COMPARATIVE ECONOMIC EVALUATION OF ADVANCED BUILDING EQUIPMENT TECHNOLOGIES IN THE UNITED STATES*

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COMPARATIVE ECONOMIC EVALUATION OF ADVANCED BUILDING EQUIPMENT TECHNOLOGIES IN THE UNITED STATES

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ABSTRACT

The United States Department of Energy, DOE, sponsors research in energy-efficient building equipment in a program managed by the Oak Ridge National Laboratory, ORNL, in Oak Ridge, Tennessee. As part of that program, we established in 1981 an activity called Program Planning and Analysis that is specifically dedicated to evaluating ongoing and pending research projects with respect to potential impact on energy use in the United States. The objective of these evaluations is to allow us to select those projects for further development that are most likely to make best use of our R&D funds.

In our analyses, we simulate the seasonal and annual performance of the advanced system, based on target steady-state efficiencies for the project. We then calculate the energy savings an advanced unit would achieve over one or two reference systems in eleven representative cities in the United States. From this and some empirical choices of market penetration, we estimate the annual energy savings the new technology might bring about. By doing a similar and consistent analysis of a number of advanced technologies, we are able to rank R&D projects in value to the country.

In this paper we will summarize the results of the analysis of a number of advanced technologies, including heat-actuated space conditioning systems such as absorption heat pumps and Stirling-driven and internal combustion engine-driven heat pumps and advanced electric-driven systems such as continuously-modulated and step-modulated air-air heat pumps and ground-coupled heat pumps. Areas in which improvements must be made in order for certain advanced systems to become economically viable will be noted.

A. Objectives of the Evaluations

The Building Equipment Research Program, sponsored by the U.S. Department of Energy (DOE) and managed by the Oak Ridge National Laboratory (ORNL), is dedicated to the identification and development of advanced gas-fired and electrically-driven heat pump systems. We may, in some instances, carry the R&D to the breadboard pre-prototype stage, but stop short of product development, an activity perceived in the U.S. as belonging to the private sector. We are continually searching for new ideas in equipment and system concepts that have the potential for favorably impacting future use of energy and critical fuels in the United States. This search, which ranges from the evaluation of unsolicited proposals from the private sector to an on-going in-house effort to develop new ideas, generates more potential areas for R&D than our research funds can accommodate. Consequently, we have developed a methodology for comparing the relative merits of doing research in a particular technology area.

It is far easier, of course, to do relative, rather than absolute, evaluations, since in the latter much more accurate estimates must be made of market penetrations and future energy costs. Absolute evaluations, on the other hand, would be more valuable to most of the individuals in attendance at this conference. In this paper, we will try to stress those results of our evaluations that most directly relate to the potential marketability of an advanced building equipment concept.

B. Description of Evaluation Methods

The principal strength of our analyses is, we think, our ability to simulate residential system performance, given known or projected steady-state efficiencies and capacities, in any defined structure in any of 115 cities in the contiguous United States. Building heating and cooling loads calculations are based on a validated computer program, developed at ORNL, which uses the temperature-bin method to calculate monthly thermal loads. Monthly, seasonal and annual performance factors (coefficients of performance) for a given space and/or water conditioning system are

calculated by subroutines that incorporate the unique features of each advanced system. Degradation of steady-state performance caused by system cycling, by evaporator frosting and defrosting and by the use of backup heaters in severe weather is estimated by the subroutines, as are the major parasitic energy uses (e.g., fan and pump motors). Monthly, seasonal and annual energy uses to meet the calculated loads are then computed for the system of interest in each city of interest, and annual fuel costs are determined from local or regional fuel prices.

To this point, the results derived from the calculations described above are system-, house-, and city-unique and their accuracy is dependent upon the accuracy of the input data and the capability of the models. To be viable, and hence to have a chance to impact future energy use, an advanced system must be economically competitive with other systems which will be available in the same time frame. We have chosen a number of existing systems as bases for economic comparison; they are listed in Table 1.

