposedly reached 360,024, the largest in the world (Furukawa 1981). However, upon closer examination, there is a built-in mechanism for filing minor alterations and applications characteristic of the Japanese patent situation. From the U.S. perspective, many of these applications constitute noninventions, and in fact, copy other inventors by making only minor and insignificant alterations. If we take the proportion of patent applications to eventual granting of rights (as reported in *The Japan Economic Journal*) of 185,455

(a) Private communication with Michael K. Kirk, Assistant Commissioner for External Affairs, United States Department of Commerce Patent and Trademark Office, April 1989.

applications, only 37,000 patents would have been granted. This is not extraordinarily high compared with the United States and some European countries. Because of the tolerant attitude and the insignificant difference between "application patent" and "invention patent," it is difficult to estimate how many of these Japanese patents would be considered patentable under the laws of other countries.

In this light, we present a trend of Japanese patents for scroll technology. Until 1978, ADL was virtually the only company applying for patent rights on scroll technology in Japan. Considering the time span of 1-1/2 years for patent applications to be made public, several ADL patents were publicly disclosed between 1973 and 1979. In 1979, Japanese manufacturers began a massive effort to file for both invention patents and applications patents. Hayashi (1986) reported the following:

- In 1980, foreign companies made 3 applications; Hitachi made 26 and Sanden and Mitsubishi Electric each made 25.
- The patent applications increased dramatically in 1984 to 70 from Hitachi, 40 from Mitsubishi Electric, 33 from Mitsubishi Heavy Industries, 31 from Sanden, 21 from Sharp, 19 from Toshiba, and 16 from Tokiko.
- Filings for application patents also increased significantly in the same period.

Morishita and Sugihara (1985a) gave a detailed examination of patented scroll concepts from Japan between 1975 and 1984, but the Japanese patents appear to be on a similar track with contributions from ADL and others.

For example, in the field of automotive air conditioning, several engineering modifications to tip seal, axial thrust compensation, and balance weight were proposed in the 1970s. It is evident that research work in Japan was based primarily on working experience from the actual building and operating of test scroll units in an effort to improve prior work. In the following discussion, "patent announcement" indicates that an application was made public 18 months after the submission while still being reviewed by the Patent Office, whereas "patent" indicates that the patent right was actually granted to the applicant. It is important to note the time gap between the "patent announcement" date and "patent" date.

The patent announcement of Terauchi et al. of Sanden (1980) proposed a gas-loaded tip seal by machining a groove at the tip of the fixed scroll. Terauchi, by analyzing in detail the dynamics of the flank interaction between the scroll pair, also proposed a modified wrap design in his patent of 1983. Because its design is slightly offset from the true geometrical involute, the flank contact tolerance will be tighter in the high pressure pockets (towards the eccentric center), thus avoiding plate-to-edge contact in the radial direction in the low-pressure pockets.

Hiraga et al. of Sanden (1983, patent) proposed maintaining a constant flank seal force regardless of the crank speed. This design was based on a dynamic analysis of the translating scroll pair. By allowing the crank to translate about a point offset from the eccentric center, nearly constant sealing force can be achieved by adjusting the translation axis with the change in crank speeds. This design also included a balance mechanism such that the sealing force does not depend on the crank speed. The objective of these proposals was to make a scroll compressor suitable for operation at high crank speeds: up to 13,000 rpm in the automotive air conditioning application (Hiraga 1983).

For hermetic compressor design, Shiibayashi et al. of Hitachi (1982, 1980 patent announcement) proposed the use of intermediate gas pressure to push the orbiting scroll against the fixed scroll base plate by drilling several holes for gas injection. It appears this idea is the principal reason for making the Hitachi design a "fundamentally unique invention." However, as described previously, the use of gas-loaded orbiting scroll, gas- or spring-loaded tip seal, and injection of high-pressure gas in an intermediate chamber had all been proposed in prior art inventions (see Ekelof 1933; Bennett and Hatfield 1974; Young 1975; Young and McCullough 1975; Armstrong and McCullough 1980; Shaffer 1976; and others).

Other inventions proposed by Japanese researchers are based on fabrication techniques, new materials, lubrication oil management, and driving mechanisms.

Morishita et al. of Mitsubishi Electric provides (1981, patent announcement) a detailed analysis of oil-refrigerant interaction in a flank gap of between a few microns to as much as a few tens of microns. Even at a small gap of this magnitude, significant gas leakage was observed even with oil loading of 50% by weight. Thus, these researchers confirmed the need for mechanical seals such as the tip seal and the flank seal, both of which are used in combination with a variable position crank. Allowing the crank to orbit about a point that is offset from the eccentric center of the scroll pair appears to be repeated for applications in variable speed systems (Ishii et al. 1988; and Hirano et al. 1988).

In materials innovation, a ceramic scroll was proposed (Japan patent announcement 1983), as well as an aluminum base material coated with engineering plastics (1984, Japan patent announcement).

The present research effort yielded no significant contributions from Japanese patents in terms of original inventions to aid the commercial production of scroll compressors. The range of patents by Japanese manufacturers is limited to alteration of the prior art by ADL patents. The contribution Japanese manufacturers made, however, was in resolving the technical difficulties associated with scroll compressor technology through precision fabrication and assembly.

3.0 DESIGN AND APPLICATION OF SCROLL COMPRESSOR

The advent of computer-aided engineering (CAE) and computer-aided manufacturing (CAM), together with rapid advances in numerically controlled fabrication machines, has facilitated the commercialization of scroll compressors for residential and commercial HVAC markets. Sanden was the first company to claim the commercialization of scroll compressors. Its open-shaft compressors for automotive air conditioning applications entered the market in 1981 (Terauchi et al. 1983). Sanden was followed by Hitachi, whose hermetic compressors for commercial HVAC applications entered the market in 1983.

The scroll compressor concept has many advantages: a high energy-efficiency rating over a wide range of operation, continuous refrigerant discharge characterized by low-torque pulsation and low vibration, ease of starting and restarting, and a minimum number of moving parts. However, these advantages are challenged by the requirement of high-precision fabrication and assembly technology, seal technology for refrigerant leak prevention, and bearing and torque balancing during the compression cycle.

The basic structure of the scroll compressor, as shown in Figure 3.1 (Etemad and Nieter 1988, pp. 56-64), includes five major components: a fixed scroll, orbiting scroll, antirotation coupling (Oldham ring), crankshaft, and crankcase. The two scrolls are generally defined by involutes of circles and assembled with a 180° phase difference. The fixed scroll is attached to the crankcase, while the moving scroll orbits by means of a simple crankshaft. The antirotation coupling is accomplished by an Oldham ring, permitting the moving scroll to orbit in one direction, thus preventing any counter-rotation caused by pressure differential between the suction port and the discharge port during off-mode.

As described in Section 2.0, the orbiting scroll and the fixed scroll mate in a matching involute shape, which creates a series of paired, symmetric, crescent-shaped pockets. The suction gas is brought in simultaneously from the periphery of the scrolls. As the crankshaft rotates (with the orbiting scroll), the pair of symmetric crescent-shaped pockets move towards the center, reducing the volume of the pockets. At the center, the pair of pressurized pockets are merged together and discharged through a single port. Generally, it takes 1-1/2 to 3 shaft rotations to bring the fluid from the suction to the discharge stage.

The following subsections explain the advantages of the scroll compressor design, as well as provide background information on scroll compressor manufacturing. In general, however, the scroll compressor is 3 percent better than the reciprocating compressor (Bush and Elson 1988).

