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Mashuri L. Warren and Michael Wahlig

February 1982

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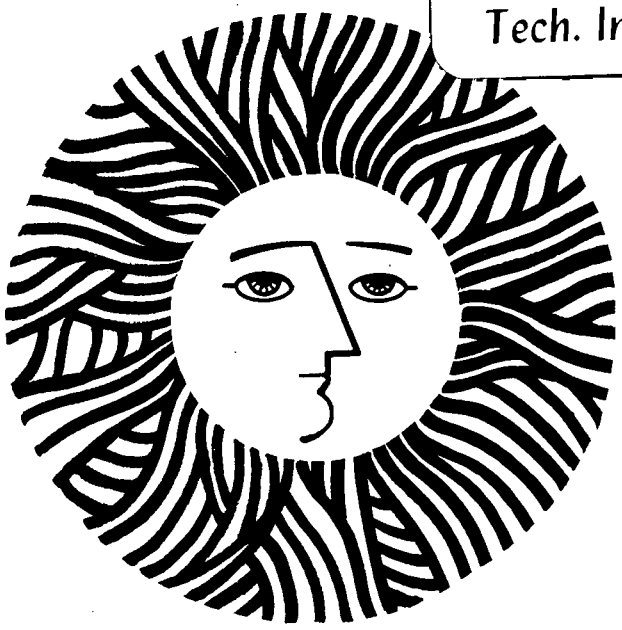

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Cost and Performance Goal Methodology for Active Solar Cooling Systems.*

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ABSTRACT

Economic and thermal performance analyses of typical residential and commercial active solar cooling systems are used to determine cost goals for systems to be installed between the years 1986 and 2000. Market studies indicate a relationship between market penetration (percent of market captured) and payback period for heating, ventilating, and air conditioning systems. Using reasonable values for fuel escalation and inflation rates, the payback period is related to the expected real return on investment. Postulating commercial introduction of solar cooling systems in 1986 with the market share increasing to 20% by the year 2000, payback and return on investment goals for cooling systems as a function of year of purchase are established. Using the results of systems analysis of representative 3 ton solar residential cooling/heating systems and 25 ton commercial solar cooling systems for four different cities (Ft. Worth, Phoenix, Miami, and Washington, D.C.), the return on investment goals are used to calculate the 20 year present value of energy savings of the solar energy systems. To be cost-effective, the incremental solar system cost must be equal to or less than the present value of the energy savings. This establishes the link between incremental solar system cost and the return on investment goal and determines the system cost goals as a function of year of purchase. In turn, the cost goals are broken down to the subsystem level. Methods for achieving these cost goals over time, based on projected solar cooling system and subsystem costs, are explored in detail.

*This work has been supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Solar Heat Technologies, Active Heating and Cooling Division, of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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INTRODUCTION.

To achieve substantial market penetration in the 1986-2000 time period, active solar cooling systems must meet certain cost goals corresponding to the desired market penetration levels. These cost goals can be derived using economic and thermal performance analyses of residential and commercial active solar cooling systems.

Market studies indicate a relationship between market penetration (percent of market captured) and payback period for heating, ventilating, and air conditioning systems. Using reasonable values for fuel escalation and inflation rates, the payback period is related to the expected real return on investment. Postulating commercial introduction of solar cooling systems in 1986 with the market share increasing to 20% by the year 2000, payback and return on investment goals for cooling systems as a function of year of purchase will be established.

Using the desired return on investment for different initial years of purchase, the 20 year present value of energy savings of the solar energy systems are calculated. To be cost-effective, the incremental solar system cost must be equal to or less than the present value of the energy savings. This establishes the link between incremental solar system cost and the return on investment goal and determines the system cost goals as a function of year of purchase.

Using the results of systems analysis of representative 3 ton solar residential absorption cooling/heating systems, the present value of the energy savings and equivalently the incremental solar system cost goals are calculated for four cities (Ft. Worth, Phoenix, Miami, and Washing-

ton, D.C.) for different years of purchase. For 25 ton commercial solar Rankine and absorption cooling systems, the incremental solar system cost goals are calculated for three cities (Ft. Worth, Phoenix, and Miami).

These cost goals are then broken down to the subsystem level. Methods for achieving these cost goals over time and the projected solar cooling system costs will be discussed. Projected costs for each of the different component subsystems are based upon typical present-day costs and reasonable scenarios for reducing those costs by means of mass production economies, design simplifications, and performance improvements resulting from additional research and development. In effect, a cost "budget" is established for each component or subsystem which will be addressed as component or subsystem goals for an engineering development effort.

A. OVERALL MARKET PENETRATION AND ENERGY DISPLACEMENT

A market penetration scenario is postulated that begins with commercial introduction of active solar cooling systems in 1986 and attains a 20% annual market share of the entire national cooling capacity by the year 2000 as shown in Figure 1. The shape of this postulated market penetration curve is based upon the actual penetration curve achieved by heat pump sales in the United States during the period 1953 to 1970 as shown in Figure 2. This is typical of historic early-market penetrations achieved by major HVAC products. The central air conditioning market began in earnest with the introduction of packaged systems in the late 1940's and increased rapidly until the 1970's as shown in Figure 3. The heat pump market began in the mid-1950's and displaced a portion of this market.

In general, air conditioning demands are expected to grow significantly over the next 20 years, driven by population shifts to the "sun belt" regions of the country. It is estimated that over 90% of the new construction in this region will have central air conditioning. Two scenarios are developed; one that establishes aggressive market penetration by active solar cooling systems beginning in 1986 and reaching an annual market share of 20% by 2000 and a second reaching a lesser goal of 10% annual market share by the year 2000. These postulated annual penetration goals are assumed to apply equally to each of the geographic regions considered.

A.1 Energy Displacement.

The annual energy used for cooling of buildings in the year 2000

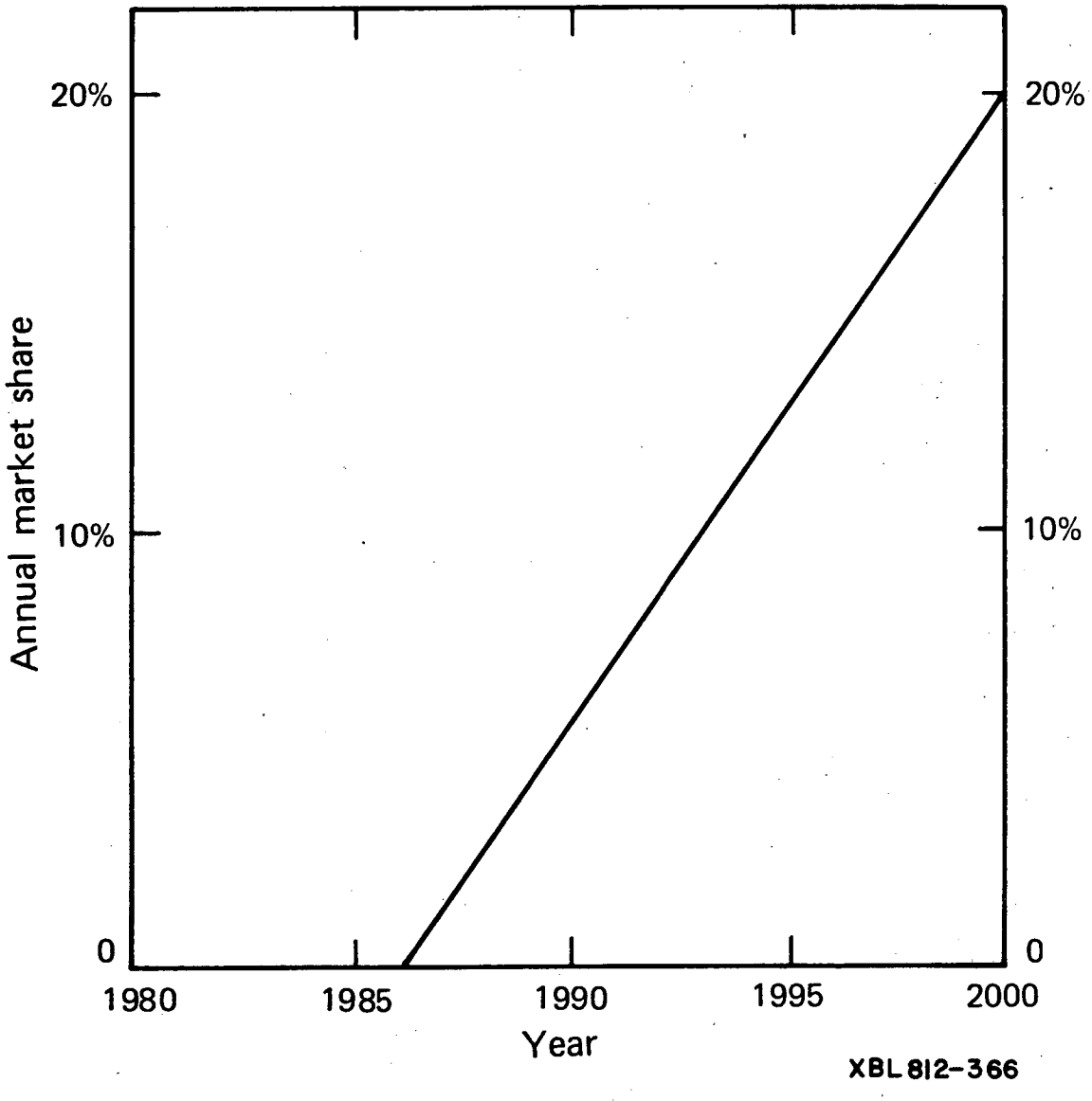

Figure 1. Postulated market share for active solar cooling systems.