Table 1. Base systems for comparison to advanced systems

Generic Advanced System	Generic Base System	Initial Cost (1982 $)	COPH[a]	COPC[a]
Heat-Actuated Heat Pump	Midline Gas Furnace/Midline Air Conditioner	4513	0.78[b]	2.56
	Pulse Gas Furnace/Midline Air Conditioner	4871	0.96[c]	2.56
Advanced Electric Heat Pump	Midline Electric Heat Pump	3903	2.75	2.40
	High-efficiency Electric Heat Pump	4103	3.30	2.61

[a]Unless otherwise noted, the end-use-electricity steady-state coefficient of performance for heating at 8.3°C (COPH) and for cooling at 35°C (COPC).
[b]Steady-state gas end-use efficiency at 100% load factor.
[c]Annual fuel-use efficiency as determined by DOE test procedures.

Because we make independent estimations of city-by-city energy use for each system under consideration, we are able to compare fuel use and fuel costs for any two systems for which we have developed computer files. Because annual fuel costs are only one of several owning and operating costs for a system, one must, to be most accurate, also estimate capital and installation costs, equipment component life expectancies, and maintenance costs. For the comparative evaluations discussed here, however, we neglect formal calculation of long-term maintenance and replacement costs, but do consider them subsequently when a final judgement is made as to the viability of a technology.

For a country as large and disparate as the United States, first costs and installation costs for a given piece of equipment can vary widely. In our evaluations we try to establish some reasonable average installed cost, and assume that, for a given type and size of equipment, that cost is constant across the country. For existing equipment, costs are derived from catalog prices, from quotes by dealers and contractors, and from construction cost handbooks such as Means (1). For non-existing (future) concepts, costs are compiled by analogy to existing hardware components, by professional estimates from preliminary design drawings, and by more-or-less educated guesses.

For advanced systems, simple paybacks are calculated by dividing the initial incremental cost (capital plus installation) by the first year's fuel cost savings. Although simple payback may not be the most logical criterion for selecting advanced equipment, it reflects the historical bent of consumers to consider first costs of paramount importance. From simple paybacks and from an empirical curve relating consumer choice to simple payback when choosing between two appliances (2), we are able to deduce for each city the fraction of buyers who would buy the advanced system rather than the base if given no other choices.

C. Summary of Assumptions and Limitations of the Evaluation Method

1. Assumptions:

   a. A single house type and insulation level is assumed to represent the average house in all regions studied. The reference single family residence is a 9.1m by 18.2m ranch-style house with crawl space, 15% single-glazed window area, major axis of house east-west, one air change per hour at a 24 km/h wind speed and a 21°C indoor-outdoor temperature difference, and with R-19 ceiling insulation, R-11 wall insulation, and R-9 floor insulation.

   b. A single city in each (U.S. census) region is assumed representative of the entire region, except for two western regions which are divided roughly in half because of large climatic differences. (See Fig. 1).