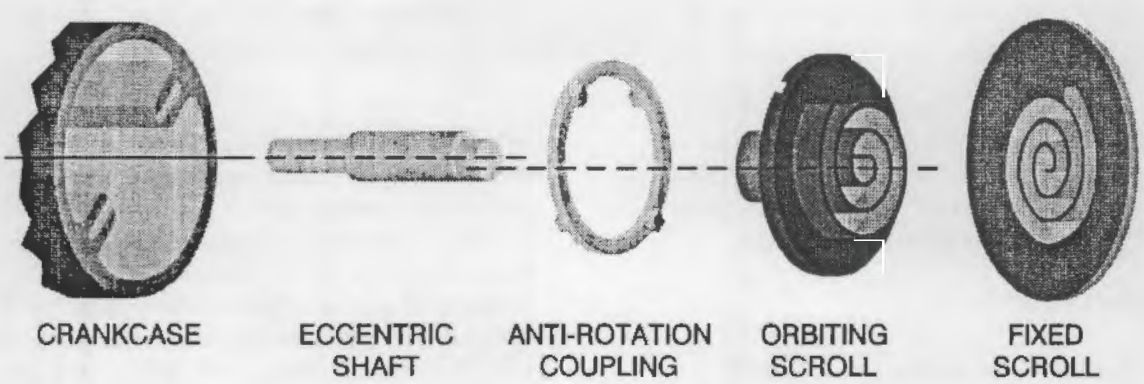

Figure 3.1. Basic Scroll Structure (Reprinted with permission of United Technologies Carrier, Carrier Corporation.)

3.1 ADVANTAGES OF THE SCROLL DESIGN

When compared with piston technology, scroll technology has several significant advantages inherent to the design. The advantages are explained in the following subsection.

3.1.1 Simplicity

Figure 3.1 illustrates the five major scroll compressor components. The Trane Company's analysis (Beseler 1987) indicated that Trane's scroll had 68 parts, compared with 187 parts for a similar-capacity reciprocating compressor. It is generally agreed that, given good wear characteristics, fewer parts mean higher reliability.

3.1.2 Efficiency

The scroll compressor offers three efficiency advantages over piston compressors:

- The suction and discharge processes of a scroll compressor are physically separated, reducing heat transfer between the suction and discharge gas. In a piston compressor, the cylinder is exposed to both suction and discharge gas, resulting in high heat transfer. This reduces the efficiency of the compressor.

- The scroll compression and discharge process is continuous and smooth. A scroll compressor compresses gas in approximately one- and one-half revolutions (Copeland 1988), as compared with less than half of a revolution for a piston. The discharge process occurs for a full 360 degrees of rotation versus 30 to 60 degrees of rotation for a piston.

- The scroll design requires no valves. While piston compressors require both discharge and suction valves, the scroll design does not require a dynamic (moving) valve. This reduces pressure losses caused by sudden expansion of gas.

3.1.3 Quiet Operation

The continuous compression cycle provides low-torque variation through continuous compression of refrigerant up to three complete rotations of the crankshaft. A reciprocating compressor, on the other hand, has one or more pistons moving back and forth. Small torque pulsation of the scroll compressor results in smooth, quiet operation, and possibly improves the motor life.

3.1.4 Matching with Variable Speed Operation

The scroll design benefits from rotary compression movement, large suction and discharge ports, and absence of valves. Because these features tend to reduce the pressure loss during high-speed operations, the scroll design in the area of variable speed technology is further improved (Copeland 1988).

3.1.5 Matching with Heat Pump Application

Figure 3.2 shows a demand curve for a typical single family residence (Copeland 1988). This curve illustrates heating and cooling requirements over a range of ambient temperatures. The example plot is for a residence that requires approximately 36,000 Btu/hour of cooling (i.e., 3 tons) at 95 °F ambient outdoor temperature. The typical house load for heating and cooling requirements is also noted in the figure. Comparing system capacity with house demand illustrates several issues familiar to the heat pump design (Copeland 1988):

- Above the cooling balance point, the system has inadequate capacity to maintain comfort.

- Below the cooling balance point, the system has excess capacity:

  - Excess system capacity loads the system coils more heavily than necessary, resulting in lower system efficiency.
  - The system must cycle on and off more often to match the demand of the home, resulting in additional efficiency losses and reducing comfort.

- In heat pump operation, the heat pump is only able to satisfy the house load at or above a certain ambient temperature (typically designed at 25 °F). Below that temperature, supplemental heat is required, which is both expensive to the homeowner and exacerbates peak demand problems for the electric utility. Above that temperature, the system suffers on/off cycling losses as indicated above.

To overcome these capacity-demand matching problems, a heat pump system using a scroll compressor is shown for comparison (Figure 3.3). The

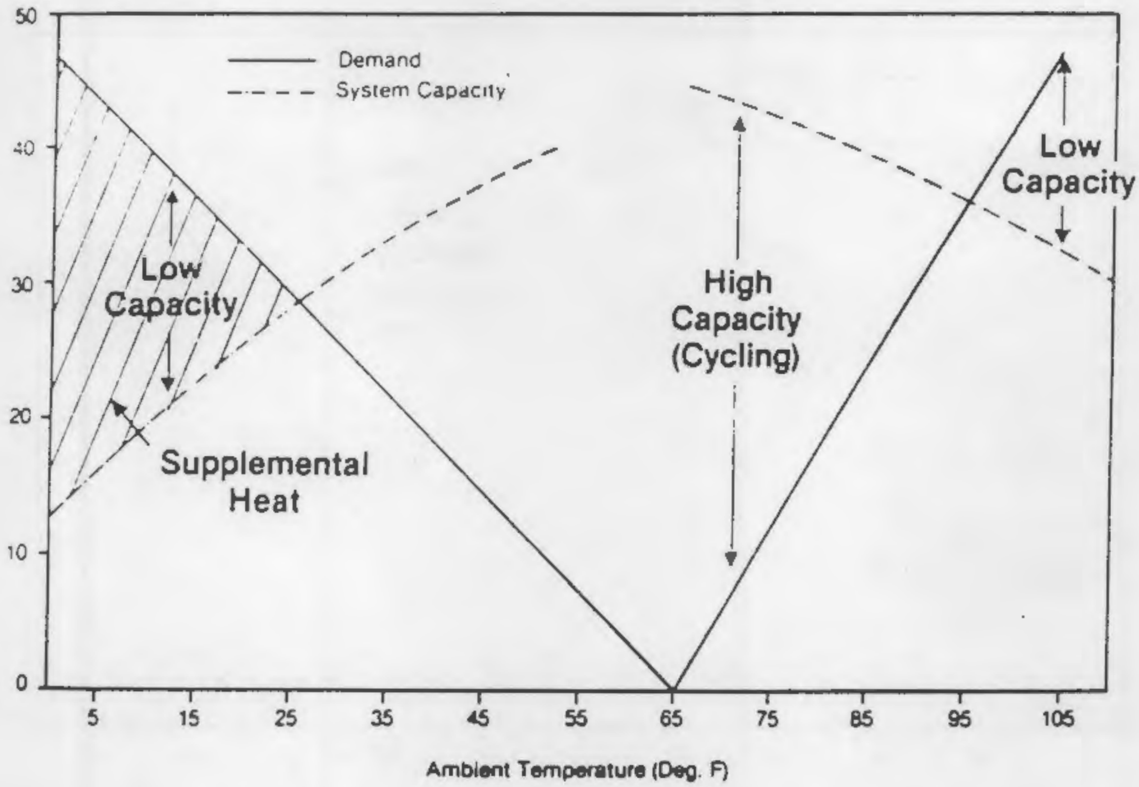

Figure 3.2. System Capacity Versus Residence Demand (Provided by Copeland Corporation, a subsidiary of Emerson Electric Co.)

benefits of the improved capacity characteristics are achievable, providing the scroll compressor can perform at a higher efficiency than the conventional compressor shown in Figure 3.2. The scroll system has higher capacity in high ambient temperature cooling, resulting in better comfort. The heating capacity of the scroll compressor is higher than the comparable piston system resulting in a lower heating balance point temperature and less supplemental heat required. These benefits will be achieved more effectively with a variable-speed drive as described previously. Thus, it is important to evaluate the combined benefits of scroll compressor with variable speed drive as a candidate for the next generation heat pump technology.

3.2 LOSS MECHANISMS FOR THE SCROLL COMPRESSOR

Each compressor type has a well-defined set of basic loss mechanisms. For example, losses for a rolling piston compressor occur in the following:

- leakage loss
- suction and discharge pressure loss
- top clearance loss
- refrigerant gas heating loss
- mechanical friction loss.