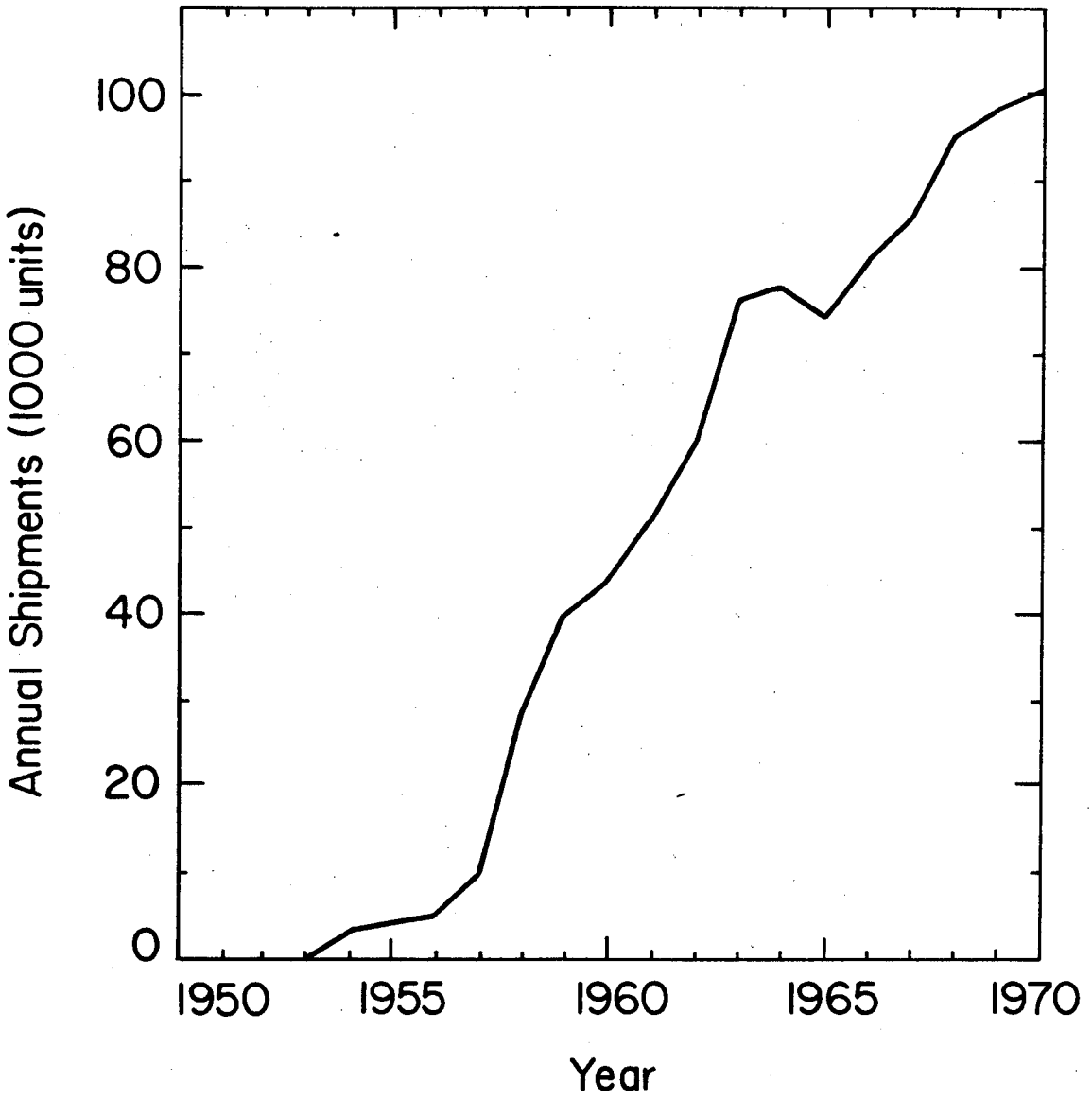

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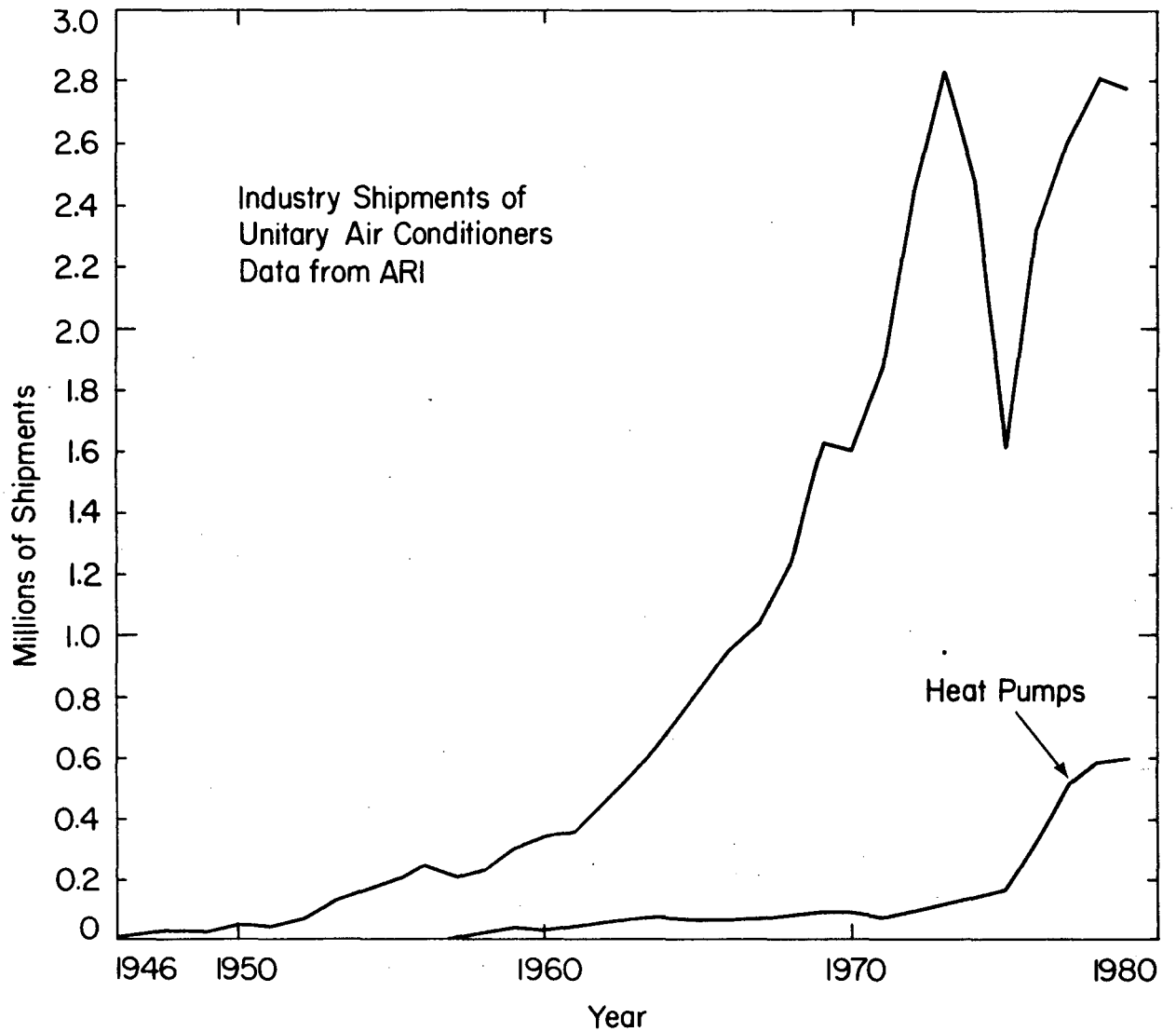
Figure 2. The heat pump market 1953-1970.

Figure 3. Industry shipments of unitary air conditioners and heat pumps. Data from Air-Conditioning and Refrigeration Institute.



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can be estimated by accounting for the expected mix of building types, regional differences in building stock and cooling loads, and residential and commercial building energy requirements.

Table 1 shows the annual new residential energy consumption for cooling and the calculations of annual energy resource savings due to solar cooling penetration by the year 2000. Tables 2 and 3 show similar calculations for the residential retrofits in the South and West and for the commercial building sector.

