PNL-7397
UC-310

JAPANESE POWER ELECTRONICS INVERTER TECHNOLOGY AND ITS IMPACT ON THE AMERICAN AIR CONDITIONING INDUSTRY

Kenji Ushimaru
Energy International, Inc.
Bellevue, Washington

G. L. Wilfert, PNL Task Manager

August 1990

Prepared by Energy International, Inc.
for Pacific Northwest Laboratory
under Contract DE-AC06-76RLO 1830
with the U.S. Department of Energy
Under Agreement B-041536-A-V
Additional support has been provided
by the U.S. Department of Commerce

Pacific Northwest Laboratory
Richland, Washington 99352

CONTENTS

thermodynamics system. Every component interacts with the rest of the system, affecting capacity, efficiency, power consumption, etc. Usually, a change in one component must be accompanied by design modifications in other components to improve system efficiency, reduce impact on manufacturing cost, and maintain high reliability.

Each incremental improvement in steady-state efficiency is evidenced by manufacturer reports, particularly from Japan, attributed to the "key technical breakthrough," such as the rolling piston compressor, microprocessor controller, solid-state relays, etc. One must be careful, however, not to blindly accept a manufacturer's assertion that the benefits of some change are attributable to a single-component improvement. Usually, the Japanese manufacturers make several improvements or changes between models and then attribute most or all of the benefits to the feature they wish to emphasize for marketing reasons. Thus, in analyzing state-of-the-art heat pump technology, it is important to keep in mind that technical papers and reports can be used for marketing purposes as well.

2.2.3 Benefits of Capacity Modulation on Seasonal Efficiency for Heat Pumps

The inverter-driven heat pump, first introduced by Toshiba in 1982, is the highlight of the developments in the Japanese heat pump market. Rather than having only the on-off control, modulation of cooling capacity to match the required load can conceivably generate energy-efficiency benefits. Regulation of the refrigerant mass flow rate is the most common method of capacity control in air conditioning systems, and an ideal flow modulation scheme should include 1) full-load efficiency unaffected by the mechanisms, 2) continuous adjustment to load, 3) good part-load efficiencies, 4) reduced starting torques, 5) unchanged compressor reliability, 6) no reduction of compressor operating range, and 7) no increase in compressor vibration and sound levels at part-load operation (Bahel and Zubair 1989). It is noted that not all benefits can be realized simultaneously by any single-capacity control technique.

Continuous variable compressor speed appears to offer the best means of capacity control and also meets most of the criteria mentioned here. With such a method, a compressor operates only as fast as is necessary to meet the building load. However, until recently this capacity control approach has been restricted to large systems by high initial costs. Now increased power rating of solid-state devices has become available on a mass-production basis. These devices enable higher-power inverter circuit designs to be achieved, thus encouraging manufacturers to seriously consider application of variable-speed electric motors for air conditioning and heat pump compressors.

A number of attractive features of inverter-driven variable-speed heat pumps have been reported (Bahel and Zubair 1989; Miller 1988; Lannus 1988; and Mohan and Ramsey 1986). In terms of seasonal energy efficiency, inverter-driven heat pumps can lessen energy consumption in a building by 1) lower start-stop (cycling) losses, 2) improved refrigerant cycle performance because of decreased compression ratios and reduced heat exchanger loading during low speed operation, and 3) lower fan power requirements through variation of air flow rates. The findings of Hori et al. (1985), Iida et al. (1982), Marquand et al. (1984), Mills (1987), Tassou et al. (1983), and Umezu and Suma (1984) show inverter-driven heat pumps can achieve seasonal energy savings of 15% to 40%.

