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A SURVEY OF ADVANCED-HEAT-PUMP DEVELOPMENTS FOR SPACE CONDITIONING*

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ABSTRACT

Because of the heat pump's appeal as an energy conservation tool and its potential impacts on electric and gas utilities, a great deal of recent attention has been focused on this type of space conditioning equipment by national energy research organizations. This paper presents a survey of heat pump RD&D projects with special emphasis on those supported by the Department of Energy, the Electric Power Research Institute, and the Gas Research Institute.

INTRODUCTION

Looking ahead to the residential and commercial space conditioning needs of the future, it is apparent that heat pumps will play an important role in this energy use sector. This is emphasized by the remarkable growth in sales of electric air-to-air heat pumps during the past few years and the extensive heat pump research and development activities under way in the United States and abroad.

At Oak Ridge National Laboratory (ORNL), we have been conducting in-house research on heat pumps since 1976, and since 1978 we have assisted in managing a contracted RD&D program for the Department of Energy (DOE) on residential and commercial heat pumps. This assignment has given us an opportunity to interface with many other organizations supporting and/or conducting similar R&D work. It is the intent of this paper, then, to present a survey of these projects (whether recently completed, ongoing, or about to start).

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With regard to scope, this survey paper covers conventional electric as well as experimental gas-fired heat pumps and focuses on unitary equipment for residential and commercial space-conditioning applications. It does not cover solar-assisted heat pumps or chemical heat pumps, both of which may be appropriate technologies for this application and which are receiving R&D support from DOE and elsewhere. This omission was not for technical reasons, but because of lack of specific project information and time limitations for obtaining it.

HISTORICAL NOTES ON HEAT PUMP DEVELOPMENT

The only type of heat pump being manufactured today for application in residential and light commercial buildings is the electric heat pump - predominantly the air-to-air heat pump. The electric air-to-air heat pump evolved directly from the electric air conditioner (which may be characterized as a cooling-only heat pump). It was introduced on the commercial market in the 1950s and for several years was a relatively successful new product. Then, as a result of some severe equipment reliability problems, the product's survival was threatened. Many manufacturers dropped heat pumps from their product lines. Others restricted sales by region to the more southern climates. Also, during this period a ban was imposed on further installation of heat pumps in military-base housing due to the poor reliability record (1). But the industry's heat pump advocates persevered.

Thanks to the diligence of several major manufacturers during the 1960s and early 1970s, the heat pump was not abandoned and, gradually, real progress was made toward developing improved designs and components that could withstand the more severe stresses of heat pump service (2). Credit should also be given to programs sponsored by the Edison Electric Institute and certain individual electric utilities such as American Electric Power and Alabama Power aimed at improving the quality of the heat pump "as installed" (3,4,5). These utility programs focused attention on installation and servicing requirements, as well as providing detailed failure data which was fed back to manufacturers to help them determine specific design weaknesses. Developments over that 15-year period yielded proven solutions to the reliability problems by some (but not all) manufacturers (1,5).

As a result, a reliable and relatively efficient heat pump product was available when the demand for it occurred in the mid-1970s due to shortages and curtailments of natural gas and heating oil in many areas of the country. For many home buyers and builders, the heat pump became the only reasonable home heating alternative during that period of moratoriums on new gas connections in many regions and rapidly escalating prices for fuel oil and electric power. The combination of these events led to a period of dramatic growth in heat pump sales.

MARKET AND EQUIPMENT TRENDS

As illustrated in Fig. 1, heat pump sales have grown markedly in the United States since 1970, when shipments totaled less than 100,000 units per year, to approximately 500,000 to 600,000 units per year during the last three years. The heat pump, which was installed in only 4% of single-family homes in 1973, captured a 25% market share last year (6). This wide acceptance in the marketplace indicates that, in the purchasers' minds at least, the mechanical and reliability problems of the past have been overcome and, further, that the current heat pump product's initial costs are acceptable in return for decreased energy consumption and lower monthly utility bills.

Heat pump manufacturers usually offer several lines, ranging from an economy builder's model to a top-of-the-line, high-efficiency model. The following tabulation characterizes the efficiency of current heat pumps in terms of Air-Conditioning and Refrigeration Institute (ARI) steady-state ratings (7).

	Heating COP* at 47°F	Heating COP at 17°F	Cooling EER†
High-efficiency model	3.2	2.1	8.8
Typical model	2.5	1.8	8.0
Small, economy model	2.0	1.3	5.9

At present, the higher efficiencies are obtained by the use of high-efficiency compressors, larger heat exchangers, and improved controls.