The results of Tables 1, 2, and 3 are summarized in Table 4. These tables indicate that, by the year 2000, an estimated displacement of 0.14 quad of energy from conventional energy sources will result from a 20% penetration (of the annual projected air conditioning market) by solar cooling.

Table 4. Total annual displacement of conventional energy sources for different market sectors at 10 % and 20 % penetration of solar cooling in the year 2000.

Sector	Market Penetration 10 %	20 %
Residential New Construction	0.011 quads	0.022 quads
Residential Retrofit	0.014 quads	0.028 quads
Commercial	0.046 quads	0.091 quads
Annual Energy Displacement	0.071 quads	0.141 quads

Table 1 ANNUAL NEW RESIDENTIAL ENERGY CONSUMPTION AND SAVINGS DUE TO SOLAR BY YEAR 2000.

1980-2000	UNITS	Region 3	Region 4	Region 6	Region 7	Region 9	Total
Cooling Energy Use Rate[1]	$kBtu_e/ft^2$-yr	7.6	14.	12.5	7.2	7.6	
Residential Construction[2]							
Single units	10^6 units	1.15	3.67	2.47	.49	2.16	
Multiple units	10^6 units	.87	1.37	.82	.27	1.66	
Total units	10^6 units	2.02	5.04	3.29	0.76	3.82	14.93×10^6 units
Residential Construction (average unit 1176 ft^2)	10^9 ft^2	2.38	5.93	3.87	0.89	4.49	17.56×10^9 ft^2
Annual Cooling Energy Use	$10^{12}Btu_e/yr$	18.1	83.0	48.4	6.4	34.1	190. = 0.19 $quad_e$
Fraction saved	solar	0.5	0.5	0.5	0.5	0.5	
Average penetration[3]	10%(2000)	0.035	0.035	0.035	0.035	0.035	
Electric Energy saved	10^{12} Btu_e/yr	0.32	1.45	0.85	0.11	0.60	3.33 = 0.003 $quad_e$
Resource Energy[4] saved	10^{12} Btu/yr						11.0 = 0.011 quad
Average penetration[3]	20%(2000)	0.07	0.07	0.07	0.07	0.07	
Electric Energy saved	10^{12} Btu_e/yr	0.63	2.91	1.69	0.22	1.19	6.65 = 0.007 $quad_e$
Resource Energy[4] saved	10^{12} Btu/yr						22.0 = 0.022 quad

[1] Electrical energy use index estimated from DOE-2.1 residential analysis.

[2] "Residential Inventory and Construction Volume", R. LeChevalier, Private Communication.

[3] The average market penetration assumes zero penetration in 1986 increasing uniformly to the stated value 10 % or 20 % in the year 2000. A 10 % market penetration in 2000 would give an average penetration of 3.5 % over the 20 year period.

[4] Resource energy saved (Btu) is assumed to be 3.3 x electric energy saved (Btu_e) to account for power plant conversion losses.

Table 2 ANNUAL RETROFIT RESIDENTIAL ENERGY CONSUMPTION AND SAVINGS DUE TO SOLAR IN THE SOUTH AND WEST BY YEAR 2000.

	UNITS	Annual	Total
Average Cooling Energy Use Rate[1]	$kBtu_e/ft^2$-yr	10.	
Residential Retrofits[2](1980-2000)	10^6 units	1.05	21.
Residential Retrofits(1980-2000) (average unit 1176 ft^2)	10^9 ft^2	1.2	24.
Annual Energy Use(Year 2000)	$10^{12}Btu_e/yr$	12.	240. = 0.24 $quad_e$
Fraction saved	solar		0.5
Average penetration[3]	10%(2000)		0.035
Electric Energy saved	10^{12} Btu_e/yr		4.2 = 0.004 $quad_e$
Resource Energy saved[4]	10^{12} Btu/yr		14. = 0.014 quad
Average penetration[3]	20%(2000)		0.07
Electric Energy saved	10^{12} Btu_e/yr		8.4 = 0.008 $quad_e$
Resource Energy saved[4]	10^{12} Btu/yr		28. = 0.028 quad

[1] Electrical energy use index estimated from DOE2.1 residential analysis.

[2] "Assessment of Active Solar Air Conditioning, 1980-2000," Planco, Inc., Draft Final Report, January 1981. See Table 6. Projected Air conditioning Shipments for the Period, 1980-2000.

[3] The average market penetration assumes zero penetration in 1986 increasing uniformly to the stated value 10 % or 20 % in the year 2000. A 10 % market penetration in 2000 would give an average penetration of 3.5 % over the 20 year period.

[4] Resource energy saved (Btu) is assumed to be 3.3 x electric energy saved (Btu_e) to account for power plant conversion losses.

Table 3. ANNUAL COMMERCIAL ENERGY CONSUMPTION AND SAVINGS DUE TO SOLAR IN NEW COMMERCIAL CONSTRUCTION BY YEAR 2000.

1980-2000	UNITS	Region 3	Region 4	Region 6	Region 7	Region 9	Total
Cooling Resource Energy Use Rate[1]	$kBtu/ft^2$-yr	125.	128.	176.	144.	140.	
Commercial Construction[2]	10^9 ft^2	2.57	6.15	2.96	1.05	2.81	15.54×10^9 ft^2
Annual Cooling Energy Use(Year 2000)	10^{12}Btu/yr	321.	790.	522.	151.	393.	2177. = 2.2 quad
Fraction saved	solar	0.6	0.6	0.6	0.6	0.6	
Average penetration[3]	10%(2000)	0.035	0.035	0.035	0.035	0.035	
Cooling Resource Energy saved	10^{12} Btu/yr	6.7	16.6	11.0	3.2	8.3	45.8 = 0.046 quad
Average penetration[3]	20%(2000)	0.07	0.07	0.07	0.07	0.07	
Cooling Resource Energy saved	10^{12} Btu/yr	13.5	33.2	21.9	6.3	16.5	91.4 = 0.091 quad

[1] Energy use index referred to resource (Resource energy, Btu, is assumed to be 3.3 x electric energy usage, Btu_e) based on Steve M. Cohn, et. al., "A Commercial Energy Use Model for the Ten U.S. Federal Regions," Oak Ridge National Laboratory Report, DRAFT ORNL/CON-40, December 1980 and weighted by the 1975 national percentage of different building types.

[2] 1980-2000. "Regional Commercial Building Inventories and Construction Volume", R. LeChevalier, Private Communication.

[3] The average market penetration assumes zero penetration in 1986 increasing uniformly to the stated value 10 % or 20 % in the year 2000. A 10 % market penetration in 2000 would give an average penetration of 3.5 % over the 20 year period.

A.2 Conservation and Passive Cooling

The effects of energy conservation and passive cooling efforts have been taken into account in Tables 1 through 4 in reducing the total cooling requirement. Conservation measures will greatly reduce the sensible heating loads. Table 5 shows the calculated heating and cooling loads for different levels of insulation for a residence in Ft. Worth, based on simulation analysis using DOE-2.[1,2] As shown in the table, conservation will significantly reduce the heating loads (about 80%); however, substantial cooling loads due to latent heat and internal loads will remain.

Passive cooling occurs when heat flows naturally to a cooler environmental heat sink: the sky by radiative cooling; the atmosphere by ventilation and evaporative cooling; or the earth by contact with the ground.[3] These passive cooling techniques seem capable of meeting most of the sensible cooling load of residential structures and part of the sensible cooling load of commercial buildings, but are not effective in removing latent heat from the air (i.e., dehumidification). Dehumidification plays a central role in achieving thermal comfort in many parts of the country. Active solar cooling is capable of meeting both the

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[1] David Goldstein, Mark Levine, and Jim Mass, "Methodology and assumptions for the evaluation of building energy performance standards for residential buildings, Lawrence Berkeley Laboratory Draft Report, March 1980.
[2] John Ingersoll, Mark Levine, and Jim Mass, "Methodology and assumptions for the evaluation of energy performance in new residential buildings, Lawrence Berkeley Laboratory Report, LBL-9110, September 1981.
[3] Marlo Martin, "Passive and Hybrid Cooling: Regional Monograph for the United States of America", Presented at the International Passive and Hybrid Cooling Conference, Miami Beach, FL, Nov. 10-13, 1981; LBL-13386, September 1981.

Table 5. Residential Conservation Options

Fort Worth

		Conservation Measures				Building Loads kBtu/ft^2-yr			
		Ceiling R-value	Wall R-value	Window Glazings	Infiltration	heating	cooling[e]	COP	cooling[th]
Current		19	11	1	HI	20.0	14.3	2.1	30.2
		19	19	2	HI	11.2	12.9	2.1	27.2
Goal 1985-1990	(gas)	30	19	2	HI	9.8	12.5	2.1	26.3
	(electric)	38	19	3	HI	7.6	11.9	2.1	24.8
Goal 1990-2000	(electric)	38	19	3	LO	3.9	11.3	2.1	23.5

Based on BEPS Series 9 DOE2 Runs.