Another attractive feature of a modulated system is the ability to operate in a low-capacity, load-following mode during periods of peak electrical demand. A number of electric utility companies in the United States have indicated interest in temporary air-conditioning curtailment during high-demand periods to shed peak electrical loads. In such situations, inverter-driven heat pumps can be restricted to low-capacity operations. This would result in retaining some cooling during high-demand periods, and at the same time produce a substantial reduction in utility peak demands. Thus, variable-speed heat pumps and air conditioners are expected to facilitate load management by the utilities and possibly operate the unit in a manner predetermined by such factors as the

4.6 IMPACT OF NEW POWER DEVICES ON INVERTER BUSINESS

The primary factors determining a power device's suitability for a given application are its power handling capability, efficiency, ruggedness, availability, support circuit complexity, and price. The complicated interactions among these factors change with each generation of devices.

The price of semiconductors, both power and digital, has historically followed what is known as the semiconductor experience curve. The price of semiconductor devices has decreased by a factor of approximately 30% (in constant dollars) whenever the cumulative unit volume for that device doubles. As a result, new devices show rapid decreases in price during their early market years. Older devices show a continuing decrease in price at a slower and slower rate.

"Moore's Law," which carries the name of Intel Corporation's President Gordon Moore, states that the complexity of integrated circuits (in terms of the number of devices or gates per chip) approximately doubles every year. This trend has remained valid throughout most of the 1960s and 1970s. Whether this trend continues into the early 1990s, or the rate of advance will slow the trend, is uncertain. However, the significant market success enjoyed by the leading Japanese HVAC systems manufacturers, who are also leading developers of BJTs and microprocessors, will most likely exert downward pricing pressure on the world semiconductor business. This hypothesis will be examined in detail in Section 5 of this report.

4.7 IMPACT OF FOREIGN COMPETITION

The United States faces a strong task of international competition. In the 1980s, the United States has encountered the greatest magnitude of international trade competition. In the field of ASD products, however, U.S. companies are holding their own, but offshore manufacturers' influence is growing.

Examining the market areas in which U.S. concerns lost ground in international competition, we find:

- microprocessors for personal computers, i.e., microchips for volume production and volume sales
- low power (less than 5 hp) induction motor controllers
- Darlington power transistors for volume production and volume sales
- self turnoff devices for high-power applications, such as the GTO.

On the other hand, the United States still appears to lead in the fields of:

- custom ICs
- integrated power devices, such as MOSFETs
- fundamental innovations.

During the late 1970s and early 1980s, U.S. monetary policy, fiscal policy, deregulation in various industries, economic recession, and other factors contributed to maintain the value of the U.S. dollar unreasonably high in the overseas currency market. The result was a mixed blessing. Inflation was fought back and foreign capital generously flowed into the United States--fueling robust economic expansion. On the other hand, U.S. companies opted to move 20% of their total manufacturing capacity overseas, and research and development funds were cut back to cope in the recessional environment.

As a result, the United States was unable to compete in the consumer electronics market on the basis of quality-for-price on products. In the electronics field, personal computers are being sold as a consumer electronics product. Mass-produced microprocessor chips are being installed on a wide variety of products from automobiles to TV and VCR sets. Continuing loss of the computer-chip market share in the world compelled the U.S. chip manufacturers to claim illegal dumping practice by the Japanese, for which the U.S. federal government agreed to assess a substantial tariff penalty. Furthermore, in the area of Darlington power transistors and low-horsepower inverters, a significant change is taking place. Figure 4.9 shows the estimated cost of an ac variable-speed drive from fractional to 220 hp in constant 1980 dollars. This prediction was made in 1981 by Masher and Smith (see reference). They stated, "A major limit on the penetration of (ac variable-speed) drives is the minimum cost. Even in the year 2000, the minimum cost for fractional horsepower units is estimated at about $400." Today, ac inverter drives, at 1 hp, using a Darlington power bridge with a PWM adjustable speed range of 30 to 180 Hz, are available at approximately $120 in Japan for application in residential variable-capacity heat pumps. Toshiba introduced the first residential variable-capacity heat pumps in 1983 when less than 100,000 units were sold. The market grew explosively to 1.1 million units sold in 1987. If we put this trend in the context of the semiconductor experience curve, we expect the price of the inverter module to have dropped in price by a factor of four. It was clearly demonstrated in Japan that low-horsepower inverters for residential and commercial applications are market viable, and the more they are sold, the lower the price. The influence from foreign manufacturers has certainly changed the tone of previous predictions.