These loss mechanisms represent the difference between the theoretical adiabatic compression work and required mechanical work. For example, Otaki (1986) reported a typical proportion of rolling piston compressor loss to be as follows:

- The adiabatic compression efficiency is 57.2%.
- The compression efficiency losses are 42.8%. The sources of these losses are motor loss, 20.5%; mechanical friction loss, 6%; leakage, 5%; suction and discharge pressure loss, 5.7%; top clearance loss, 1.6%; and gas heating loss, 4%.

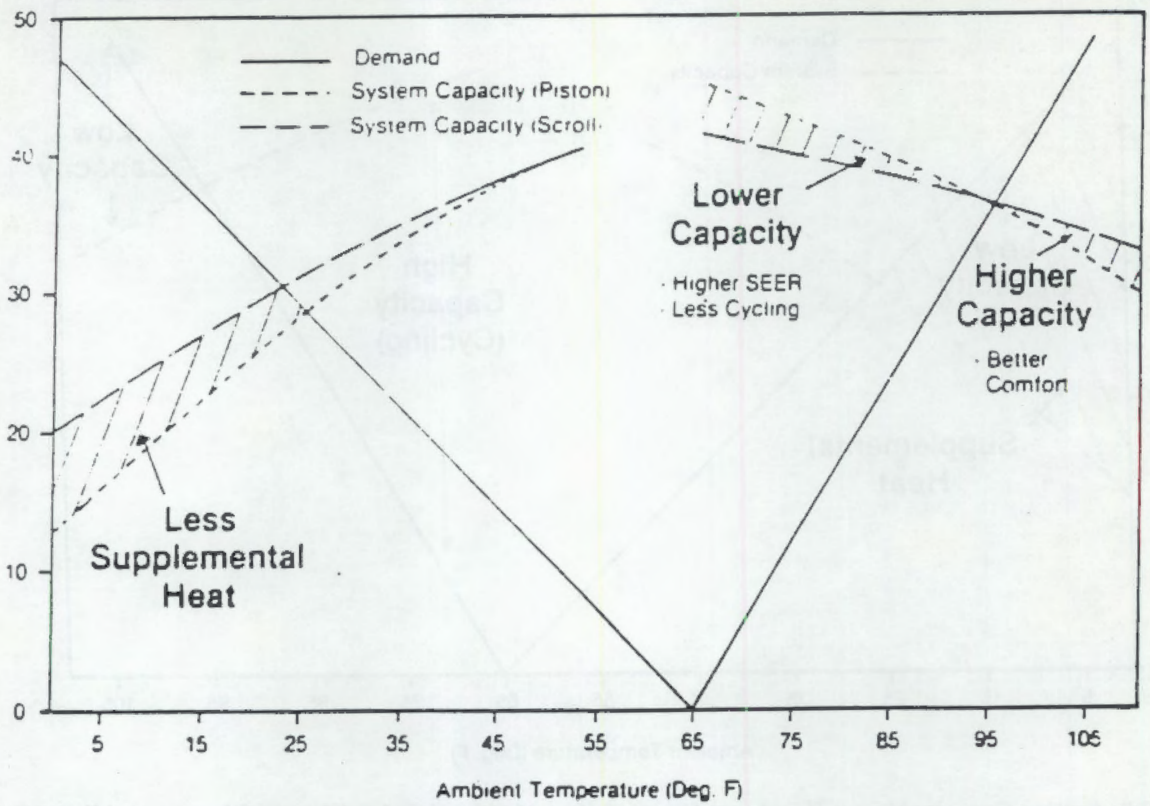

Figure 3.3. Scroll Versus Piston Capacity Curves (Provided by Copeland Corporation, a subsidiary of Emerson Electric Co.)

Compared with the rotary-type compressor, the list of scroll loss mechanisms are motor loss, mechanical friction loss, leakage loss, and gas heating loss.

Because the scroll compressor is a continuous compression machine that does not require suction and discharge valves, pressure drop due to sudden expansion across the refrigerant ports is eliminated. Furthermore, because the scroll compressor is a once-through compression machine in which all high-pressure refrigerant is discharged, the top clearance loss of a reciprocating compressor is eliminated (although there is a debate whether reciprocating-type compressors actually benefit from the high-pressure gas left in compression cylinders as gas springs to improve compression efficiency (Riegger 1988). The scroll compressor is claimed to have greater volumetric efficiency than the rotary- or reciprocating-type compressors.

The fabrication assembly and tolerance requirement is a dominant factor in reducing the leakage loss. For example, the rolling piston compressor generally has seven critical locations where refrigerant may leak. To reduce leakage loss, an especially high manufacturing tolerance is required to fabricate these machine parts.

In scroll compressors, critical leakage may occur in the contact between the top of the orbiting scroll and the base of the fixed scroll, as well as the flank contact between the high-pressure pocket on one side of the crescent zone and the low-pressure pocket on the other side. These, in fact, are the parts that had to be developed and fabricated to a high degree of accuracy.

3.3 THE RADIAL COMPLIANT DESIGN

Controlling leakage between the wrap tip and the base plate is one of the most critical sealing requirements in the scroll compressor. Typically, the potential leakage in this area may be several times that of the flank contacts (Bush and Elson 1988, pp. 83-97). Usual methods of controlling this leakage are tip seals and biasing the scroll members together using gas or spring forces. Various patents have been granted in the technique of axial leakage control.

A distinction can be made between leading scroll designs in flank leakage control. Some Japanese designs use a scroll set (fixed and orbiting scrolls), which mate very closely to satisfy extremely precise flank contact, e.g., Hitachi design (Arata and Murayama 1987). The orbiting scroll is rigidly connected to the crankshaft and moves in a fixed orbit in this design. Fabrication and assembly tolerance in the rigid mounting design is approximately one micron for both the contact between the tip of the orbiting scroll to the base plate and the flank contact.

The Mitsubishi Heavy Industries' design uses a swing link mechanism to allow flexible flank contact. The U.S. manufacturers have termed this contact technique "radial compliance." The Sanden design for the open-shaft automotive air conditioning compressor also uses radial compliance (as invented by ADL). In both cases, the use of tip seal and radial compliance design can be achieved without the stringent fabrication and assembly tolerance (Hiraga et al. 1987).

The "compliance" technique has been practically implemented by Copeland Corporation of the United States. Depending on the direction of the movement, the compliance design is applied to "radial compliance," "axial compliance," or the combination of the two called the "3-D compliance." "Radial compliance" means either the fixed or the moving scroll can move slightly in the radial direction: movement of the two scrolls toward each other could improve the seal between the two scrolls; movement away from each other is useful to prevent damage to the scrolls in case the fluid to be compressed contains contaminants. "Axial compliance" means either the fixed or moving scroll can move slightly in the axial direction, i.e., the direction of the axis of the motor's drive shaft. Movement of the two scrolls toward each other could improve the seal between the tip of the fixed scroll and the plate of the moving scroll and between the tip of the moving scroll and the plate of the fixed scroll.

This freedom of motion is usually accomplished by connecting the bearing that drives the orbiting scroll to the crankshaft by a pivoting or sliding linkage. The centrifugal force generated by the orbiting scroll mass can be used to counter the gas forces and provide a flank sealing, and the thrust force generated by high-pressure gas can be used to provide the axial sealing loads. Thus, the compliant design allows the orbiting scroll to seek its own dynamic sealing route to reduce leakage. Trane (*The News* 1988) and Copeland (Bush and Elson 1988 pp. 83-97) indicate that for solid and liquid ingestion contamination, the orbiting scroll simply moves out of the way of the ingested contaminants so there would be little physical damage. These reports indicate that the problem of solid and liquid contamination has been solved by the compliance design developed by Trane/ADL and Copeland.

3.4 MATERIAL SELECTION AND LUBRICATION

Critical contact characteristics and modes of movement in key parts of rotary-type compressors are shown in Table 3.1. Principal rotary compressor designs are the rolling piston and the scroll. Critical contact parts can be classified into load-carrying parts (bearings) and seals as follows:

- Planar contacts with unidirectional sliding - Journal bearings for both rolling piston and scroll compressors must carry the load, which depends on the compressor operating condition. Furthermore, these bearings must support linearly varying loads (which makes the contact plane slanted). Much engineering know-how is required for bearing design, load uniformity, material selection, and lubricant management in this area.