HI = 0.6 air change/hr.; LO = 0.2 air change/hr + 0.4/hr through heat exchanger

* Goals established by Benefit/Cost ratio of 1. The goal depends on competing fuel.

e electric

th thermal

latent as well as the sensible cooling loads.

Thus, energy conservation and passive design will reduce sensible cooling loads in commercial and residential buildings, but substantial latent loads will still require mechanical systems such as active solar cooling except in the semi-arid regions in the West and Southwest.

B. ECONOMIC PERFORMANCE GOALS

Certain cost and economic performance goals must be achieved by the solar space conditioning industry before market demand will rise to a level that will produce the desired market penetration. Therefore, the market penetration goal must be converted into an economic performance goal for the solar cooling system (such as payback period or return on investment) which is understandable to the consumer and which would influence the "purchase" decision. Marketing studies[4] indicate that for heating and air conditioning products the relationship between market penetration and payback period is as shown in Fig. 4. We assume that the behavior of solar cooling systems in the market place will be similar to that of other heating and air conditioning products.

In this report we examine four market penetration goals in detail. Goal A assumes only a 10% penetration of the market and has a payback period (Fig. 4) of about 11 years in the year 2000. Goal B postulates a 20% penetration of the market and has a payback period of about 9 years in the year 2000. Goal C estimates a 40% penetration of the market and has a payback period of about 6 years in the year 2000. Goal D postulates a payback period of about 5 years in the year 2000 corresponding to a market penetration of about 60% in that year. This would make active solar cooling an attractive investment.

Postulating a linear market penetration curve from 1986 to 2000 (such as that shown in Fig. 1, which corresponds to Goal B), the depen-

[4] Gary L. Lilian and Paul E. Johnston, "A Market Assessment for Active Solar Heating and Cooling Products, Category B: A Survey of Decision Makers in the HVAC Market Place," OR/MS Dialogue, Inc., Final Report DO/CS/30209-T2, September 1980.

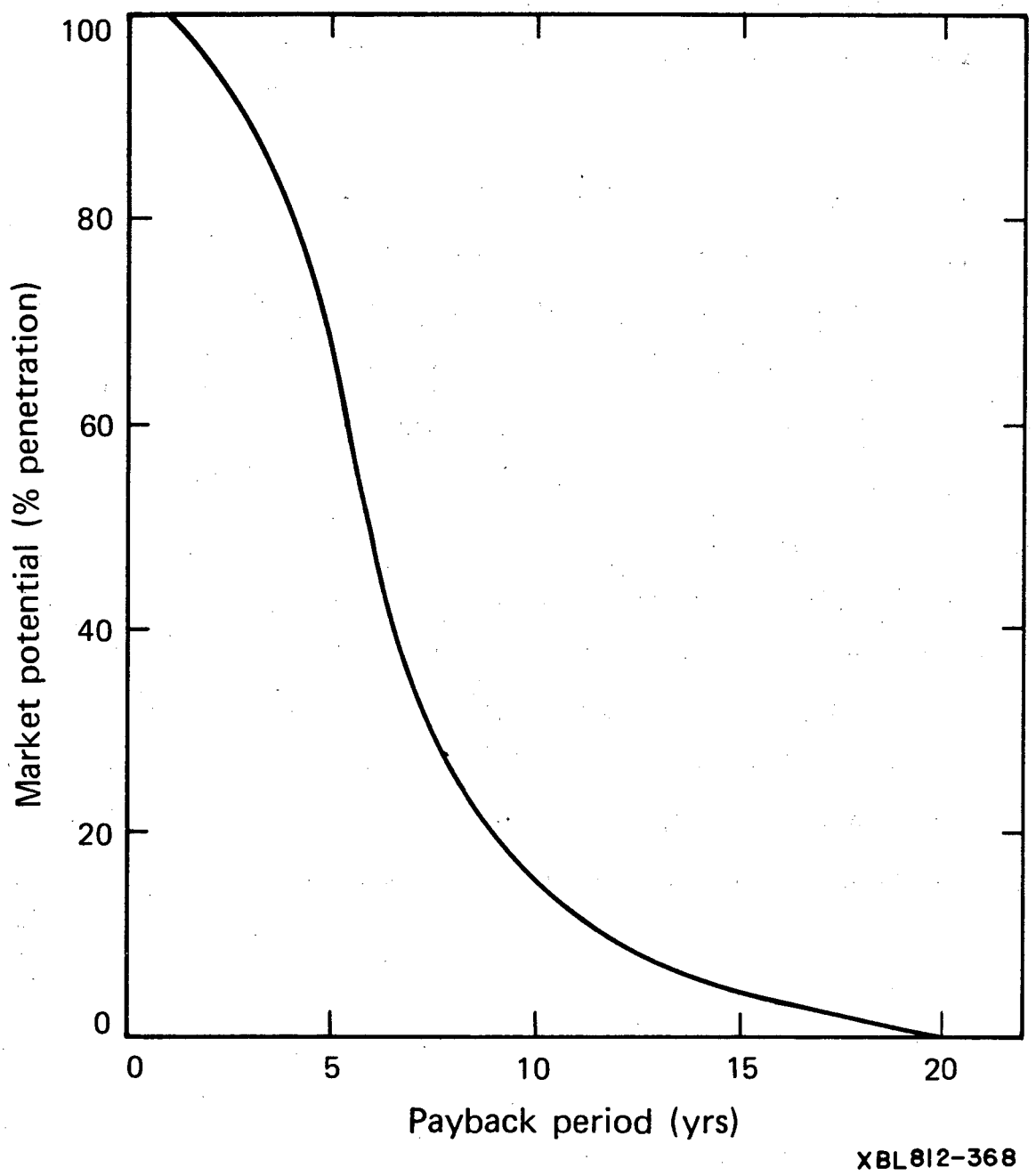


Figure 4. Market potential as a function of payback period. From Gary L. Lilian and Paul E. Johnston, "A Market Assessment for Active Solar Heating and Cooling Products," final report, OR/MS Dialogue, Inc., Cambridge, Mass., September 1980.

dence of market penetration on payback (Fig. 4) can be used to generate payback goals as a function of year of purchase. Figure 5 displays such payback goals vs. time for the cases of market penetration Goals A, B, C, and D.

It is necessary to derive the relationship between payback period and "real" return on investment. The "real" return on investment is the return on investment after considering the effects of inflation. The payback period is the number of years for the undiscounted fuel cost savings (zero discount rate) to equal the incremental cost to produce those savings. Assuming an inflation rate of 10%, a fuel cost escalation rate of 3% over inflation, and a maximum allowable incremental cost equal to the present value of fuel savings over the system life time (20 years) at a desired rate of return, the payback period is related to the return on investment as shown in Figure 6. Using this relationship between payback period and real return on investment, the return on investment required for the cases of Goals A, B, C, D as a function of year of purchase is thereby established and is shown in Figure 7.