Just as reliability was the key issue for heat pumps in the 1960s and early 1970s, performance and efficiency have been the key target for improvement since the mid-1970s. Because of the heat pump's appeal as an energy conservation tool and its potential impacts (both positive and negative) on electric and gas utilities, much of the impetus for performance improvement has come from outside the heating, ventilating and air-conditioning (HVAC) equipment manufacturers.

Research programs supported by DOE (and its predecessor organizations, the Federal Energy Administration and the Energy Research and Development Administration) began in that period, including the work at the National Bureau of Standards (NBS) and at ORNL. Those programs, together with special contracted studies on heat pump technology (8) and input from organizations such as EPRI and, later, GRI were influential in formulation of the DOE R&D programs that will be described in subsequent sections of this paper.

However, it is doubtful that those in the HVAC industry would rate the increase in heat pump R&D as the highlight of the last five years in the heat pump business. Rather, it is more likely that they would identify the federal energy conservation legislation that resulted in establishment of new government test procedures and proposed minimum efficiency regulations for their heat pump and air conditioner products (9,10).

Much of the manufacturer's engineering resources are and will likely continue to be involved, near-term, either in responding directly to those new testing procedures or in striving to obtain maximum available rating credit under the new procedures. And although the chief effect of the efficiency standards may be to eliminate the lower efficiency, "economy" models now being sold, there should be some effect on advancing the state-of-the-art. Near-term trends in heat pump performance improvement are therefore likely to be highly influenced by regulations, as well as by outside R&D support and market forces.

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*COP, Coefficient of Performance, is defined as the ratio of the heating capacity in Btuh to the electrical power input in Btuh (Watts × 3.412 Btuh/Watt) at a given rating condition and is the standard efficiency measure for heat pumps in heating mode.

†EER, Energy Efficiency Ratio, is defined as the ratio of the cooling capacity in Btuh to the electrical power input in Watts at a given rating condition (expressed in Btuh/Watt).

RECENT ELECTRIC HEAT PUMP RESEARCH

Research work initiated by NBS during the 1974-75 winter season in a test house (11) and later augmented by their own laboratory investigations (12) and those of Carrier Corporation (13) was influential in focusing R&D attention on two effects that significantly degrade heat pump performance under actual operating conditions: (1) "on-off" cycling losses resulting from the need to reestablish steady-state operating conditions in the system after each "off" cycle and (2) effect of frost buildup on the outdoor coil under certain weather conditions and the associated energy required for a periodic defrost operation.

During the same period, research was undertaken at ORNL to determine the potential for improving steady-state efficiency or COP utilizing state-of-the-art computer modeling techniques for heat pump design and component matching. This work (which is summarized on Table 1) has involved experimental studies to assemble a detailed data base of system and component performance for heat pumps in addition to development of the computer simulation models.

Table 1. DOE/ORNL heat pump technology studies

Project	Objective
Heat pump performance data base	Detailed component and system performance/model validation (14,15)
Heat pump computer model	Explore efficiency improvements/ tool for industry use (16,17)
Heat pump optimization	Define efficiency limits, best cost-effective system (18)
Cycling and frosting tests	Characterize loss mechanisms (15)

ORNL also developed and demonstrated an innovative heat pump/thermal storage concept called the Annual Cycle Energy System (ACES) during the late 1970s. The system employs a unidirectional water-source heat pump to heat the house and simultaneously to make ice during the heating season; this ice is stored in a large, insulated tank to provide a source of cooling in the following summer (air conditioning) season. Work has continued on this system, both in-house and under subcontracts, to evaluate and improve the system's economic competitiveness against more conventional systems (19,20).

EPRI began to support contracted research on electric heat pumps in the mid-1970s and, over the past 5-6 years, has sponsored several systems analysis and field testing projects aimed at evaluating seasonal performance of air-source heat pumps and potential effects on electric utilities. Those projects, listed in Table 2, have focused primarily on the heating seasonal performance factor (SPF)* and its improvement in northern climates and on utility concerns about maximum electric power demand and time-of-day load profiles.

*SPF, Seasonal Performance Factor, is defined as the total heating or cooling effect delivered during the season in Btu's divided by the total electrical energy input in Btu's (Watt-hours × 3.412) during the same period (an integrated COP value).