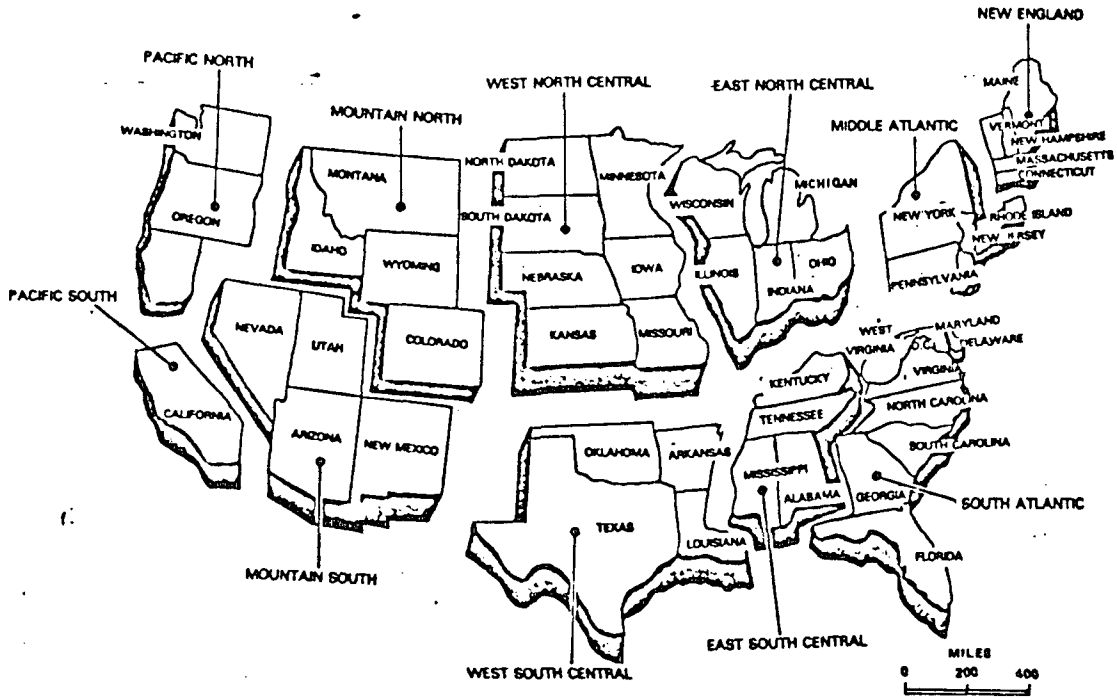

Fig. 1. Division of states into representative climatic regions, based on United States Census Regions.

c. A single unit cost for electricity and each fuel is assumed for each region. No demand charges or seasonal or time-of-use rates are assumed.

d. All possible buyers are confirmed buyers and they make a choice between only the advanced and the base systems.

e. All systems considered provide both heating and cooling, and the advanced system will not be marketed in regions in which the annual fuel costs for the advanced system exceed those of the base system. In addition, if an advanced system is estimated to have a wide range of simple paybacks with respect to the base system, only those regions with the most acceptable paybacks are chosen for the summary of relative values.

2. Limitations:

a. The choice of a single size and insulation level for the standard house is obviously incorrect, although in a relative evaluation, where the relative ability of a system to meet efficiently a building load is the criterion of value, it is

probably generally satisfactory. It is most likely to be unsatisfactory for systems which can save appreciable gas or oil during the heating season but which have high first costs. Such systems would benefit from being used in large, drafty houses in areas with severe climates.

b. For advanced systems, the efficiencies and capacities assumed are either targets or calculated values, and may not be achievable in practice at all, or may not be achievable at the system cost assumed. Errors in system cost generate errors in simple payback periods, and these errors in turn affect the estimates of market penetration.

c. Local differences in electricity and fuel prices may add or detract from the economic attractiveness of a given system as determined by using regional averages. Likewise, differences in price escalation rates for different fuel types may change the future relative attractiveness of different systems.

d. The analysis makes no attempt to determine realistic market penetration levels for advanced systems in any part of the country. If the loads calculations and performance simulation programs were applied to a proper mix of houses, however, and if regional equipment and installation costs could be obtained, important equipment-related components of a market survey would be in hand.

D. Summary of Results

A listing of the advanced-concept equipment evaluated to date, together with assumed mature-market costs and steady state performance parameters, is given in Table 2. The gas-fired absorption heat pump systems (1, 2, and 3 of Table 2) represent three stages in the recent development of such systems, culminating in the advanced cycle systems currently being investigated. Systems 4 and 5 represent alternative ways of improving the efficiency of using fossil fuels in space conditioning equipment. Three of the five electrically-driven systems, 6, 7, and 9, incorporate capacity modulation to improve seasonal efficiencies. System 7

Table 2. Characteristics of advanced systems evaluated

Advanced System	Initial Cost[a] (1982$ US)	COPH[b]	COPC[b]
HEAT-ACTUATED SYSTEMS			
1. State-of-art (SOA) gas-fired absorption heat pump	5479	1.25	0.5
2. Double-effect gas-fired absorption heat pump with high-efficiency burner	6379	1.8	0.9
3. Advanced-cycle gas-fired absorption heat pump	5923	1.9	1.4
4. Linear IC engine-driven vapor-compression heat pump (two-stage)	5515	2.2/4.9	1.5/1.8
5. Free-piston Stirling engine-driven heat pump with two firing rates	6943	1.5/1.9	1.1/1.3
ELECTRIC-DRIVEN SYSTEMS			
6. Advanced dual-stroke (two capacity) electric heat pump	4263	3.5/3.8	2.7/2.5
7. Optimized, continuously capacity-modulated electric heat pump (theoretical)	5003	2.8/4.9	2.1/3.3
8. SOA ground-coupled heat pump with horizontal ground coil	5566	4.18[c]	2.82
9. Two-stage ground-coupled heat pump with horizontal ground coil	5702	4.5/5.2[c]	3.5/5.2[d]
10. Electric motor-driven Stirling cycle heat pump, assuming isothermal compression	4924	2.9	2.2