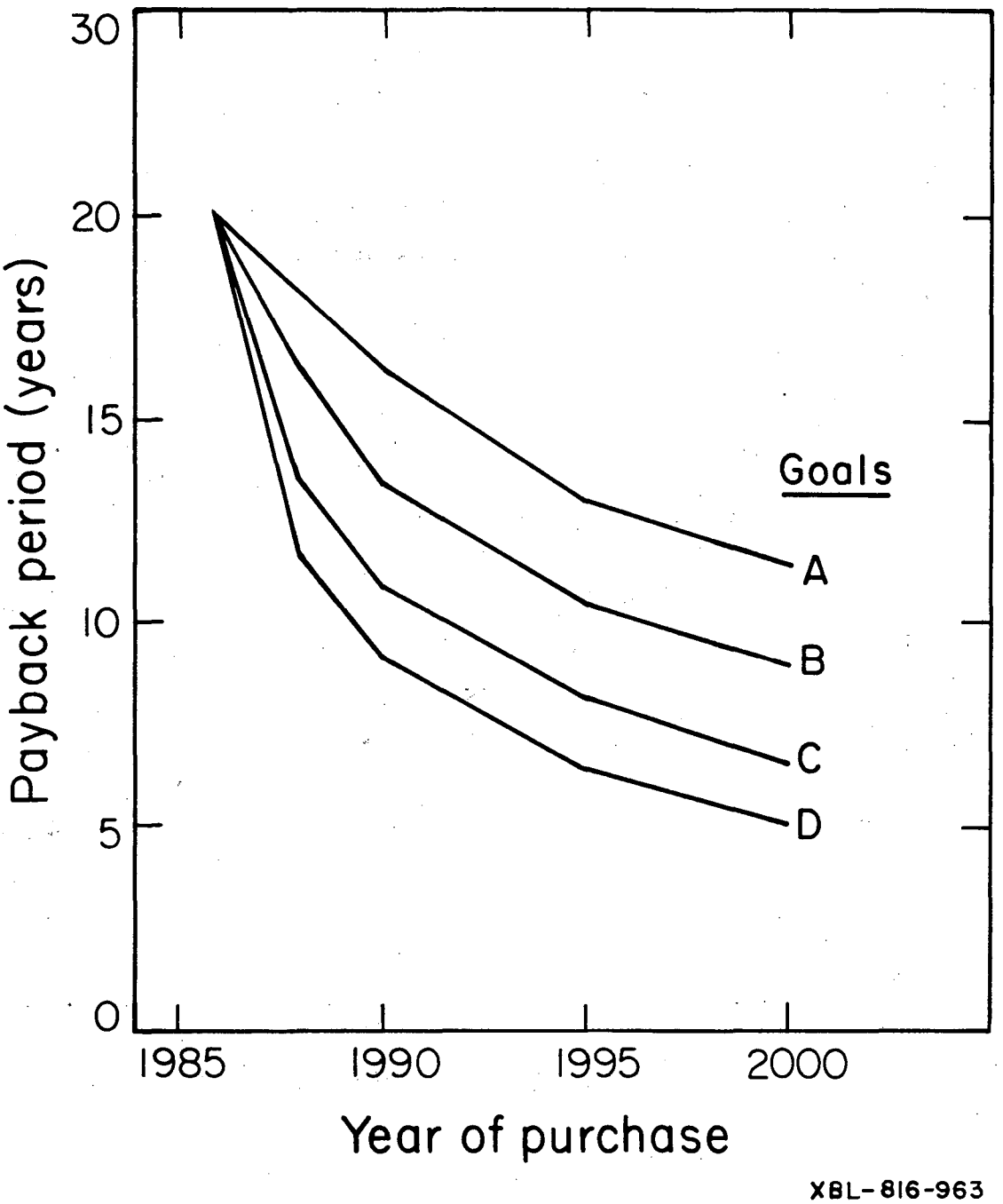


Figure 5. Payback goals as function of year of purchase.

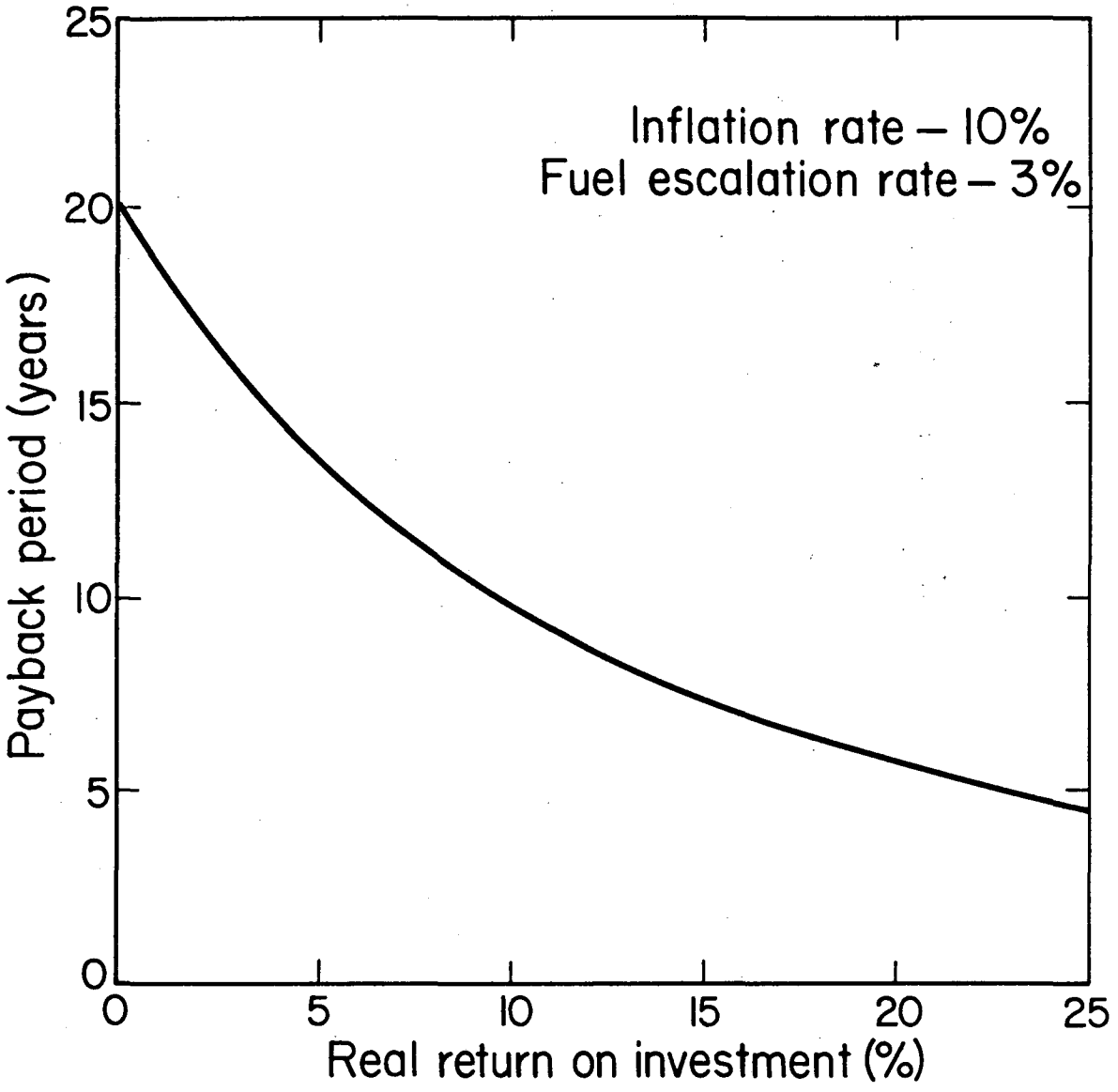


Figure 6. Payback period as a function of real return on investment assuming 10% inflation, 3% fuel escalation, and 0% discount rates.

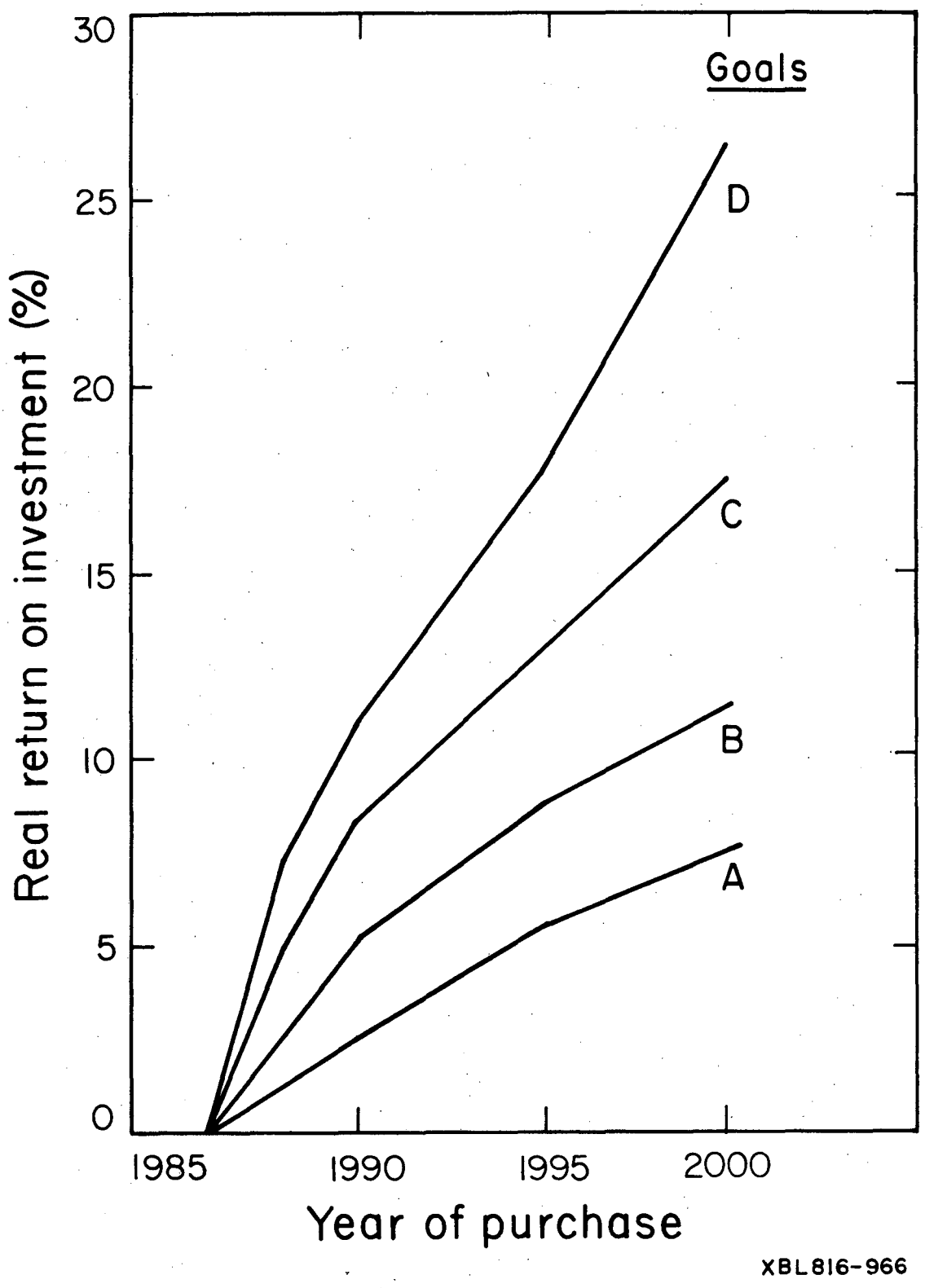


Figure 7. Return on investment goals as a function of year of purchase.