Table 2. Recent EPRI-sponsored heat pump research projects

Project No.	Contractor	Title/description
RP-432[a]	Westinghouse	Load and use characteristics of heat pumps in single-family residences/Field tests of heating operation at 120 houses in 12 regions (21)
RP-1100	Gordian Associates	Impacts of residential heat pump technologies on utility system loads/Analysis of data developed in RP-432 to assess effect on utilities
RP-544	Westinghouse	Investigation of methods to improve heat pump performance and reliability in northern climate/Comprehensive systems analysis and methodology development (22)
RP-789[b]	Carrier Corporation	Investigation of heat pump performance in northern cliamtes through field monitoring and computer simulation (23)
RP-1201-6	Science Applications Inc., (SAI)	State-of-the-art assessment of hybrid electric heat pump system with oil or gas supplementary heat (in lieu of electric resistance) (24)

[a]Jointly sponsored with the Association of Edison Illuminating Companies with participation of 12 electric utilities.

[b]Cofunded with Niagara Mohawk Power Corporation and Carrier Corporation.

DEVELOPMENT OF ADVANCED ELECTRIC HEAT PUMPS

Most of the research work in the late 1970s led to the same general conclusions about the key technical issues in improving electric heat pumps for the future:

- improve part-load performance (reduce system "cycling" losses),
- improve low-temperature performance (reduce supplementary electric resistance heat),
- improve system steady-state performance (optimize system design and improve component efficiency),
- reduce frosting/defrosting losses (reduce frost buildup, improve defrost method/controls),
- continue to maintain/improve reliability.

Development of cost-effective variable-capacity compressors addresses two of those issues, namely reduction of cycling losses and reduction of supplementary resistance heat requirements at low ambient temperatures. Accordingly, development work on capacity modulation (variable-capacity compressors together with

appropriate advancements and modifications in other components and controls to take full advantage of variable capacity on a systems basis) of the electric air-source heat pump is considered a high development priority.

A second need is for innovative defrost methods to replace the current refrigerant flow reversing scheme. Currently, losses attributed to frost buildup and those associated with the defrost cycle are considered second only to cycling losses in most locations (climates), especially when it is considered that a significant fraction of the electric resistance heat is used to "temper" the air supplied to the house when the system is switched over to the cooling mode. In addition, the effect of the defrost transient on the compressor is seen to represent the most severe "shock" that the compressor experiences; therefore, its elimination may represent one of the primary means of improving reliability.

Component improvement and design optimization is a third research and development area, first for determining the limits of heat pump steady-state efficiency (maximum reasonable COP without cost constraints), then for determining the highest COP which is possible in a cost-effective configuration heat pump, and finally for determining the relationship between dynamic (seasonal) and steady-state efficiencies by integrating dynamic losses (cycling, defrosting, etc.) into the optimization process.

In the subcontracted RD&D program that ORNL manages for DOE, system development or "product development" projects provide a way of addressing such technical issues on an integrated or "systems" basis. This approach is also consistent with the program's commercialization thrust in that developments can be more readily implemented if developed by or for a present or potential heat pump manufacturer in a manner similar to that used for developing a new product line.

Development work has started on two such residential-sized advanced electric heat pump projects (see Table 3) selected in 1979 and 1980 via a request for proposals (RFP). Like all major DOE/ORNL product development projects, these projects involve cost sharing by the contractor. They employ different approaches for capacity modulation and related advancements to achieving their seasonal efficiency targets.

Table 3. Electric heat pump system development (residential application/size)

System	Developer	Target SPF[a] improvement
Advanced electric heat pump I (systems approach, featuring 2-step capacity modulation of compressor, high-efficiency fans/motor, new defrost, microprocessor control, diagnostics)	Westinghouse	20% min. (northern climate SPF 2.5)
Advanced electric heat pump II (fully variable modulating compressor with linear motor)	MTI	25-35%

[a]SPF is defined as the total heating or cooling effect delivered during the season divided by the total electric energy input during the season.

Much of the current hardware development in the Westinghouse project is based on the system analysis and methodology developed under EPRI Project No. RP-544 (see Table 2).

As mentioned previously, market and regulatory pressures will also result in new heat pump models and product features designed to improve energy-efficiency ratings. Variable-capacity compressors, for example, have recently been introduced by some manufacturers, including both two-speed and continuously speed-modulated compressors and a dual-compressor configuration. Field and laboratory studies are planned as part of both the DOE/ORNL program and the continuing EPRI-supported research activities to test and evaluate these different variable capacity designs, their seasonal efficiency potential, and their cost-effectiveness.