- Linear (edge) contacts with unidirectional sliding - Spring-loaded blades in a rolling piston compressor are in contact with both the piston surface and the cylinder wall. Proper sealing action is required for high compression efficiency as well as proper lubrication and material selection to ensure high durability.

Table 3.1. Critical Characteristics and Modes of Movement in Rotary-Type Compressors

Compressor Type	Parts	Contact Characteristics	Mode of Movement
Rolling piston	Tip of blade	Linear (edge) contact with annular wall of cylinder	Sliding motion - unidirectional
	Blade surface	Planar contact with blade casing	Sliding motion - repetitive
	Journal bearings	Planar contact with outer annulus of the rolling piston	Sliding motion - unidirectional
Scroll	Crank bearings	Linear contact with guide cylinder	Rolling or sliding - unidirectional
	Wrap	Linear contact with flank surfaces	Rolling or sliding - unidirectional
	Tip seal	Planar contact with base plate	Sliding - unidirectional
	Thrust bearings	Planar contact with orbiting plate	Sliding - unidirectional
	Oldham Connection	Planar contact with orbiting plate	Sliding - repetitive

- Planar contact with repetitive sliding - The blade casing of a rolling piston compressor and the guide track of the Oldham ring in a scroll compressor must carry the varying load resulting from pressure variation. The blade must provide essentially leak-free contact but also low friction for higher efficiency. Proper design, material selection, and lubrication are essential here.

- Planar contact with unidirectional sliding (orbiting) - The thrust bearing and the tip seal of a scroll compressor undergo sliding (translation) motion while in contact with the base plate. This plate-to-plate contact is complicated by the nonuniform pressure loading caused by the distribution and variation of compression pockets of the scroll pair. Support design, lubrication, and sealing action will be crucial for maintaining good performance and high durability.

- Linear contact with rolling or sliding motion - Each scroll pair is always in contact in at least two locations in the radial direction; this is the flank contact. Without good flank-sealing action, performance of a scroll compressor rapidly deteriorates. Sliding motion in the suction side (outer perimeter) is high and pressures are low; then sliding speed drops and pressure load increases as the flank contact proceeds toward the high-pressure side in the center. Wear, temperature deformity, lubricant management, and alignment must be controlled to ensure good performance and high durability.

3.5 SCROLL COMPRESSOR OPTIMIZATION CHART

Because the scroll is a unique technology, many of the design criteria previously used by reciprocating and rotary compressor designers must be modified to achieve an optimal scroll product of high performance and durability. For reciprocating compressor optimization, pumping geometry is selected based on an optimum bore/stroke ratio for a given displacement volume. Because of the larger number of variables in the analysis of scroll compressors, the optimization study becomes more complex. A method for generating scroll pumping geometry should be based on satisfying performance specifications, packaging dimension constraints, and manufacturing optimization constraints. The following discussion was originally developed by Carrier Corporation in its application of the scroll compressor technology (Etemad and Nieter 1988 pp. 56-64).

Figure 3.4 illustrates one possible approach to scroll compressor optimization. In this study, capacity, volume reduction ratio, and wrap thickness are used to generate the necessary data for scroll manufacturing and packaging. The output data versus wrap height are plotted for different starting angles and categorized under three distinct areas of manufacturing constraints and energy losses.

3.5.1 Performance Specifications

The criteria for the performance specifications are explained in the following.

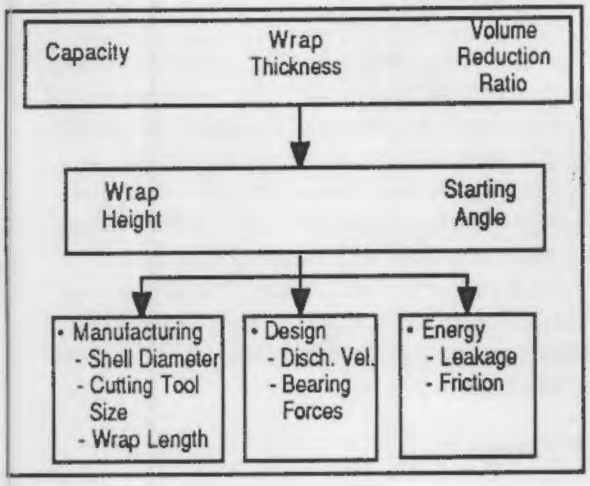

Figure 3.4. Scroll Compressor Optimization Chart (Reprinted with permission of United Technologies Carrier, Carrier Corporation.)

Capacity

The capacity is chosen and considered as an input. The volumetric efficiency for the scroll-type compressor is generally greater than 90%, depending on the leakage and suction gas conditions. This compares with the typical volumetric efficiency for reciprocating compressors of 75% (Etemad and Nieter 1988 pp. 56-64).

Wrap Thickness

Etemad and Nieter (1988 pp. 56-64) provided a comprehensive selection analysis of the design wrap thickness, which plays an important role in the design. These factors include the following:

- rigidity of the scroll element structure during machining
- sustainment of gas forces and thermal distortion during operation
- minimization of the tip leakage during operation.

Depending on the manufacturing process, it may be necessary to compromise between machining conditions and the magnitude of the scroll height and thickness to avoid any undesirable warpage and surface finish deterioration. The beginning and end of the wrap, where there is no side support, are the most critical regions in the manufacturing and machining processes.

Volume Reduction Ratio

The scroll compressor is a fixed compression ratio machine. Matching the proper volume ratio compressor to the application is important when optimizing for efficiency. This is especially true in variable-speed applications when the fixed volume machine has to operate over a wide range of suction gas conditions, loads, and capacities. The volume reduction ratio must satisfy application needs.

3.5.2 Package Requirements

An explanation of the components of the package requirements follows.

Wrap Height and Starting Angle

The starting angle is the angle that is formed by the innermost wrap of the orbiting scroll and the discharge port at the beginning of the orbit path (at 0° location in Figure 2.3).

The main reason for selecting the height and starting angle as dependent variables in the optimization process are (Etemad and Nieter 1988 pp. 56-64) as follows:

- Most major parameters, except discharge velocity, are not sensitive to the magnitude of the starting angle within its practical range.
- Most parameters are a strong function of height. This provides a simple way of demonstrating data solely as a function of height.
- The starting and final involute wrap angles geometrically determine the sealing points that contain the pair of crescent-shaped pockets at the beginning and end of the suction stage.

3.5.3 Optimization

Elements comprising scroll compressor optimization are summarized below.

Manufacturing Parameters

Shell Diameter - The outside configuration of the compressor is a major contributing factor for HVAC unit design and compressor marketing. Ideally, the intent is to provide the smallest overall pumping assembly diameter and height. A major factor affecting shell diameter is the diameter of the motor used for that specific capacity. .

Cutting Tool Size - The major manufacturing design issue influencing the optimum scroll parameter selection is the size of the cutting tool. The ideal would be to have a large-diameter cutting tool and short-shaft flute length to avoid cutting tool deflection. For this purpose, the wrap height-to-thickness ratio plays a major role in determining the cutting tool height-to-diameter ratio. A rigid cutter (smaller deflection) corresponds to a smaller tool height-to-diameter ratio. The maximum allowable cutting tool parameter should be determined experimentally for a given material, cutter, and cutting operation.

Wrap Length - The overall scroll wrap length is significant from a manufacturing point of view. The wrap length determines the manufacturing time required for machining each scroll wrap, one of the dominant cost (and productivity) factors. In general, for a given capacity, the wrap length decreases as the height increases. This effect is the most significant at the shorter heights. In addition, the wrap length decreases by decreasing the starting angle.

3.5.4 Design

The design description for components of the scroll compressor is in the following subsections.

Discharge Velocity

The size of the discharge port is the major factor controlling the size of the central pocket and thus, the starting angle. The goal is to maximize the port area within the central oval-shaped pocket formed between the orbiting and fixed scroll wraps just before the start of the discharge process. This requires a compromise between the discharge port area and manufacture of a noncircular hole.