C. SYSTEM COST GOALS

The return on investment of a solar cooling system is dependent upon a large number of variables. The incremental solar cooling/heating system cost is the additional cost compared to that of a conventional cooling/heating system. The solar system incremental cost is the dominant term in the economics of solar cooling/heating systems, and the main expression of the cost/performance goals. The "allowable" incremental cost of the solar system consistent with return on investment goals depends on the following: the thermal performance of the solar system; the thermal performance of the conventional cooling system being replaced; the cost of conventional fuel (fossil fuel or electricity) being displaced; the value of money (discount, interest, and inflation rates); maintenance expenses; the system life; and the expected rate of return on investment. Most of these parameters are a function of time and of geographic location. System life for the purpose of this analysis is assumed to be a "reasonable" 20 years.

The method used to establish solar system cost goals is to:

1) establish test cities that are representative of a broad range of the cooling market;

2) choose typical residential and commercial buildings for analysis;

3) use the results of systems analysis for test cities to determine typical system performance and fuel savings;

4) establish fuel costs and projections by region;

5) determine the 20 year discounted present value, at different rates of return on investment, of the fuel saved by using the solar system;

6) establish the allowed incremental solar system cost for each value of

return on investment by equating the incremental solar system cost to the 20 year discounted present value of the fuel saved (to be cost-effective the solar system incremental cost must be equal to or less than the value of the fuel saved);

7) use the return on investment goals as a function of year (Fig. 7) to establish the corresponding incremental solar system cost goals as a function of year of purchase.

This analysis is thus used to establish incremental solar system cost goals based on the present value to the customer of future fuel savings.

C.1 Establish Test Cities.

The geographic distribution of cooling degree days is shown in Figure 8. The geographical distribution of the space cooling load as represented by annual residential heating and cooling loads for 32 cities (based on DOE2.1 simulation runs) is shown in Figure 9. From this analysis five cities were identified as being representative of a wide range of cooling and cooling/heating climates. These cities are Miami, Phoenix, Ft Worth, Atlanta, and Washington, D.C.

C.2 Buildings for Analysis.

Residential Buildings. The residential buildings used in the analysis were taken from the document "Standard Assumptions and Methods for Solar Heating and Cooling Systems Analyses[5]. "Typical single family residences were chosen for southern cities represented by Ft. Worth, and for more northerly locations represented by Washington, D.C. Hourly building load calculations were based on a TRNSYS-compatible standardized residential load model[6]. Hourly residential load calculations

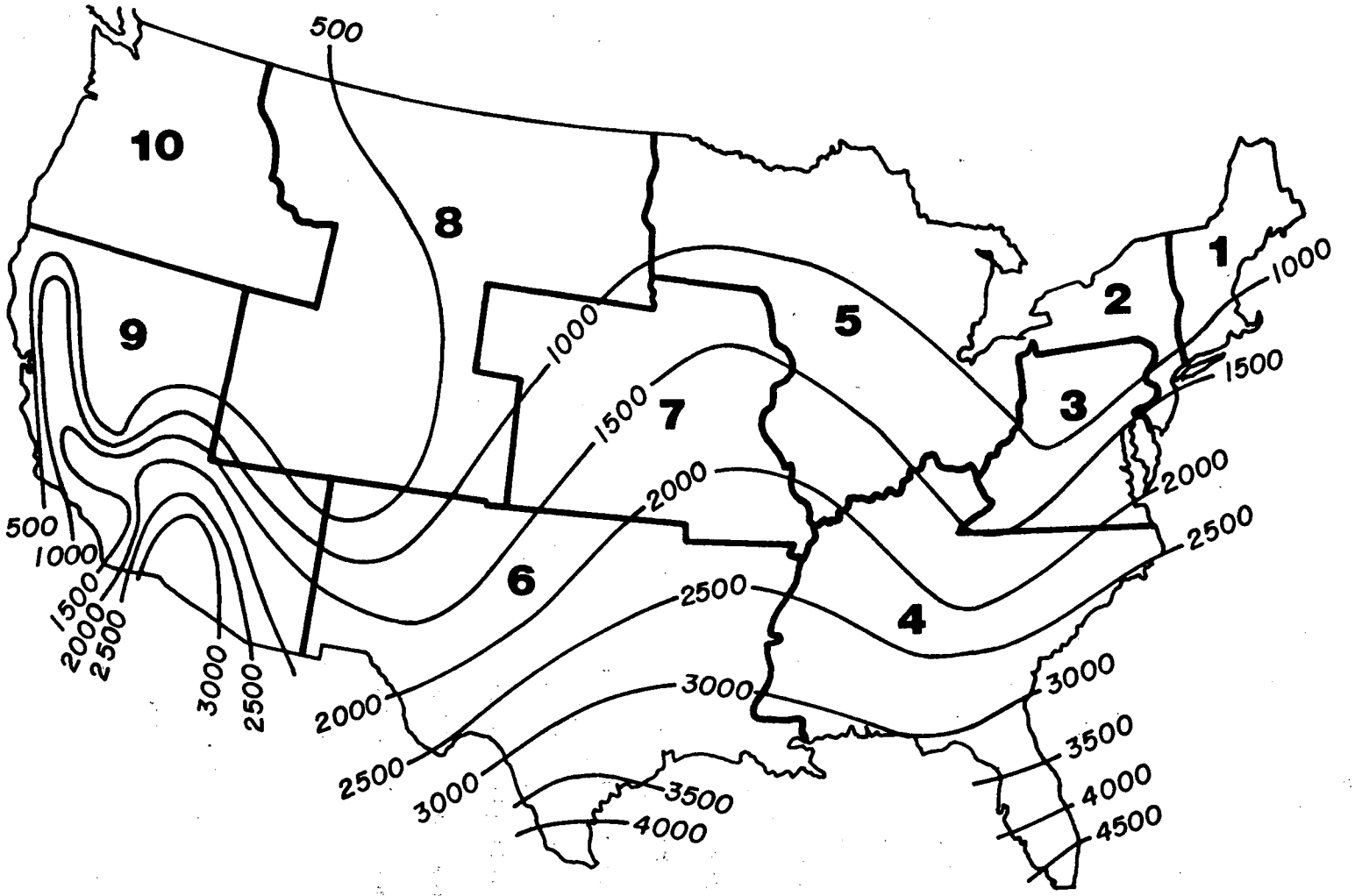


Figure 8. Average annual (1953-1957) total number of cooling degree-days (^{o}F-days) showing the principal DOE Regions with significant cooling loads.