In addition to the field testing and systems analysis activities sponsored by EPRI, we understand that some "product development" work similar to the DOE/ORNL-sponsored projects is in the planning stage at EPRI. EPRI has advised us that they plan to report on the ongoing and planned EPRI-sponsored heat pump R&D projects at the upcoming 16th IECEC in Atlanta (August 9-14, 1981) (25).

WELL WATER AND GROUND-COUPLED HEAT PUMPS

Another way to improve heating performance at low ambient temperatures is to use alternative heat sources such as well water or ground-coil heat pump arrangements. These relatively constant-temperature heat sources offer considerable potential for improved capacity and COP during extreme winter weather when ground (and groundwater) temperatures are much higher than outdoor air temperatures. Also, because the outdoor coil is replaced by a refrigerant-to-water heat exchanger, frosting/defrosting losses will not be a factor in performance degradation. A notable achievement in this area during the past year was completion of a DOE-sponsored comprehensive study on well water heat pumps (by the National Water Well Association), including assessment of groundwater availability and quality on a state-by-state basis, investigation of environmental and legal problems, and an analytical evaluation of energy use and economics (26). Due to the analytically assessed energy conservation potential of this currently available technology (energy savings of 10-25% on an annual heating and cooling basis and 20-60% for heating only relative to an air-source heat pump), field performance projects have been initiated by DOE/ORNL to establish energy savings of well water heat pumps under actual residential service conditions. One of these is a cooperative project with EPRI, and a second is being cosponsored with New York State Energy Research and Development Authority (NYSERDA) and Empire State Electric Energy Research Corporation (ESEERCO).

Other projects are under way to assess ground-coil heat pump technology. Both EPRI and DOE/ORNL are supporting research in this area, although the effort is relatively small at present, pending favorable indications of energy conservation potential and commercial viability.

HEAT-ACTUATED HEAT PUMP DEVELOPMENT

A major portion of the DOE/ORNL contracted R&D resources are allocated toward development of heat-actuated heat pumps. Conventional combustion heating equipment (gas or oil furnace, for example) currently achieves about 60% efficiency and, when

developed to its ultimate potential, can approach but not exceed 100% efficiency. Heat-actuated heat pumps, of which the gas-fired heat pump is the predominant example, offer potential heating COPs exceeding 1.0, that is, delivering a heating effect greater than the heating value of the input fuel. Heat-actuated heat pumps are a product concept not presently manufactured or marketed in the United States.

Such a product could be an important option for improved efficiency in residential and/or commercial space heating in the mid- to late-1980s if its viability in the marketplace can be established. A gas heat pump currently envisioned as a typical 1990 residential product should provide both heating and cooling service using 30 to 50% less gas, depending on climate, than a conventional gas furnace uses for heating alone. About 55% of the nation's homes (over 40 million homes) are heated using natural gas. Furnaces and other gas heating appliances generally have a 15-20 year life expectancy, which creates a continuing replacement market of about a million units per year. With addition of the new home market, the total residential gas heating market is estimated at approximately 1.5 million units annually. With the cooperative support of the gas utility industry, the gas heat pump is now emerging as a leading candidate for providing more energy efficient heating for these consumers in the mid-1980s and beyond (27).

There are two basic types of gas-fired heat pumps. The first uses an absorption cycle and the second replaces the electric motor of the conventional heat pump with a gas-fueled prime mover (engine-driven). Of course, one of the key advantages of the heat-actuated system is that in the heating mode, waste heat can be recovered to augment the heating effect produced by the heat pump cycle, thus increasing the heating COP and capacity significantly.

Development efforts are under way on four residential and two commercial gas-fired heat pumps. As summarized in Table 4, two of the residential heat pump projects are of the absorption type and two are Stirling-engine-driven. Both commercial-sized heat pump systems are engine-driven, as described in Table 5. In most cases, systems developed for use with natural gas can also be oil-fired with appropriate modifications to the combustion system.

For the heat-actuated (gas- or oil-fired) heat pumps, the priority issues and technical risks seem to focus on three elements:

1. seasonal efficiency (which involves the same potential losses due to cycling and defrosting as the electric heat pump faces but with different design options to alleviate some of those losses);

2. endurance, reliability, and reasonable maintenance (e.g., seal life in engine-driven systems); and

3. initial cost/selling price.