U.S. manufacturers are not far behind. In 1989, two major air-conditioning equipment companies were expected to introduce their own ECM-driven adjustable-capacity heat pumps for residential applications. These units will use IGTs on their power units with capabilities up to 5 hp.

As we have pointed out, device manufacture know-how can only be gained from an iterative design process between devices and driven equipment. Devices need to be stressed, field tested, destroyed, and improved many times before they can be considered market-ready. At least in the area of high-voltage application, Japanese and European manufacturers have accumulated an extensive body of experience and knowledge using the advanced high-voltage circuits and advanced induction motors for popular applications.

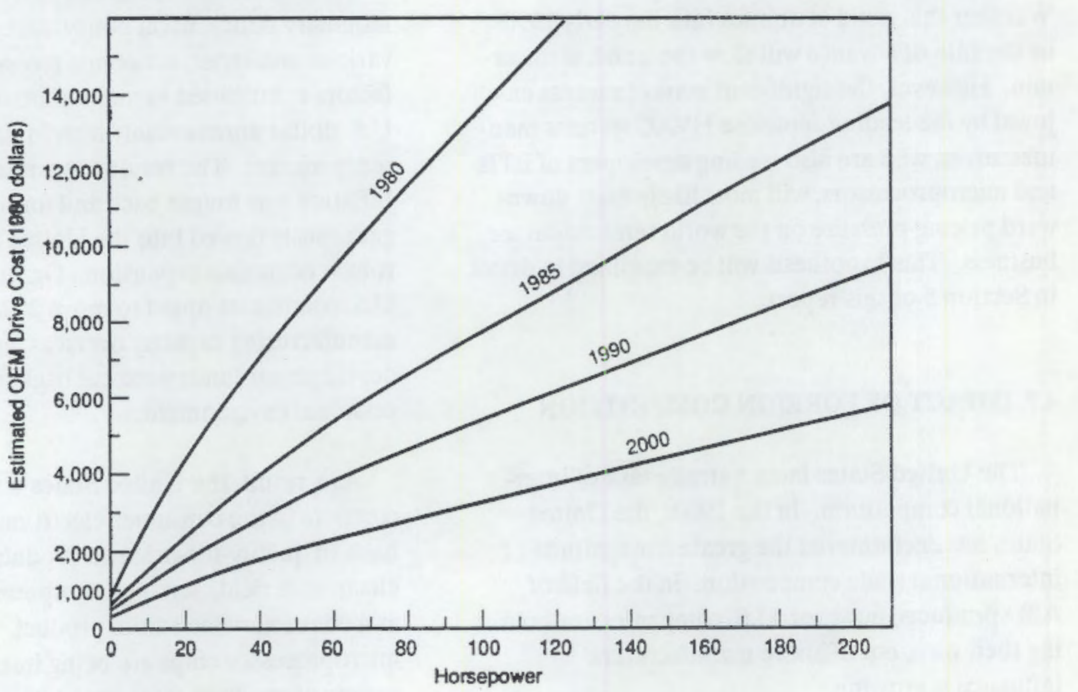


Figure 4.9. SRI Estimated ac Variable-Speed Drive Costs (Source: Masher and Smith 1981)

5.0 STATUS OF THE POWER ELECTRONICS INVERTER APPLICATION IN JAPANESE HVAC INDUSTRY

The status of the power electronics inverter application in the Japanese HVAC industry is described in the following subsections.