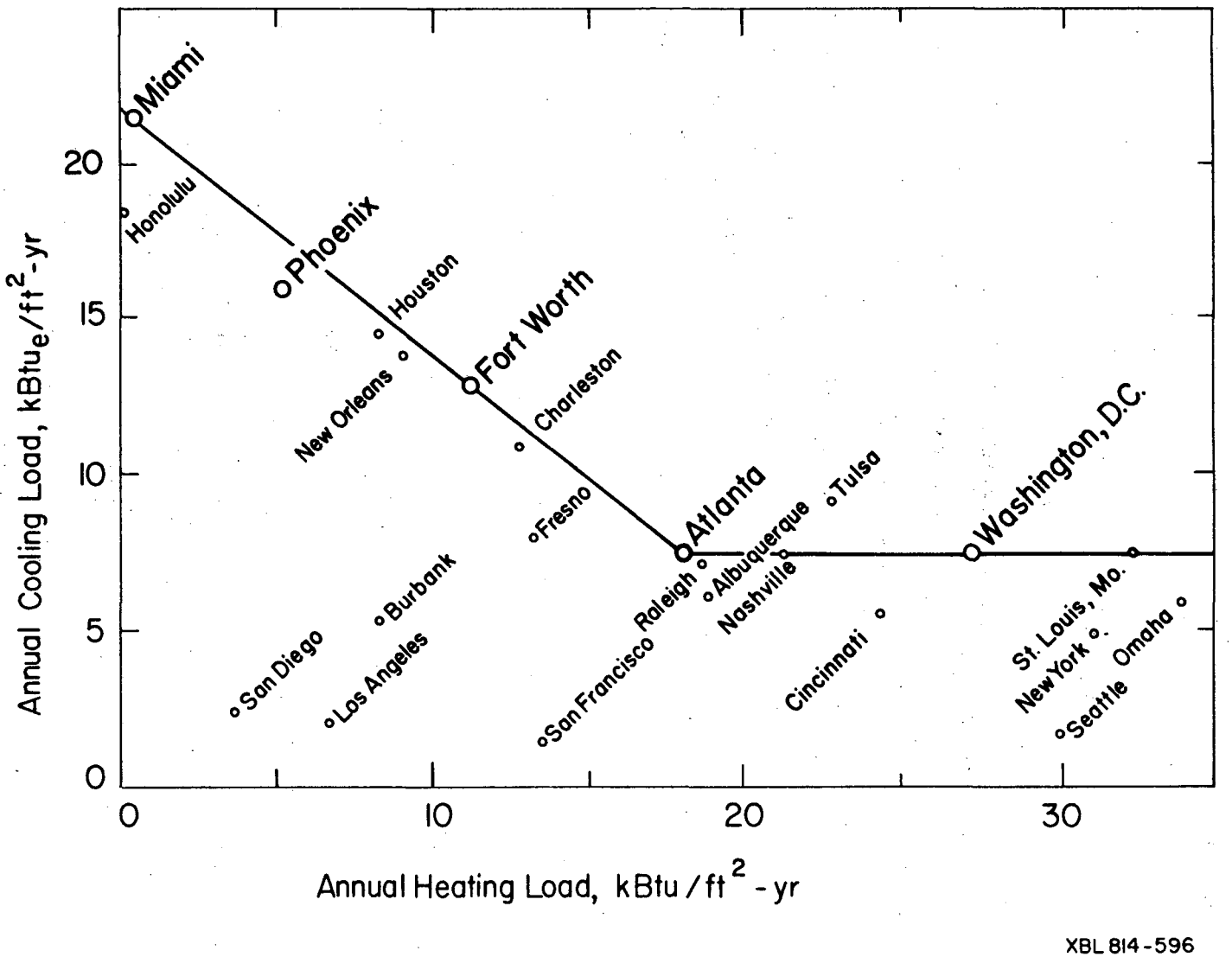


Figure 9. Annual residential cooling load (electrical) and heating load (thermal) for selected cities based on DOE 2.1 simulations.

and system performance calculations proceed simultaneously in the hourly TRNSYS simulation. Thermal insulation characteristics were obtained by using ASHRAE 90--75 and Characteristics of New Housing, US. Dept. of Commerce, Bureau of the Census.

Commercial Buildings. The small seven zone commercial office building chosen for the analysis is also based on reference 5. The small well-constructed office building has a nominal design cooling load of 25 tons, and meets or exceeds ASHRAE 90-75 standards. Additional energy conservation features such as low total lighting levels and minimum ventilation rate were incorporated. The building was orginally described for Washington, DC; however, the description is adequate in other geographic locations if the gross air circulation value is changed for each location. Simulations upon which the preliminary cost goals are based used loads generated by BLAST [7,8]. More recent simulation work uses building loads calculated with DOE 2.1.

C.3 Thermal Performance Analysis.

The preliminary cost goals developed in this report are based on previous annual system simulations of the thermal performance of active solar Rankine and absorption cooling/heating systems using TRNSYS.[7,8]

[5] Cecile Leboeuf, "Standard Assumptions and Methods for Solar Heating and Cooling Systems Analyses," SERI Report TR-351-402, January 1980.
[6] P. J. Hughes and J. H. Morehouse, "A TRNSYS-Compatible Standardized Load Model for Residential System Studies," Final Report, SAI, Inc., June 1980.
[7] P. L. Versteegen and J. H. Morehouse, "A Thermal And Economic Comparative Analysis of Absorption and Rankine Solar Cooling Systems for Commercial Buildings," Draft Final Report May 1979.
[8] P. J. Hughes, et. al., "Evaluation of Thermal Storage Concepts for Solar Cooling Applications", Science Applications, Inc., Final Report, January 1981.

These calculations were carried out for residential solar cooling/heating systems in four cities (Fort Worth, Phoenix, Miami, and Washington, D.C.) and for commercial solar cooling-only systems in three cities (Fort Worth, Phoenix, and Miami). Three types of systems were evaluated: residential 3 ton absorption (ARKLA), commercial 25 ton absorption (ARKLA), and commercial 25 ton Rankine (AiResearch). This work provides baseline thermal performance predictions for these cooling systems. New analysis work will include simulation of commercial systems with heating and cooling, as well as improved models for the chiller performance.

C.4 Fuel Costs and Projections by Region.

Regional Fuel Costs. Fuel costs have regional variations. Diverse sources of fuel supply, along with differing conversion and transportation costs, result in a wide range of fuel prices across the United States. Fuel markets with homogeneous characteristics do not spatially correspond to the boundaries of governmental units such as cities, states, census regions, or DOE regions. Not only do wide price variations exist among states, but within some states substantial differences in fuel prices exist among cities. A recent study[9] concludes that for electricity, considerable price variation is evident at all levels of aggregation; and for natural gas, price variation among cities, states, and regions is strong. For this reason, local prices[10] have been used to establish energy costs and energy cost savings in the analysis. Table 6 shows the energy costs used in our analysis.

[9] "Regional Variations in US Residential Sector Fuel Prices: Implications for Development of Building Energy Performance Standards," by L. A. Nieves, J. J. Tawil, and T. J. Secrest, Battelle Pacific Northwest Laboratory Report PNL-3605, March 1981.

Table 6. 1980 Fuel costs (1980$) used to establish cost goals.

	Electricity		Heating Oil		Natural Gas
	c/kW-hr	$/MBtu	$/Gal	$/MBtu	$/MBtu
Ft. Worth, TX	4.80	14.08	0.97	7.01	2.59
Phoenix, AZ	6.58	19.29	0.95	6.89	3.16
Miami, FL	5.96	17.47	0.94	6.79	3.72
Washington, DC	5.42	15.88	0.96	6.95	3.74

Fuel Escalation Rates. As fuel prices escalate with time, the value of the energy displaced by the active solar cooling system will be greater. Considerable variation in escalation rates has been pointed out by the Battelle study[9]. It concludes that, for escalation rates, the highest aggregation that can be justified is at the state level. For natural gas, city-level escalation rates seem to be the most appropriate alternative.

Table 7. Annual escalation rates for gas and electricity.

	Electricity	Gas	Fuel Oil
CONAES A	3.3 %	5.7 %	
CONAES B	2.0 %	4.5 %	
1971--1978 National Average	5.7 %	6.7 %	6.4 %
1971--1978 State Range	(+12.8 % -6.6 %)	(+14.1 % -1.6 %)	(+9.0 % +2.9 %)

The local fuel escalation rates depend on many uncertain local conditions, which has made it impractical for us to estimate individual city escalation rates over the next 20 years. Therefore, in order to establish cost goals we have chosen to use local 1980 energy prices and use estimates of national fuel escalation rates as provided by the CONAES Report[11]. The CONAES A scenario assumes a 2% annual average

[10] "Regional Conventional Fuel Prices and Future Projections: An update reflecting October-December 1980 conditions," LASL Report LA-8838, May 1981. Representative future energy costs (1980$) are also shown.

[11] The CONAES Report, "Energy in Transistion, 1985-2000.", Final Report of the Committee on Nuclear and Alternative Energy Systems, National Research Council, 1979.

growth in GNP with an average quadrupling of energy prices from 1975 to 2010. Fuel escalation rates are shown in Table 7. For comparison the 1971 to 1978 national average and state ranges of real average fuel escalation rates [11] are also shown. The table shows that while the real average fuel escalation rates vary widely, the national average escalation rates for both natural gas and electricity have exceeded the CONAES A projection. Thus the CONAES A scenario is likely a conservative estimate of the escalation of fuel prices. Table 8 shows the consequence of the CONAES A fuel price escalation in constant (1980) dollars for Washington D.C.

Table 8. Typical (Washington, DC) Fuel Price Escalation (1980$) assuming CONAES A scenario.

		Escalation	1980	1985	1990	1995	2000
Electricity	($/MBtu)	3.3 %	15.88	18.68	21.97	25.84	30.40
Natural Gas	($/MBtu)	5.7 %	3.74	4.93	6.51	8.59	11.33

C.5 Return on Investment Analysis.

Return on investment (ROI) analysis is used to calculate the present value over the life of the system (20 years) of the fuel saved by an active solar system, assuming a given real rate of return on the initial investment. The present value is based on the modified uniform present worth which is a function of the fuel escalation rates and the expected real return on investment or the discount rate. Present values at some future date are expressed in constant dollars (1980$). The payback period for a given ROI is then determined from the number of years required for the discounted present value of the energy saved to equal the initial cost invested to bring about that energy savings (the 20 year present value discounted at the rate of return).