[a]Assumed cost of nominal 3-ton unit. Unit size scaled to give minimum life-cycle costs while meeting cooling loads.
[b]Steady-state heating COP (COPH) at 8.3°C and cooling COP (COPC) at 35°C. Where two numbers are given (xx/yy), the first indicates the capacity in the high-capacity stage, the second that in the low-capacity stage.
[c]For an inlet water (or brine) temperature of 21.1°C.
[d]For an inlet water (or brine) temperature of 29.4°C.

was used to test analytically the advantages of making optimum use of midline heat pump component technology in a system with continuous modulation of capacity. The electric-driven Stirling cycle heat pump concept, System 10, was investigated because of its potentially superior capacity at low ambient temperatures.

The results of some comparative analyses of advanced heat actuated systems are given in Table 3 for three representative cities (eleven cities were actually used). For the purposes of this paper, Chicago, IL, was chosen to represent cities with a high annual heating to cooling load ratio (76.1/16.9, in million Btu); Atlanta, GA, to represent cities with similar heating and cooling loads (33.7/31.6); and Phoenix, AZ, to represent cities with a low heating to cooling load ratio (14.0/54.5). A simple payback is given which is the average for several of the eleven cities (not the three shown) for which the system looks most promising.

The first absorption heat pumps developed under the DOE program (System 1) did little more than prove that such systems could provide both heating and cooling. Our analyses showed that, except for use under very limited circumstances, e.g., in buildings with very large heating loads and very small cooling loads, they would not save energy and

Table 3. Annual energy savings per unit and average simple payback for advanced heat actuated heat pumps in comparison to two reference systems

	Advanced System	Energy Saved Annually (million Btu)[a]			Simple Payback (years)
		Chicago	Atlanta	Phoenix	
	VS. MIDLINE GAS FURNACE/ELECTRIC AIR CONDITIONER				
1.	SOA absorption heat pump	(-4.7)	(-30.1)	(-55.6)	Infinite
2.	Double-effect absorption heat pump	28.7	4.1	3.3	9.5
3.	Advanced-cycle absorption heat pump	132.1	41.8	46.7	3.8
4.	IC-engine-driven heat pump	101.0	60.2	53.9	2.5
5.	FPSE-driven heat pump	38.7	19.1	27.8	11
	VS. PULSE GAS FURNACE/ELECTRIC AIR CONDITIONER				
1.	SOA absorption heat pump	(-27.9)	(-42.0)	(-60.8)	Infinite
2.	Double-effect absorption heat pump	5.6	(-7.7)	(-1.8)	32
3.	Advanced-cycle absorption heat pump	37.5	26.3	37.7	3.6
4.	IC-engine-driven heat pump	37.1	30.4	40.9	4.2
5.	FPSE-driven heat pump	15.6	7.3	22.7	20

[a]Primary energy, assuming a U. S. national average heat rate of 11,580 Btu/kWh.

they would not compete economically with even the midline reference systems. However, with upgraded target efficiencies, (see System 2, Table 2), the absorption systems began to show some energy-saving potential under a variety of climatic conditions. Their relatively high incremental costs, however, resulted in long paybacks, and they could not be considered viable consumer products. Recent conceptual advances in absorption cycles indicate substantial improvements in efficiencies, especially for cooling, at moderate increases in cost, and such systems (System 3, Table 3) promise significant energy savings and paybacks under five years.

System 4 of Table 3 also shows promise as a heat-actuated system. The concept currently being investigated under DOE sponsorship is a gas-fired engine hermatically coupled to a compressor. This analysis assumes that the 10-ton preprototype system under test can be successfully scaled to residential size.

Free-piston Stirling engine-driven heat pumps (System 5) are under investigation because they should be relatively simple, durable, and inexpensive systems. Our initial analyses indicate that these heat pumps have appreciable energy-saving potential, but that to be economically viable, either first costs must come down or engine efficiencies must increase from the values assumed in these analyses.

In Fig. 2, we have plotted the improvement in either incremental cost or efficiency that these five advanced heat-actuated systems must attain if they are to reach three- or five-year paybacks with respect to the pulse gas furnace/electric air conditioner reference system.