5.1 OVERVIEW

Although the energy conservation benefit of inverter application in the HVAC industry is well known, only recently have inverter technology and digital control modules advanced to the point of being small, lightweight, and cost-competitive for implementation in residential applications. It is important to note that the success of inverter-driven space conditioning equipment occurred first in the Japanese HVAC market. Whereas similar technology was tried in the United States for use in the residential unitary heat pump market in the late 1970s, the variable-speed equipment did not (and has not) become popular in the United States. The success of inverter technology penetration into the Japanese HVAC market has been attributed to significant advances in power electronics, rotary compressor, and microcircuitry technology. Although inverter technology was widely available in industrial applications, size and cost were problems from the 1960s to the late 1970s. In the early 1980s, however, advances in technology and volume-based production of rotary compressors, power electronics devices, and microprocessors took place simultaneously in Japan; all of which contributed to the timely development of a low-cost, lightweight, solid-state inverter for residential HVAC application (Tsuji and Hamaguchi 1987).

In this section, state-of-the-market inverter technology, heat pump control strategy, and new motor technology are reviewed.

5.2 INVERTER DESIGN FOR AN HVAC APPLICATION

The function of an inverter is to modulate and control the available power from the local utility to provide a variable voltage, variable frequency power source to the motor. The ultimate control parameter of a motor is its torque production, but the speed of an induction motor is expressed as:

$$N(rpm) = 120\, f(1-s)/p$$

where f = frequency of the alternating current source
s = slip
p = the number of poles.

The speed of an induction motor is controlled by the frequency of the ac source. Furthermore, the magnetic flux Φ of the rotor can be expressed approximately as

$$\Phi = kV/f$$

where k = the proportionality constant of the given rotor
V = source voltage
f = the frequency of the ac source.

For induction motors, the magnetic flux is limited by a certain maximum value above which the rotor current reaches the saturation point. Above the saturation point, the rotor current increases rapidly to cause damage to the rotor windings. One requirement of the inverter during low-speed (low f) operations is to control voltage to maintain constant V/f or volts/Hertz (Figure 5.1). The method of voltage and frequency control is commonly referred to in Japan as the variable voltage, variable frequency (VVVF) control. The V/f pattern is selected for each motor type and load profile (Tsuji and Hamaguchi 1987).

Both the VSI and CSI can provide constant V/f induction-motor control, but usually the current