The final risk facing any heat-actuated heat pump development venture is attractiveness to potential manufacturers as a business opportunity. With the substantial investment in development and manufacturing facility costs required, manufacturers will need to be assured of a substantial rate of return on investment before accepting the risk. Outside support can reduce the development costs but not the tooling and facility costs.

Table 4. Heat-actuated heat pump system development (residential application/size)

System	Developer (Major subcontractor)	Assessed risks (technical and business)
Free-piston Stirling[a] (spring-mass resonating engine/compressor)	General Electric[b]	High
Diaphragm free-piston Stirling[a]	Consolidated Natural Gas (with MTI)	High
Organic fluid absorption[c] (R133a/ETFE)	Allied Chemical[b] (with Phillips Engineering)	Moderate to high
Ammonia-water absorption[c]	ArkLa Industries	Moderate

[a]Target fuel COP of 1.6 (heating) and 0.85 (cooling), where fueld COP is defined as the heating or cooling effect divided by the energy value of the fuel used. Target values are steady-state ratings (excluding parasitics) for prototype hardware.

[b]Cosponsored with GRI.

[c]Target fuel COP of 1.25 (heating).

Table 5. Heat-actuated heat pump system development (commercial application/size)

System	Developer (Major subcontractor)	Assessed risks (technical and business)
Gas turbine driven[a]	Garrett/AiResearch	Moderate to high
Braun linear engine driven[b] (free piston, internal combustion engine)	Honeywell/Techtonics	High

[a]Target fuel COP of 1.5 (heating) and 1.3 (cooling), where COP is defined as the heating or cooling effect divided by the energy value of the fuel used. Target values are steady-state ratings (excluding parasitics for prototype hardware.

[b]Proof of concept.

At the present time, absorption heat pump technology is in the more advanced stage as a result of prior work in developing absorption chillers and air conditioning equipment. Therefore, the lower performance potential for the absorption heat pump is offset by the reduced technical risk associated with its development, as compared to the higher risk Stirling engine heat pumps. Thus, the general strategy is one of supporting different concepts with correspondingly different levels of risk and ultimate performance potential. Because no single heat pump concept is likely to be optimum for all climatic regions, then more than one option could be developed and commercialized on a competitive basis.

Two of the residential and one of the commercial gas-fired heat pump projects are continuing efforts cosponsored by the GRI with cost sharing by the respective contractors (General Electric, Allied Chemical, and Garrett/AiResearch). The other three were selected via competitive proposals solicited by RFP in 1979 and also involve contractor cost sharing.

In a following talk one of the ongoing projects cosponsored by DOE/ORNL and GRI will be described in some detail. It involves development of a commercial-sized Brayton/Rankine gas-fired heat pump system by AiResearch.

In addition to the gas-fired heat pump projects being cosponsored by GRI and DOE, GRI is supporting two other heat pump projects (27). Mechanical Technology, Inc., (MTI) is conducting one of those development projects, which involves a Rankine/Rankine system in a novel configuration employing rotating heat exchangers. That project is cost-shared by MTI, DuPont, and NYSERDA. The other gas-fired heat pump project involves a Phase I feasibility study of a Stirling/Stirling system. That project is being conducted by Sunpower, Inc.

INTERNATIONAL INTEREST IN HEAT PUMPS

As this survey indicates, there is much R&D activity under way in this country to develop advanced heat pumps for the future. Similar efforts are under way in other countries and, in fact, the R&D programs in Europe may be even more extensive than in the United States. DOE and ORNL have been involved in a cooperative program on advanced heat pumps through the International Energy Agency (IEA) since 1977. The final report on the first phase of that work provides a fairly complete technology survey in the 13 participating countries (28). In addition, EPRI (jointly with RWE, a German electric utility) and Carrier have sponsored international conferences, the proceedings of which provide additional information on the varying energy situations in other countries and the role that heat pumps may play in their energy conservation efforts (29,30).

CONCLUSIONS

This paper represents an attempt to describe not only the heat pump R&D projects with which we at ORNL are involved as part of our responsibilities to DOE, but also the work being conducted and/or sponsored by other national research organizations. As this survey illustrates, the private sector HVAC equipment manufacturers continue to play the major role in developing advanced heat pump systems, and the general objective of contracted R&D programs is to accelerate and complement the internally supported efforts of industry. As can be inferred from the variety of projects described, there is no consensus as to the "best" space-conditioning system.

There are too many unpredictable factors, such as fuel availability and electric-to-gas price ratios, to accurately judge the ultimate commercial viability of some of these developmental systems. Therefore, much of the impetus for the development is to increase the available space-conditioning options for the future by ensuring that advanced energy-efficient heat pump products are available to meet the needs of various market sectors.