Bearing Forces

Another major design limiting parameter is the bearing forces on the thrust surfaces. By increasing the wrap height, for example, the radial and tangential gas forces on the wrap increases, resulting in higher journal-bearing forces. In contrast, by increasing the wrap height, the radius of the orbiting scroll decreases and the area exposed to high pressure gas is reduced. The limiting condition for the thrust force on each surface depends on material combination, surface condition, velocity, and lubricant distribution.

3.5.5 Energy

Leakage

For a given clearance, the effect of tip leakage loss is significantly higher than the flank leakage. This is due to the difference in leakage path lengths, both along and through the clearance. The leakage path length along the clearance for tip leakage is related to the wrap length, and in the case of flank leakage, is in direct proportion with wrap height. In general, the tip path length is longer than the wrap path length, which results in a higher tip leakage than flank leakage loss through the clearance. Previous studies (for example, Etemad and Nieter 1988) indicate that more emphasis must be made on reducing tip leakage loss, in particular, for the configuration of low wrap height.

Friction

The same trend as for bearing forces is also observed for frictional losses. The coupling pad losses are at least an order of magnitude smaller than thrust and journal-bearing losses. By increasing the wrap height, the thrust frictional losses reduce while the journal bearing losses increase.

3.6 SCROLL MANUFACTURING TECHNOLOGY

Because of the stringent requirements placed on the component fabrication tolerance for scroll compressor manufacturing, the commercialization of this technology took nearly 100 years from when the invention was first conceived. The advent of a reliable numerically controlled fabrication machine made possible the fabrication and commercialization of the technology.

In Japan, where high-precision fabrication machines for high-volume production have played a critical role in today's quality standards for industrial manufacturing, the development work by Amada Machines Corporation is noteworthy. The Japanese development of rolling piston compressors required precision fabrication machinery, which would maintain predictable fabrication tolerance over a long time. The ability to predict in advance the wear periods of critical components was a significant engineering development.

Compared with the reciprocating-type compressors, which require a fabrication tolerance level of 10^{-1} mm, rolling piston compressors require a tolerance of 10^{-2} mm, and scroll compressors between 10^{-2} to 10^{-3} mm, depending on a particular design. In scroll compressor technology, for which the fabrication technique is an integral part of the product design (as explained earlier), each manufacturer regards the machining technology and fabrication technique to be a closely held proprietary secret.

While machining equipment has features unique to each company, the three-dimensional tolerance measurement equipment commonly used in Japan is the Zeiss (West Germany) three-axis measurement unit. Most manufacturers fabricate the fixed scroll wrap and the orbiting scroll wrap independently, measure the machined surfaces for tolerance, record the measured data on a computer, and match the fixed wrap and the orbiting wrap for best mating.

4.0 IMPACT OF SCROLL TECHNOLOGY ON THE BASIC MANUFACTURING INDUSTRY IN THE UNITED STATES

As discussed in the preceding sections, the scroll compressor designs commercialized during this present decade can be traced to earlier developments. The majority of patents and engineering modifications were the result of an effort to improve scroll technology's most difficult challenges:

- tip leakage control
- flank leakage control
- driving mechanism
- discharge port design.

These challenges have been resolved by precision fabrication techniques, variable eccentricity design, and computer simulation of the dynamic compression process for detailed geometrical analysis. In general, scroll technology's challenges had been analyzed and solved, but practical production and detailed design improvements based on actual operation of prototype units had to wait for the advent of CAD and CAM techniques.

Therefore, the key element to the commercial production of the scroll compressor was not the original invention, but rather the advent of an integrated design fabrication system for high-precision machining and assembly. The scroll design requires greater precision than is required to produce reciprocating compressors, resulting in heavy capital investment. Japanese manufacturers have been quoted as saying the required investment will inhibit American manufacturers from competing effectively (*The News* 1987).

However, the present research revealed that the problem is not whether American manufacturers can or cannot compete against the Japanese, but whether the fundamental difference between economic and trade policy structures in Japan and the United States created today's discrepancies. The argument is based on the following reasoning and observations:

1. Prior scroll technology was established between 1905 and 1970. What remained for the industry in the 1970s was to put prior designs into practical production.

2. Discrepancies between Japanese and American patent laws and unclear interpretations created "perceived unfairness" in the industrial competition between the two countries.

3. The decline of the American machine tool industry delayed the development of the next most important element of practical production of scroll technology: precision fabrication and assembly technology.

In this section, the relationship between the machine tool industry and its impact on the HVAC industry will be presented. Observations on the past perspective of "invention," present trend of "productivity," and the future outlook for "competition" will be examined for establishing a basis for a sound research and development program. Such a program means that the incubation time of a new technology can be shortened, practical implementation of a new device can be accelerated, and the United States can once again be the technological leader in the global market.

4.1 INVENTIVENESS OF PRIOR ART

The original inventions, as disclosed in a large number of patents, overcame many inherent technical challenges. Prior art designs (which evolved from 1905 to 1970) basically covered the essence of today's design, that is the engineering contributions occurring since 1970 are principally how to implement prior art into the practical production process. Of course, prototype evaluations and application-specific testing revealed additional technical challenges because of the dynamics of scroll operation under varying conditions, but they too had to wait for a new generation of fabrication techniques.

4.2 DISCREPANCIES IN PATENT PROTECTION OF INTELLECTUAL PROPERTY

The initial peak of scroll-related patents from the United States occurred in the early 1970s when researchers at ADL and other affiliated institutions filed a large number of patents in the United States, Europe, and Japan. About 5 years later, the number of patent applications by Japanese inventors both in Japan and the United States increased dramatically. While patents already granted in the United States were protected by the General Agreement of Trade and Tariff (GATT), new patent applications, when filed in Japan, are made public after 18 months from the date of submission. This gives potential competitors the opportunity to study the patent documents and file their own "application patents," i.e., minor alterations of the original invention as new patents. The philosophy behind patent law is universal: to provide legal protection of intellectual property from exploitation by others for financial gain without due compensation. However, significant discrepancies between the filing and examination procedures and interpretation of law create some anomalies in Japan, such as:

- First-to-invent is proven not from prior art but by the postmark on the application. Because of this requirement, applicants are compelled to file minor and insignificant alterations to prior art in hopes of obtaining new patents. The applicant does not have to request for final examination for patent for several years.

- The patent announcements publicly disclose the essence of original invention before a formal patent is granted. This aspect of the Japanese system gives a relative advantage to potential competitors to make minor and insignificant alterations to the original invention and file for new patents.

- The process for the application patent, when used in combination with the patent announcement, gives an advantage to potential competitors. When an original invention is filed and is publicly disclosed after 18 months, potential competitors can file for application patents to secure their rights to market the original invention in certain key markets.

As a result, the process sometimes creates a discrepancy in the legal protection of intellectual property between Japan and the United States. For example, an original invention may be protected in the United States, but its applications in certain markets, which require nonobvious improvements to the original invention may be excluded by the Japanese application patents (Kirk).[a] If a nonobvious application requires the original invention by a prior inventor for its use, the applicant may be awarded a compulsory license in arbitration under Japan's patent law (Kirk).[a] In other words, if a new niche application can be found for an American invention, the Japanese patent law can require the American inventor to grant a license for use of the invention in Japan. Furthermore, the artificially elevated number of patent applications in Japan (the results of the built-in mechanism of over filing) creates a situation requiring an extraordinary level of technical, legal, and financial resources to file for patent infringement on behalf of American inventors.

In addition to the exploitation of the differences in patent laws, Japanese manufacturers have been purchasing technical licenses of American technologies. The Economic Planning Agency of the Japanese central government made a point in a 1980 survey (*Japan Economics Planning Agency* 1980 p. 135):

> "Japan's technological progress has been achieved so far through the introduction of foreign technologies. This has been inevitable, it may be said, because Japan made a late start and therefore had to catch up to advanced nations in a short period . . . A brisk introduction of foreign technologies may be taken as an indication that a country has a great capacity to assimilate them."

It appears that the industry-government infrastructure of Japan has a built-in mechanism to "assimilate" technologies while securing applications markets and fabrication processes. A number of case studies giving consistent arguments of long-term market exploitation based on knowledge-intensive, technology-intensive markets are presented in other references (Abegglen and Stalk 1985; Ohmae 1982; and Prestowitz 1988).