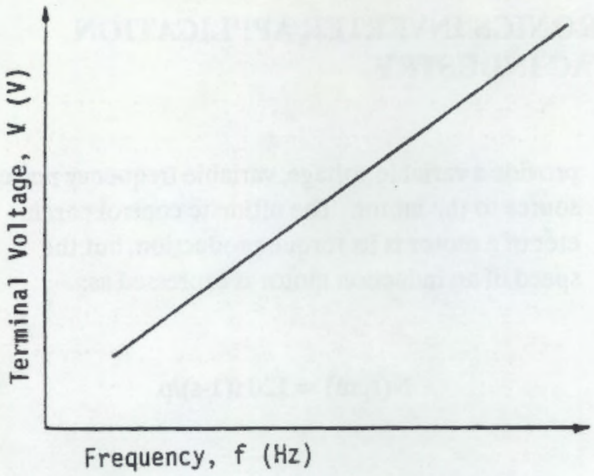


Figure 5.1. A Typical V/f Pattern

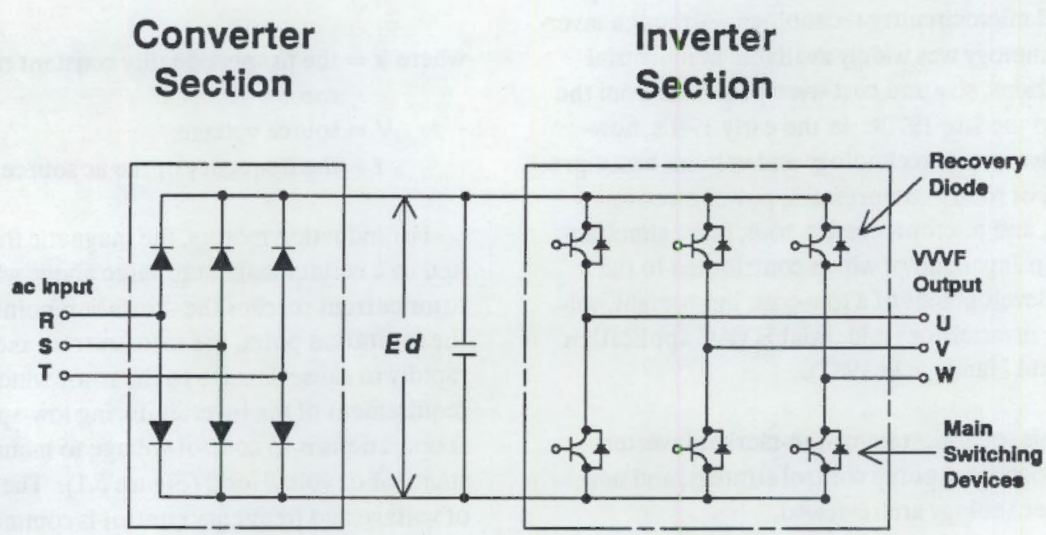
source-type inverter is used only when high-speed response to transient-load conditions is required. The VSI is already in use for industrial, commercial, and residential applications because of its simple topology and low cost.

A schematic of a VSI is illustrated in Figure 5.2. The ac source is rectified to dc voltage E_d in the converter section, and is inverted to synthesized sinusoidal waveform at controlled frequency in the inverter section. Converter section can be built from either diodes or thyristors. For application voltage below 900V, power transistors are commonly used in the inverter section.

To provide variable-voltage output at a controlled frequency, either the pulse amplitude modulation (PAM) or the PWM method is used. Here, we present factors that affect the technology selection in the residential heat pump application.

5.2.1 Efficiency

The PWM inverter takes advantage of high-frequency power switching to synthesize variable-frequency sinusoidal waveform. Switching speeds are usually on the order of 1-2 kHz. The loss mechanisms of solid-state inverters in this application include forward conduction loss and switching loss. Due to this high-speed switching requirement, the PWM inverter has slightly higher



R, S, and T comprise the three-phase power input into the converter.
E_d is the voltage across the converter section.
U, V, and W comprise the three-phase power output from the inverter.

Figure 5.2. Circuit Diagram of PWM Inverter (Source: Ushimaru et al. 1987)

losses than a similarly sized PAM inverter. Furthermore, a PWM inverter contains large, low-frequency harmonics distortion in its synthesized waveform. This distortion can cause torque pulsation in the rotor section of the induction motor causing a reduction in mechanical efficiency of the system, whereas output from a PAM inverter can be filtered out to maintain reasonable system efficiency.

However, a total system loss due to inverter use, consisting of forward conduction loss, switching loss, and mechanical loss from torque pulsation, is nearly constant at all speeds. Thus, the combined losses at low-speed operations can amount to a few percentage points. It follows that the seasonal efficiency gain of a heat pump from inverter use must be based on an optimum match between load variation and compressor sizing.

5.2.2 Audible Noise

PWM-type inverters require high-frequency switching to synthesize variable-frequency sinusoidal waveform over the entire range of operation. Thus, even at low-motor-speed operation, the device switching continues at the carrier frequency of 1-2 kHz. On the other hand, PAM-type inverters tend to have lower audible noise at low-frequency operation (Tsuji and Hamaguchi 1987).

5.2.3 Mechanical Vibration

Generally, mechanical vibration for a variable-speed system is attributed to harmonic power distortion for the PWM-type and torque ripple for the PAM-type. Furthermore, over the range of motor speeds, the mechanical system will undergo certain periods of resonant vibration at various characteristic frequencies. Increased mechanical vibration, due to inverter use, is inherent to the concept of variable-speed motor operation. Sound engineering should be exercised to reduce harmonics, improve current source torque ripple, and avoid operation around resonant frequencies in the product design stage.