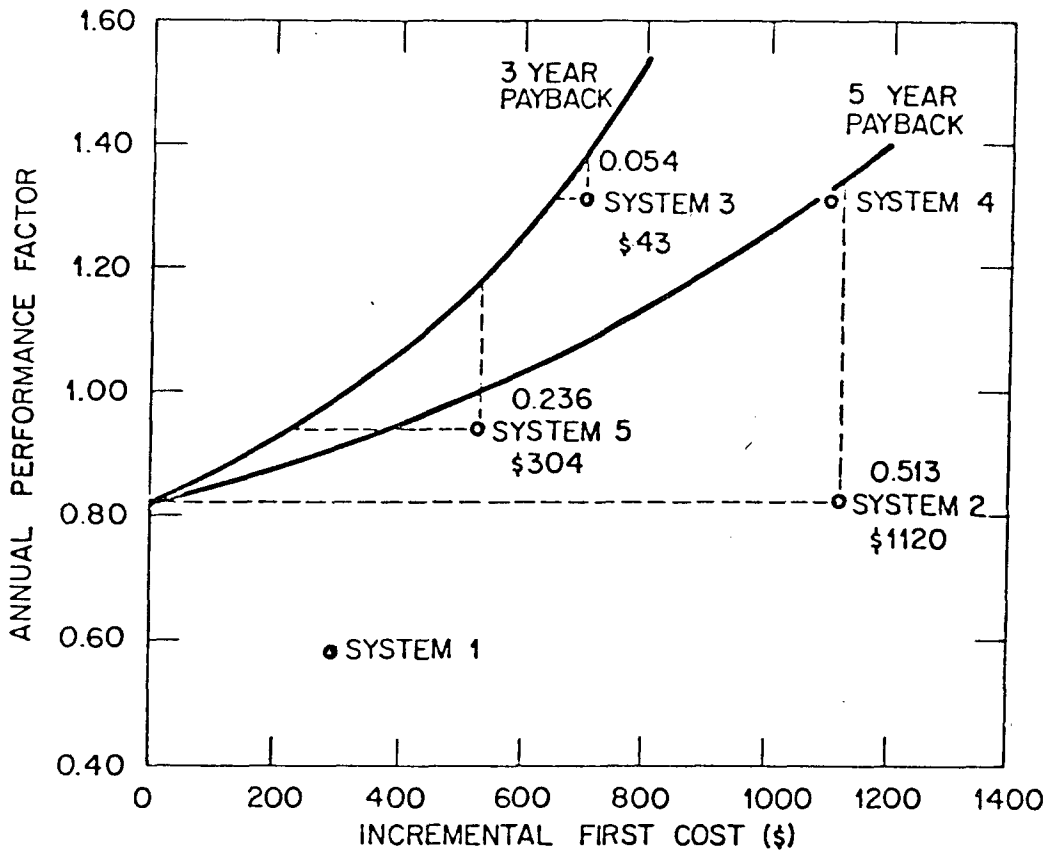

Fig. 2. Graph of improvements needed to make five heat-actuated systems economically competitive with the pulse gas furnace/electric air conditioner system. Systems are described by number in Table 2.

Table 4 gives similar results for the electric-driven heat pump systems we have evaluated. All of the advanced systems show a capacity to save appreciable energy in comparison to the reference systems, and all except the state-of-the-art ground-coupled heat pump show attractive simple payback periods. System 6, a dual-stroke (two-capacity) preprototype heat pump developed by Westinghouse under DOE sponsorship, has very short simple payback periods because of its low cost increment over the reference systems. Although the two-capacity ground-coupled systems save more energy than any of the others, the paybacks are not as favorable because of the high incremental costs associated with the ground coils. It should also be noted that the

Table 4. Annual energy savings and average simple payback for advanced electrically-driven heat pumps in comparison to two reference systems

Advanced System	Energy Saved Annually (million Btu)[a]			Simple Payback (years)
	Chicago	Atlanta	Phoenix	
VS. MIDLINE ELECTRIC HEAT PUMP				
6. Dual-stroke heat pump	50.1	32.4	22.1	1.5
7. Optimized capacity-modulated heat pump	48.9	38.2	38.7	3.1
8. SOA ground-coupled heat pump	48.4	29.7	13.4	8.2
9. Two-stage ground-coupled heat pump	78.7	52.7	55.3	5.2
10. Isothermal Stirling cycle heat pump	49.1	23.1	13.1	0.6
VS. HIGH EFFICIENCY ELECTRIC HEAT PUMP				
6. Dual-stroke heat pump	32.9	23.2	12.2	0.9
7. Optimized capacity-modulated heat pump	31.7	29.0	28.9	3.5
8. SOA ground-coupled heat pump	31.2	20.5	3.5	11.4
9. Two-stage ground-coupled heat pump	51.5	43.6	45.4	6.0
10. Isothermal Stirling cycle heat pump	31.9	13.9	3.2	3.2