(a) Private communication with Michael K. Kirk, Assistant Commissioner for External Affairs, United States Department of Commerce Patent and Trademark Office, April 1989.

4.3 THE DECLINE OF THE AMERICAN MACHINE TOOL INDUSTRY

Paralleling the rapid pace of the technical evolution of scroll technology in the 1970s, the U.S. machine tool industry was experiencing a rather painful decline and restructuring process. In fact, at the time when inventions and technical resolutions for practical production of scroll compressors were proceeding, the next critical element for the technology, precision fabrication and assembly, was not materializing in the U.S. HVAC industry.

While machine tool technology is important to the fabric of a manufacturing-oriented economy, it is not glamorous to economic policy-makers. The industry is relatively small. Sales of $6 billion are considered "good," (about 5% of General Motors' volume (Prestowitz 1988)). Those sales, however, support the entire industrial economy (Prestowitz 1988). At the simplest level, machine tools make screws, screwdrivers, and simple tools. At a more sophisticated level, they make presses, casters, robots, and scroll compressors.

The key to the machine tool industry has traditionally been skilled craftsmanship. All over the world, and particularly in the United States, this industry had been ideal for entrepreneurial engineers and machinists starting small companies based on skill rather than financial strength. The industry was thus characterized by small, undercapitalized companies.

The importance of the machine tool industry for the collective strength of a nation's economy, defense, and trade is well known. The United States and Japan have often recognized the lack of tools and fabrication machinery to be the critical bottleneck during rapid economic growth periods and in times of war. The U.S. Congress established a system of national reserve of machine tools for emergency production in the past (Prestowitz 1988). The Japanese central government's Ministry of International Trade and Industry (MITI) established the Extraordinary Measures Law for the Promotion of Specified Machinery Industries in 1956. Similar to, and a forerunner of, the Extraordinary Measures Law for the Promotion of the Electronics Industry of 1957, the law created a council to oversee the industry and directed MITI to develop and execute the plans to promote the industry (Prestowitz 1988).

Over the next 30 years, both Japan and the United States took steps to ensure a stable machine tool industry in their countries. The United States, under the auspices of the Air Force, funded the Manufacturing Technology program (MANTECH) for improving manufacturing techniques for aerospace equipment (Prestowitz 1988). The program funded an effort at the Massachusetts Institute of Technology to improve machining and fabrication resulting in the development of numerically controlled, (also known as NC), machine tools.

Japan's MITI established a series of plans for combining domestic market protection, subsidized research and development, and promotion of export sales. MITI quickly recognized that the machine tool industry was characterized by small-size, high-risk, and undercapitalized firms and that the industry would continue with those traits unless a government-industry infrastructure provided a foundation for a fundamental change. As a result, MITI "guided" the machine tool industry by executing plans for consolidating the manufacturers. The idea was implemented by creating a market in which research and development, financial strength, scaled economy, tax incentives, procurement policy, and an industry cartel gave an advantage to large, consolidated companies. The Japan Machine Tool Builders Association established the Manufacturing Share Deliberation Committee, which determined the areas of concentration for each manufacturer (Prestowitz 1988). The program was supported by the usual set of market protection and subsidy measures including preferential depreciation, reserves for export losses, price guidelines, various tax credits, and procurement policies.

MITI's public research and development program was led by its Agency of Science and Technology. Government research and development work is now progressing in several key areas:

<u>Flexible Manufacturing Systems with Laser for Post Robotics Industry [1977-1983, budget of ¥ 3,600 million (approximately $150 million U.S. dollars)]</u>. As the relative importance of an industrial sector where production techniques remain labor-intensive with high skills and production lots tending to be small, research is being conducted on an integrated production system to increase speed and flexibility. The goal is to allow the adoption of laser processing techniques in the small-batch production of machine parts (Anderson 1984).

Mechanical Engineering Laboratory (of the Agency of Science and Technology) at the Tsukuba Science Park (1982 budget ¥ 2,800 million; staff 307, research staff 222). The Mechanical Engineering Laboratory has several key departments that are involved in developing machine tool and fabrication technology, such as

- Systems Science Department (high-precision optical measurement, machinery control, automated systems, high-precision pointing and tracking systems, artificial intelligence and hierarchical command and control of fabrication and assembly equipment, etc.)

- Material Engineering Department (tribology, new machining and forming technology, electrochemical machining, electron beam machining, plastic forming, CAD, integrated fabrication and assembly system for high tolerance in three-dimension, improvement of the forming limit and forming accuracies, etc.)

- Production Engineering Department (machining technology, production control technology, adaptive control turning lathes and grinders, milling machines with laser reference axes, high-precision traverse grinders, free-curved surface fabrication, tool-grinding operations, life-cycle study of tools, etc.).

Japanese government support of machine tool research and development appears extremely low (only $21.5 million in 1982). However, MITI has "off-budget funds" derived from bicycle and boat racing (a gambling activity legalized in Japan and controlled by municipalities). In fact, the Bicycle Racing Fund and the Motor Boat Racing Association are controlled by MITI, and a portion of the income goes to a program for the promotion of machine-related industries (Prestowitz 1988). Thus, a substantial source of off-budget funds for various MITI or MITI-organized programs are funneled to the machine tool industry (Covington and Burling 1982 p. 10).

The results of this were dramatic. By 1986, Japan had become the world's largest producer of machine tools. Since the mid-1970s and through this decade, Japan's investment per worker is nearly double that of the United States (Prestowitz 1988). While the industry had shrunk from 1,000 firms to about 600 in the United States, Japan had pared its industry down to only about 250 companies (National Academy of Engineering 1983). Fifty percent of all Japanese machine tool workers are employed by companies with over 1,000 workers, while it is 20 percent in the United States (National Academy of Engineering 1983). As a result, America's share of the world machine tool market has declined rather steadily this decade to less than half its 1980 level (Figure 4.1) (National Machine Tool Builders' Association 1989). Despite a dip in 1987, Japan still holds a slight lead over West Germany in the global machine tool market.

Most importantly, Japan dominated the numerically controlled machine market, which was originally invented in the United States. By 1982, Japanese firms controlled more than a third of the American machine tool market; the numerically controlled machine market share was as much as 40% (Covington and Burling 1983 p. 10). During this time, MITI had a cartel-based floor price system (which was usually undercut to promote export sales), and the industry carried a large inventory (as much as 1 year's worth) to provide rapid delivery and parts replacement.

Although American industry management was severely criticized for not meeting this challenge, it could not take the financial risk associated with the

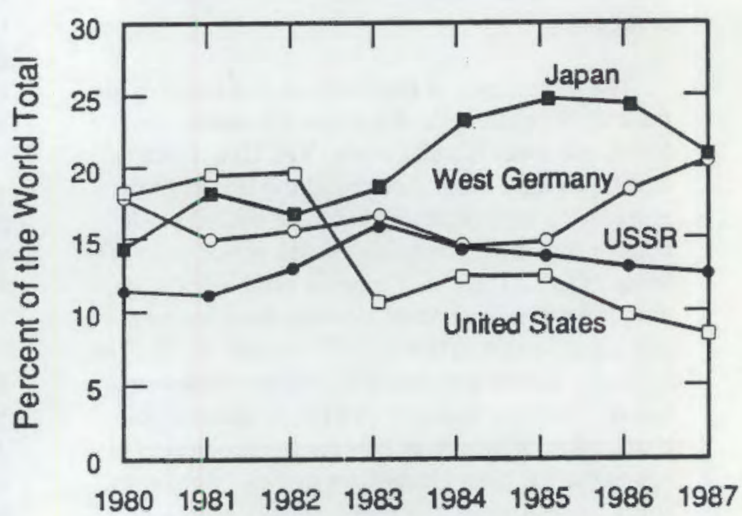

Figure 4.1. Share of World Machine Tool Output (Reprinted with permission of National Machine Tool Builders' Association.)

business practice used by its competitors. Carrying large inventories meant that the Japanese did not always realize a profit, and price fixing by a domestic (U.S.) cartel is closely watched by the U.S. government. The Americans simply could not afford to take losses as the Japanese did (Prestowitz 1988). Sales of American-made equipment in Japan remained small as countermeasures similar to those in the semiconductor industry were put into effect. In addition, the Americans also found their licenses and patents being violated (Prestowitz 1988).