5.2.4 Cost

Cost is the most critical selection factor for small-capacity inverter drives for residential HVAC applications in Japan. Whereas the PWM-type can be built from a converter section using inexpensive diodes and the inverter section using power transistors, the PAM-type requires power transistor switching devices in both the converter and the inverter section. Thus, the PAM inverter is more expensive to build than the PWM inverter. As a result, all inverter-driven heat pumps in Japan use the PWM-type inverter (Tsuji and Hamaguchi 1987).

5.3 FIRST INVERTER-DRIVEN HEAT PUMP IN THE JAPANESE RESIDENTIAL MARKET

Toshiba Corporation announced its introduction of an inverter-driven heat pump for residential applications in 1982 (Cohen 1982). The introductory product used a power-transistor-based PWM inverter for a 0.75-ton cooling capacity at 60 Hz with a control range of 30 to 90 Hz. The rated heating capacity was obtained at 75 Hz.

The initial unit used a 4-bit microprocessor to control inverter frequency for the appropriate heating or cooling, according to an algorithm based on measured temperature of the ambient condition around the unit and the set temperature. Digital data needed to synthesize the inverter waveform is stored in a read only memory (ROM) for 1.25-Hz steps. For each frequency, the data gives the on-time for six successive 30-degree increments during a half cycle of alternating current.

Digital circuits replicate the remainder of the three-phase voltage from the data for a half cycle. The other two phases are obtained by shifting the first phase. Three pairs of power transistor switching devices, one for each phase of the motor, connect the corresponding phase lead of the motor to the positive or negative terminal of the power supply during the time that it receives either a positive or negative pulse to its base terminal.

Another feature important in Japan is constant capacity at different line frequencies. The inverter's power source is direct current, obtained by rectifying and filtering the commercial power source. The air conditioner will provide the same output in the part of Japan with 50-Hz power as it does in the region with 60-Hz power, or in different countries with different line frequencies. Similarly, the unit may be adjusted to work in regions with slightly different voltages, abrogating the need for different motor design.

At the time of introduction, the price of the Toshiba inverter-driven heat pump was set at $1,372, and was only 13% higher than a fixed-speed heat pump of similar capacity and features (Cohen 1982).

In the first 16 months after the introduction, Toshiba sold 20,000 units. During this time period, the downturn in economy and record-setting cool summers in Japan caused a severe recession in the air conditioning business. Despite the unfavorable business conditions, Toshiba achieved some 40% increase in sales of inverter-driven heat pumps from 1983 to 1984. The 1984 model sold for $1,204, down from $1,372 of the 1983 model, and only $182 more than conventional fixed-speed models of similar capacity. Toshiba claimed an average operating cost savings of $36 per year with the average simple payback of 5 years. Toshiba's product announcement in 1982 was followed by announcements from Hitachi and Sharp in 1983 and by Mitsubishi Electric, Sanyo, and Matsushita in 1984.

During the first 2 years of product marketing, Toshiba incorporated a number of significant product design changes. The most notable improvement resulted from the development of a large-scale integrated (LSI) chip for inverter control. One LSI chip was claimed to have replaced ten integrated circuits formerly needed in the waveform synthesizer. Furthermore, the rectifier bridge was used to boost the source voltage from 100 V (the line voltage in Japan) to 200 V into the inverter section. The combined benefit of higher voltage source and high-speed operation above 60-Hz line frequency was a 25% reduction in the weight of the compressor from 4.5 to 3.5 kilograms (Berger 1983). Actually, a smaller compressor was used at higher speed and torque production capability to provide the same performance at lower cost through the use of the inverter. Thus began the dramatic growth of residential inverter-driven heat pumps in Japan.