[a]Primary energy, assuming a U. S. national average heating rate of 11,580 Btu/kWh.

simulation of ground-coupled heat pump performance assumes good coupling between ground coil and ground in both the heating and cooling modes. This may not be true in practice.

The results for System 7 illustrate the desirability of designing heat pumps as systems, rather than collections of components. All of the components of System 7, including the compressor, are of midline heat pump quality.

Figure 3 graphically depicts the improvements necessary in these advanced systems to reach three- or five-year paybacks. System 6, the dual-stroke heat pump already exceeds those goals.

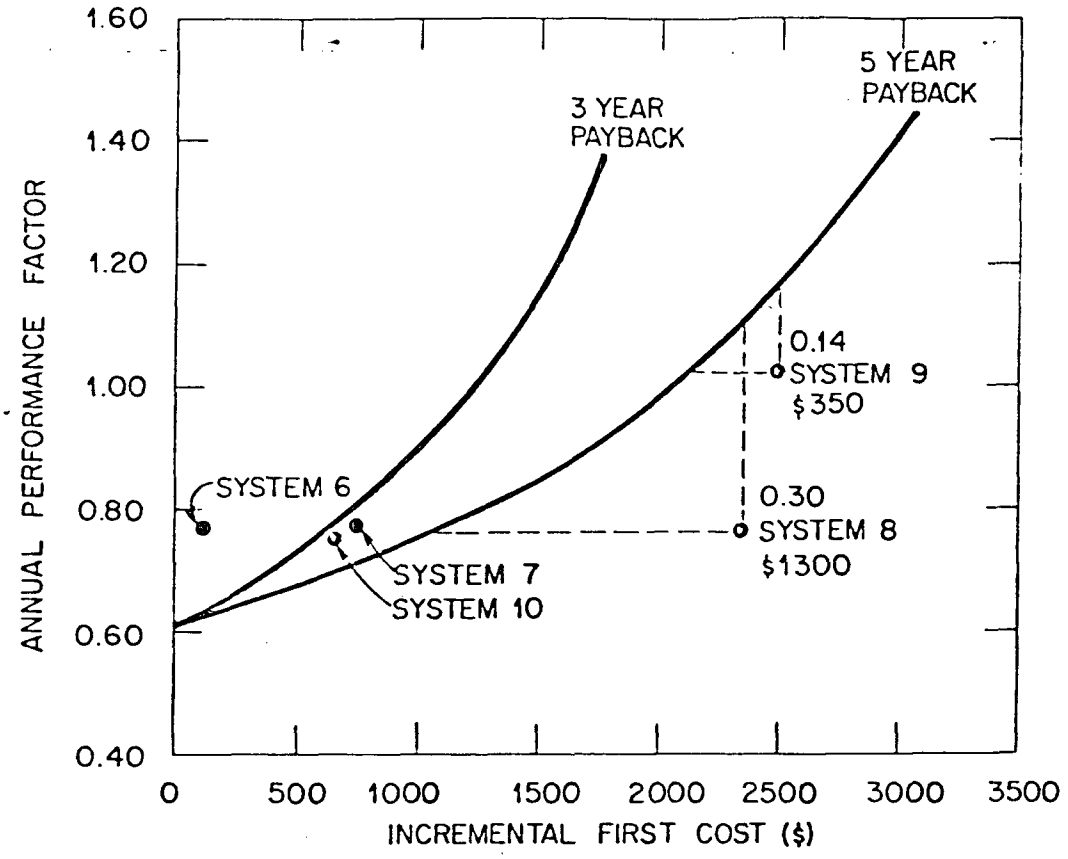

Fig. 3. Graph of improvements needed to make five electrically-driven systems economically competitive with a present day high-efficiency electric heat pump. Systems are described by number in Table 2.

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1. "Building Construction Cost Data 1982", 40th ed., R. S. Means Co., Inc., Kingston, MA, 1981.

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