The parallel occurrence of initial commercialization of scroll compressors and the decline of the U.S. machine tool industry is significant. In both cases, the fundamental innovations were developed and patented in the United States. Nevertheless, in both cases, Japan's export-oriented policy and technology assimilation practices resulted in the earlier commercialization of new products and subsequent penetration of Japanese conglomerates into the U.S. market, with no U.S. penetration in the Japanese market. In fact, the early commercialization of scroll technology by Japanese conglomerates is not a reflection of the U.S. air conditioning industry's lack of research and development effort; it is a reflection of the hardship experienced by the U.S. machine tool industry over the last 15 years.

5.0 CONCLUSIONS

In Japan, refrigerant compressors have attained a high level of advancement and diversity. Supported primarily by private industry funding, compressor technology is the result of a design philosophy based on low noise, compactness, light weight, high efficiency, good reliability, and low cost.

Since the rolling piston compressors for the air conditioning market were introduced in 1975, the small-capacity refrigerant compressor market in Japan has completely turned over to the rolling piston-type. Now, virtually 100% of all residential refrigerators, room air conditioners, and heat pumps under 2.5 tons use rolling piston compressors. The highlight of Japanese compressor development is the commercialization of scroll compressors. The impetus for developing scroll compressors was setting a goal for improving the performance of air conditioning equipment in the 3-6 hp range. Traditionally, air conditioners in this capacity range used either reciprocating or large multivane rotary compressors. Today, scroll compressors are rapidly replacing reciprocating and rotary vane compressors in the 3-6-hp market.

Because of the scroll compressor's smooth flow process and minimal number of moving parts, it offers inherently high durability. For a typical scroll compressor, the only moving parts consist of an eccentric shaft, an orbiting scroll, an Oldham coupling, and, where radial compliance is present, an additional coupling to provide variable eccentricity. These components, when used in a fully compliant design, provide a high tolerance for both system contaminants and liquid flooding (Bush and Elson 1988). Furthermore, the compliant design will adjust the orbit eccentricity aided by centrifugal force to find "its own optimum sealing." Thus, the compliant design significantly reduces the fabrication tolerance requirements (Morishita and Sugihara 1985b).

The target market for the scroll compressor is liquid and gas compression (over 3-hp range). In terms of market structure in Japan, however, this falls in the category of commercial-size equipment. Although the multiplex system (single outdoor unit with two to four indoor units) is becoming somewhat popular in the Japanese residential market, the number of sales in this area is quite small. The Japanese market demand for 2.5- to 6-ton heat pumps and air conditioners is estimated at 150,000 units per year. In addition, water chillers, refrigerated display cases, and other commercial equipment are expected to reach 350,000 units. In commercial areas, reciprocating compressors are being rapidly displaced by scroll compressors.

In the U.S., the growing unitary heat pump market requires compressors in the range of 3-5 hp. This is a popular size for U.S. scroll development. Aided by an enthusiastic marketing strategy, Trane, Lennox, Heil-Quaker, and Rheem Manufacturing have announced the introduction of air conditioners and heat pumps equipped with scroll compressors.

As the enforcement date (January 1, 1992) of the 1987 National Appliance Energy Conservation Act (NAECA) approaches, the demand for high-efficiency scroll compressors is expected to increase significantly. The NAECA will set the minimum Seasonal Energy Efficiency Rating (SEER) for heat pumps at 10.0. In other words, the least efficient unit on the market will be required to have the SEER of 10.0 by 1992. More efficient equipment will have a SEER rating up to 15.0. To achieve the higher SEER rating, a fundamental change will be needed in heat pump equipment design. Considering that it would take 2 to 3 years of developing the product prior to commercialization, Copeland's introduction of high-efficiency scroll compressors has been well-timed to match the industry's needs. It is anticipated that aided by the NAECA and the growing demand for air conditioning and heat-pump equipment in the United States, scroll compressors will rapidly gain a market share in the U.S. HVAC industry.

One of the main reasons scroll compressors were not commercialized more quickly after their invention in 1886 is that the scroll is a complex curve that requires precise fabrication if the compressor is to be efficient. Such precise fabrication on a low-cost, volume-production base was impractical or impossible until the development of the computer-aided, numerically-controlled tools. Numerically-controlled machine tools were invented in the United States, but in 1971, the government of Japan adopted a plan to promote numerically-controlled tools; by the 1980s, Japan absolutely dominated the world market in machine tools (Prestowitz 1988). If American manufacturers of scroll compressors purchase or are essentially forced to purchase their numerically-controlled tools from Japan, then to that extent they will become dependent on their own competitors because the same Japanese conglomerates that make numerically-controlled tools also make scroll compressors.

Thus, the present work leads to a potential policy implication that consistent national trade and industrial leadership is crucial to revive the machine tool industry--the foundation of our industrial strength and national security. The successful introduction of scroll compressors in the early 1980s by Japanese manufacturers before their U.S. competitors is primarily a result of the U.S. machine tool industry falling behind during the decade of 1970s when technology for high-precision fabrication and assembly was needed. Scroll technology had to be developed by parallel advances in design engineering and fabrication technology; every successful product is based on an integrated design fabrication system. Future competition for basic manufacturing industry in the U.S. by international conglomerates is likely.

Although Japanese targeting techniques are often labeled "unfair" by leaders in the U.S. and Europe, they deviate far less from the world means of government intervention outside Japan than is usually believed. Several policy tools, such as preferential tax provisions and research and development subsidies, are used nearly everywhere to promote high-technology industries (Okimoto 1986 p. 51). Some methods, such as quotas and tariff rates, are taken to greater extremes in Europe. Taken as a whole, Japanese industrial policy tools are not deviant cases in today's global economy (Okimoto 1986 p. 51). It is evident that the United States is lacking a consistent national policy for ensuring a uniform set of competitive rules for the industry--both for defense and non-defense production--for the industry to plan and execute a long-term program without fear of rapid policy change. In the past, American manufacturers suffered from rapid change in cost of capital and protection of innovation.

The present study illustrates the importance of the basic machine tool industry to the health of the U.S. economy. Without a strong industry, it is difficult for American manufacturers to put innovations, whether they are patented or not, into production. As we experience industry transformation in the air conditioning and refrigeration market, it will be critical to establish a consistent national policy. This is necessary to provide healthy competition between producers, promote innovation of technology, enhance assimilation of new technology, and eliminate practices that are incompatible with these goals.

Sustaining competition by American scroll manufacturers is important because in the future, scroll and other compressors could be important factors in the competitiveness of American manufacturers of heat pumps and air conditioners. If, in the future, American manufacturers of heat pumps and air conditioners purchase, or are essentially forced to purchase their compressors from Japan, then to that extent they could become dependent on their own competition because the same Japanese conglomerates that make compressors also make heat pumps and air conditioners. Although Japanese conglomerates now concentrate on small-capacity heat pumps for the Japanese market, it is not inconceivable that in the future they could begin to manufacture larger-capacity heat pumps for the mainstream American market, just as they began by selling small cars developed for the Japanese market and progressed to selling larger cars for the mainstream American market. In short, Japanese conglomerates began by dominating the numerically-controlled machine tool industry. They are now making a strong bid for the compressor industry. In the future, these same conglomerates might well become the dominant worldwide producer of heat pump and air conditioner compressors.

6.0 REFERENCES

Abegglen, J.C., and G. Stalk. 1985. *Kaisha, The Japanese Corporation*. Basic Books, New York.

Anderson, A. M. 1984. *Science and Technology in Japan*, Longman Group Limited, pp. 268-295. Essex, United Kingdom.

Arata, T., and A. Murayama. 1987. "Hermetic Type Scroll Compressors," *Journal of the Japanese Association of Refrigeration*, 62(720):70-75.

Armstrong, A. E., and J. E. McCullough. March 1980. U.S. Patent 4,192,152.

American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE). 1988. Chapter 12 in *Handbook of Equipment*. ASHRAE, Atlanta, Georgia.

Audemar, P. December 1961. U.S. Patent 3,011,694.