5.4 CURRENT TECHNOLOGY LEVEL OF JAPANESE INVERTER-DRIVEN RESIDENTIAL HEAT PUMPS

A typical Japanese heat pump inverter, inverter components, and system efficiency are explained in the following subsections.

5.4.1 Inverter

The state-of-the-market inverter technology available in Japan for residential heat pumps (less than 2.5 tons) is PWM-type. Figure 5.3 shows the key features of a typical heat pump inverter, and its approximate performance ratings are described in the following.

Typical residential inverter power rating is 100-V, 25-A, single-phase ac input. The ac input from the standard residential electric service is at 50 Hz in the Tokyo area (the Eastern region), and 60 Hz in the Osaka area (the Western region). The single-phase ac input goes through a dc-link (an ac-dc converter) with maximum dc voltage of approximately 300 V. The dc output from the dc link module is fed into a dc-ac inverter. All Japanese heat pump inverters are of the PWM-type for frequency and voltage control. The PWM inverter requires the least number of solid-state switching devices (six devices for three-phase output as compared to at least 12 devices for a PAM inverter). For the particular type of torque-frequency required for the operation of a variable-speed compressor (nearly constant torque and a liner power increase with the speed), the PWM has been selected on the basis of low manufacturing cost and reliable performance.

State-of-the-market inverter technology in Japan consists of a Darlington-type power

7.0 CONCLUSIONS

This report covered technical issues relative to inverter-driven heat pump technology and policy issues surrounding the implicit motivation for the technology.

Of the 4.5 million air conditioning units sold in the Japanese domestic market in 1988, over 60% were heat pumps (as opposed to cooling-only equipment) and slightly over 50% of the heat pumps were inverter-driven. In 1988, inverter-driven residential heat pump sales totaled 1.5 million units and are still growing.

The Japanese residential market still revolves around the 0.75-ton inverter-driven heat pump; this is their most competitive and popular market. The evolution of technical advances in the small-capacity heat pump market can be characterized as:

- The basic structure of the inverter is ac PWM with Darlington-type power transistors.

- The popular motor choice is a low-cost induction motor.

- Production sources for inverters, controllers, and mechanical equipment are all internal, thus creating the important vertical integration environment.

On the other hand, the U.S. technology base has revolved around the following component technologies:

- Strong emphasis on motor efficiency, especially in the HVAC applications, provided an impetus for developing an efficient brushless dc motor in the 3- to 5-hp range.

- Component purchasing from a variety of vendors is common--some components are purchased from domestic suppliers and others from overseas. However, consolidation in the HVAC and other industries through mergers and acquisitions resulted in virtual sole-source integration structure within some manufacturers.

The key difference between the technology bases in Japan and the United States is the size of the market and the focus of the market segment. In Japan, the most important market segment is the 0.75- to 1-ton split-type equipment market, whereas in the U.S. it is the 2- to 4-ton unitary market. Because of the unique economics and performance trade-off issues based on a critical difference in equipment sizing, it is not appropriate to conclude whose technology base is more advanced. It is more meaningful to analyze what technology base will be the most economically beneficial for the future market.

The major concern this work has identified is the aggressive production and pricing policies Japanese manufacturers employ to build an infrastructure of overproduction. When domestic demand of key ingredients in inverter-driven heat pumps was finally outpaced by increases in production capacities of those components, low-cost inverters were applied to add another dimension in the residential heat pump market. In terms of future competition in the U.S. HVAC market, leading U.S. variable-speed heat pump manufacturers should be cautioned to expect a challenge from the Japanese producers of power devices and microprocessors. Because of the vertically integrated production structure in Japan, as opposed to the outsourcing practice of the United States, price competition at the component level may impact the structure of the industry more severely than final product sales.

From a market perspective, it is anticipated that Japanese consumers will continue to move toward larger size equipment and U.S. manufacturers will be driven to improve equipment efficiency. Facing the effective date of new appliance efficiency standards [the National Appliance Energy Conservation Act of 1987 (NAECA)] in the early 1990s, U.S.