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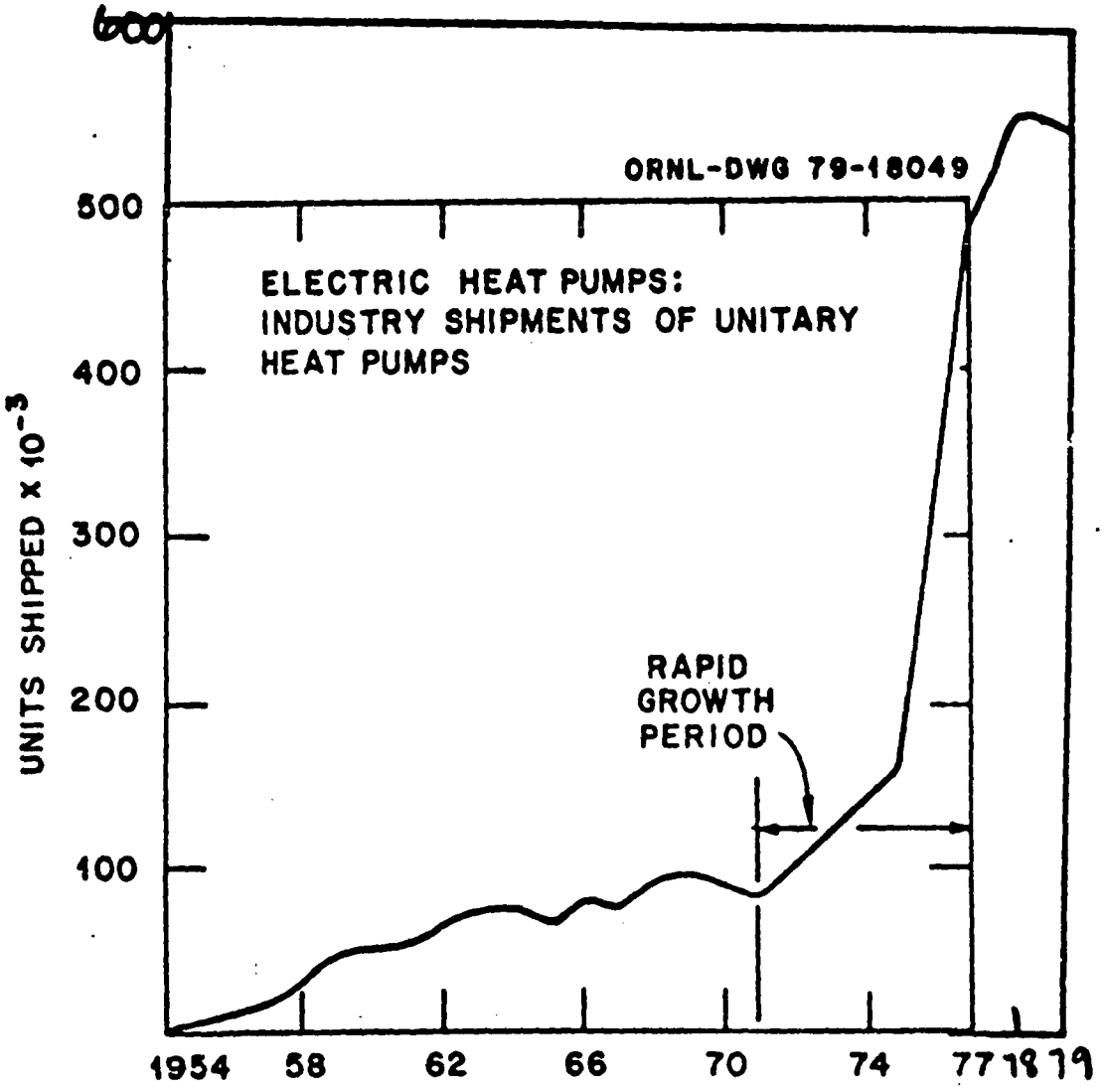

Fig. 1. Growth of heat pump sales in the United States since 1954.

Source of 1954 to 1977 data: Gordian Associates, Inc., Heat Pump Technology: A Survey of Technical Development Market Prospects, U.S. Department of Energy, HCP/M2121-01 (June 1978); source of 1977 to 1979 data: Air Conditioning, Heating and Refrigeration News Statistical Panorama, Apr. 7, 1980.

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