Bennett, J. S., and E. A. Hatfield. June 1974. U.S. Patent 3,817,664.

Beseler, F. 1987. "Scroll Compressor Technology Comes of Age," *Heating, Piping and Air Conditioning*, 59(7):67-70.

Bush, J. W., and J. P. Elson. 1988. "Scroll Compressor Design Criteria for Residential Air Conditioning and Heat Pump Applications." In *Proceedings of the 1988 International Compressor Engineering Conference at Purdue*, Vol. 1. Office of Publication, Purdue University, West Lafayette, Indiana.

Coffin, D. O. 1982. *J. Vac. Sci. Technol.* 20(4):1126-1131.

Copeland Corporation. 1988. *Copeland Compliant Scroll™ Product Brochure*, Sidney, Ohio.

Covington and Burling. July 31, 1982. *Comments by the petitioner at a testimony hearing*. Washington, D.C.

Creux, L. October 1905. "Rotary Engine." U.S. Patent 801,182.

Dovorak, M. and A. Lepsi. August 1971. U.S. Patent 3,600,114.

Ekelof, J. April 1933. U.S. Patent 1,906,142.

Etemad, S., and J. Nieter. 1988. "Computational Parametric Study of Scroll Compressor Efficiency, Design, and Manufacturing Issues." In *Proceedings of the 1988 International Compressor Engineering Conference at Purdue*, Vol. 1. Office of Publications Purdue University, West Lafayette, Indiana.

Furukawa, K. 1981. *Procedures for Patent Filing*, p. 11. Nikkei Bunko, Tokyo.

General Agreement of Trade and Tariff (GATT).

Girvin, W. L. W. October 1957. U.S. Patent 2,809,779.

Girvin, W. L. W. February 1958. Canada Patent 553,253.

Hayashi, H. 1986. "Trends in Patents for Scroll-Type Compressors." *Nikkei Mech*. 212:151-154.

Hidden, W. P., and J. E. McCullough. July 1979. U.S. Patent 4,160,629.

Hiraga, M. et. al. May 1983. Japan Patent 58-19875.

Hiraga, M. 1983. *The Spiral Compressor: An Innovative Air Conditioning Compressor for the New Generation Automobiles*, SAE Paper No. 830540, SAE International Congress and Exhibition, Detroit.

Hiraga, M., M. Sakai, S. Shimizu, A. Mabe, Y. Tsukagoshi, and K. Terauchi. 1987. "Scroll Compressors." *Journal of the Japanese Association of Refrigeration* 62(720):60-69.

Hirano, T., N. Matsumura, and K. Takeda. 1988. "Development of High Efficiency Scroll Compressors for Air Conditioners." In *Proceedings of the 1988 International Compressor Engineering Conference at Purdue*, Vol. 1. Office of Publications, Purdue University, West Lafayette, Indiana.

Ishii, N., M. Yamamura, H. Morikoshi, M. Fukushima, S. Yamamoto, and M. Sakai. 1988. "On the Superior Dynamic Behavior of a Variable Rotating Speed Scroll Compressor." *In Proceedings of the 1988 International Compressor Engineering Conference at Purdue*, Vol. 1. Office of Publications, Purdue University, West Lafayette, Indiana.

Japan Air Conditioning, Heating & Refrigeration News (JARN). February 25, 1988. Special Edition for Refrigeration Compressors, p. 19. Tokyo.

The Japan Economic Journal. 1988. "Japan, U.S. Businessmen Agree to Bridge Patent-Law Chasms," 26(1322).

Japan Economic Planning Agency. 1980. *Economic Survey of Japan 1978/1979*.

Japan Patent Announcement 55-37520, 1980.

Japan Patent Announcement 58-214689, 1983.

Japan Patent Announcement 59-218383, 1984.

Johnson, J. P. June 1932. U.S. Patent 1,862,220.

Jones, J. L. July 1958. U.S. Patent 2,841,089.

Kirk, Michael K., *Testimony Before the Subcommittee on Foreign Commerce and Tourism, Committee on Commerce, Science and Transportation, United States Senate*, February 28, 1989.

McCullough, J. E. December 1975. U.S. Patent 3,924,977.

McCullough, J. E. October 1976. U.S. Patent 3,986,799.

McCullough, J. E. November 1976. U.S. Patent 3,994,635.

McCullough, J. E. December 1977. U.S. Patent 4,065,279.

McCullough, J. E. April 1978. U.S. Patent 4,082,484.

McCullough, J. E. October 1978. U.S. Patent 4,121,438.

McCullough, J. E. December 1978. U.S. Patent 4,129,405.

Mikulasek, J. July 1949. U.S. Patent 2,475,247.

Mikulasek, J. January 1950. U.S. Patent 2,494,100.

Ministry of International Trade and Industry (MITI). 1956. Extraordinary Measures Law for the Promotion of Specified Machinery Industries. Japan.

Moore, R. W. 1976. "A Scroll Compressor for Shipboard Helium Liquefier Systems." In *Proceedings of the 1976 Purdue Compressor Technology Conference*. Office of Publications, Purdue University, West Lafayette, Indiana.

Morishita, E., and M. Sugihara. 1985a. "Increase in Practical Use of New Age Capacity-Type Compressors." *Sci. Mach.* 37(4):496-500.

Morishita, E., and M. Sugihara. 1985b. "Realization of a New Generation of Scroll Compressors." *Sci. Mach.* 37(3):377-382.

Morishita, E. et al. 1981. Japan Patent Announcement 56-56991.

Moriyama, K. April 1970. U.S. Patent 3,506,275.

National Appliance Energy Conservation Act (NAECA)

National Academy of Engineering. 1983. *The Competitive Status of the U.S. Machine Tool Industry*. Washington, D.C.

Ohmae, K. 1982. *The Mind of the Strategist*. McGraw-Hill Book Company, New York.

Okimoto, D. I. 1986. "Regime Characteristics of Japanese Industrial Policy." *Japan's High Technology Industries*, ed. H. Patrick, p. 51. University of Washington Press, Seattle.

Otaki, T. 1986. "The Latest Small-Scale Refrigeration Compressors." *Sci. Mach.* 35(1):19-26.

Prestowitz, C. V. 1988. *Trading Places*. Basic Books, New York.

Riegger, O. K. 1988. "Variable-Speed Compressor Performance." *ASHRAE Transactions*. Vol. 94, Part 2. American Society of Heating, Refrigerating and Air Conditioning Engineers, (ASHRAE), Atlanta.

Rolkerr, R. April 1921. U.S. Patent 1,376,291.

Shaffer, R. W. November 1976. U.S. Patent 3,994,633.

Shiibayashi et al. March 1980. Japan Patent Announcement 55-37520.

Terauchi, K. et al. June 1980. Japan Patent Announcement 55-81296.

Terauchi, K. et al. February 1983. Japan Patent 58-6075.

The News (The Air Conditioning, Heating, and Refrigeration News). August 6, 1987. "Hitachi Plans to Sell Scroll Worldwide; Recip Compressors May Phase Out." Business News Publishing Company, Troy, Michigan.

The News (The Air Conditioning, Heating, and Refrigeration News). August 8, 1988. "Rapid Changes in Compressor Designs Challenge Industry. Business News Publishing Company, Troy, Michigan.

Uchikawa, M., and M. Shiibayashi. September 1982. Japan Patent Announcement 57-153984.

Ushimaru, K. 1988. "Assessment of Japanese Variable Speed Heat Pump Technology." *In Proceedings of the Second DOE/ORNL Heat Pump Conference*, Washington, D. C., April 1988.

Ushimaru, K. 1987a. *Evaluation of the Energy Efficiency of Japanese Variable Speed Heat Pumps in Residential and Commercial Application*, Report No. 545R118. Energy International, Inc.

Ushimaru, K. 1987b. *Technical Assessment of Small Capacity Refrigerant Compressors in Japan*, Report No. 545R080A. Energy International, Inc.

Vulliez, P. April 1974. U.S. Patent 3,802,809.

Young, N. O., and J. E. McCullough. May 1975. U.S. Patent 3,884, 599.

Young, N. O. April 1975. U.S. Patent 3,874,827.

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