Modified Uniform Present Worth Factor, UPWF

The modified uniform present worth factor, UPWF, is a function of R_{int}, R_{esc}, R_{inf}, and N, where:

R_{inf} is the inflation rate;
R_{int} is the real interest, discount (R_{disc}), or return rate (ROI);
R_{esc} is the real fuel escalation rate; and
N is the number of years of system life.

$$UPWF(R_{int},R_{esc},R_{inf},N) = \sum_{k=1}^{N} \left[\frac{(1 + R_{inf} + R_{esc})}{(1 + R_{inf} + R_{int})}\right]^{k}$$

UPWF can be alternately expressed as

$$UPWF(R_{int},R_{esc},R_{inf},N) = \left[\frac{(1 + R_{inf} + R_{esc})}{(R_{int} - R_{esc})}\right]\left[1 - \left\{\frac{(1 + R_{inf} + R_{esc})}{(1 + R_{inf} + R_{int})}\right\}^{N}\right]$$

when $R_{int} \neq R_{esc}$; and

$$UPWF(R_{int},R_{esc},R_{inf},N) = N \quad ;$$

when $R_{int} = R_{esc}$.

<u>Present value of energy saved by a solar energy system.</u>

The present value of energy saved by a solar system is given by the present value of future fuel savings and the present value of future tax savings, less the present value of future maintenance expenses.

$$\begin{aligned} P = {} & Fe*UPWF(R_{int},R_{esce},R_{inf},N) \\ & + Fg*UPWF(R_{int},R_{escg},R_{inf},N) \\ & - MAINT*UPWF(R_{int},0,R_{inf},N) \\ & + Tax \end{aligned}$$

where P= present value;
F= first year fuel cost savings, Fg (gas), Fe(electricity);
MAINT = annual maintenance expense; and
Tax = present value of future tax savings.

Potential tax savings include tax credits for renewable energy use, property taxes, and interest expense. For commercial owners, the fuel displaced by the solar system is a decrease in business expense which can result in a negative tax savings. For the purposes of this analysis we will assume that income tax savings from interest expense and property taxes compensate for maintenance expenses. This assumption has been used previously[12]. For a single fuel the ratio of the present

value to the first year fuel costs is given by

$$P/F = UPWF(R_{int}, R_{esc}, R_{inf}, N)$$

Payback Period.

The payback period is equal to the number of years for the discounted present value of the energy saved to equal the initial cost invested to bring about that energy savings. The payback period is determined from the number of years required to recover the present value, assuming a nominal discount rate. Assuming that all fuels have the same escalation rate, $R_{esce} = R_{escg} = R_{esc}$, then the payback period, NPAY, is found from

$$I = F*UPWF(R_{disc}, R_{esc}, R_{inf}, NPAY)$$

where I = initial cost. Writing out the equation explicitly one obtains

$$\frac{I}{F} = \left[\frac{(1 + R_{inf} + R_{esc})}{(R_{disc} - R_{esc})}\right]\left[1 - \left\{\frac{(1 + R_{inf} + R_{esc})}{(1 + R_{inf} + R_{disc})}\right\}^{NPAY}\right] .$$

This equation can be solved to give

$$NPAY = \frac{\ln\left\{1 - \frac{\left[R_{disc} - R_{esc}\right] I}{\left[1 + R_{inf} + R_{esc}\right] F}\right\}}{\ln\left\{\frac{[1 + R_{inf} + R_{esc}]}{[1 + R_{inf} + R_{disc}]}\right\}}$$

when $R_{disc} \neq R_{esc}$; and

$$NPAY = \frac{I}{F}$$

[12] John W. Andrews, "Cost/Performance Goals for Solar and Ground Coupled Heat Pump Systems", BNL Report BNL-51259, September 1980.

when $R_{disc}=R_{esc}$.

The return on investment is the discount rate at which the payback period equals the system life. For a given return on investment, ROI, and first year energy cost savings, F, the initial investment is

$$I = F*UPWF(ROI,R_{esc},R_{inf},N).$$

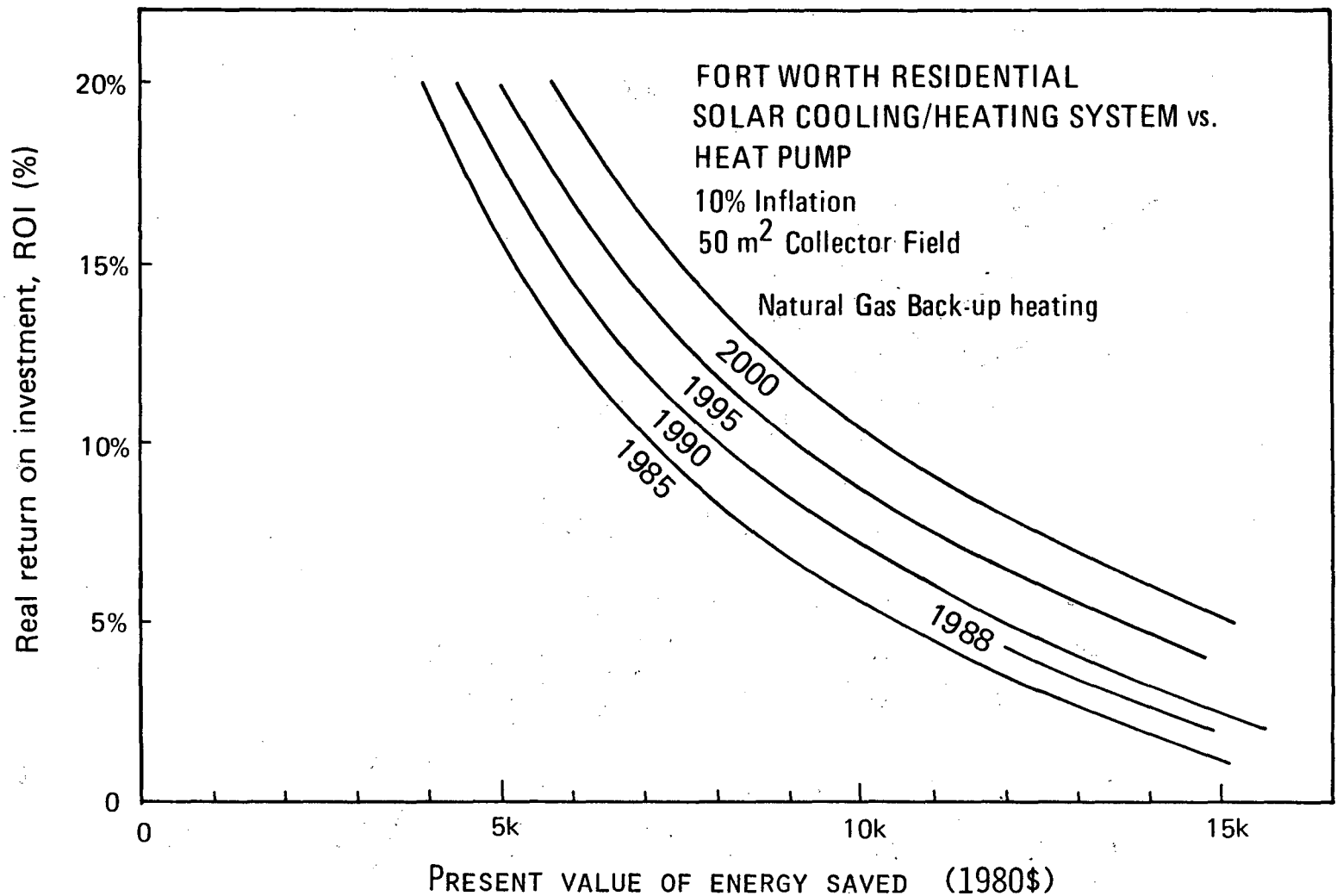
The relationship between the payback period and the return on investment can then be found by equating the initial investments

$$UPWF(R_{disc},R_{esc},R_{inf},NPAY) = UPWF(ROI,R_{esc},R_{inf},N).$$

C.6 Incremental System Cost Goals

To be cost effective, the incremental solar system cost must be equal to (or less than) the present value of the energy savings over the 20 year assumed lifetime, discounted at the expected rate of return on investment (ROI) required to achieve the desired market penetration. Present values at some future date are expressed in constant dollars (1980$).

Using local 1980 energy prices, fuel escalation rates as given by the CONAES report (5.7% natural gas, 3.3% electricity), and assuming an inflation rate of 10%, the present value of the energy saved by the solar system has been calculated as a function of return on investment for specific locations and years of purchase. Figure 10 displays the real return on investment of a residential solar cooling/heating system in Fort Worth compared with a conventional heat pump system as a function of the present value of the energy saved by the solar system, for different initial years of purchase. Figure 11 shows similar results for a commercial solar cooling (only) system in Miami compared with a conventional central air conditioning system.



XBL 812-371

Figure 10. Real return on investment as a function of the present value of the energy saved by a residential solar cooling/heating system for several years of purchase in Ft. Worth.

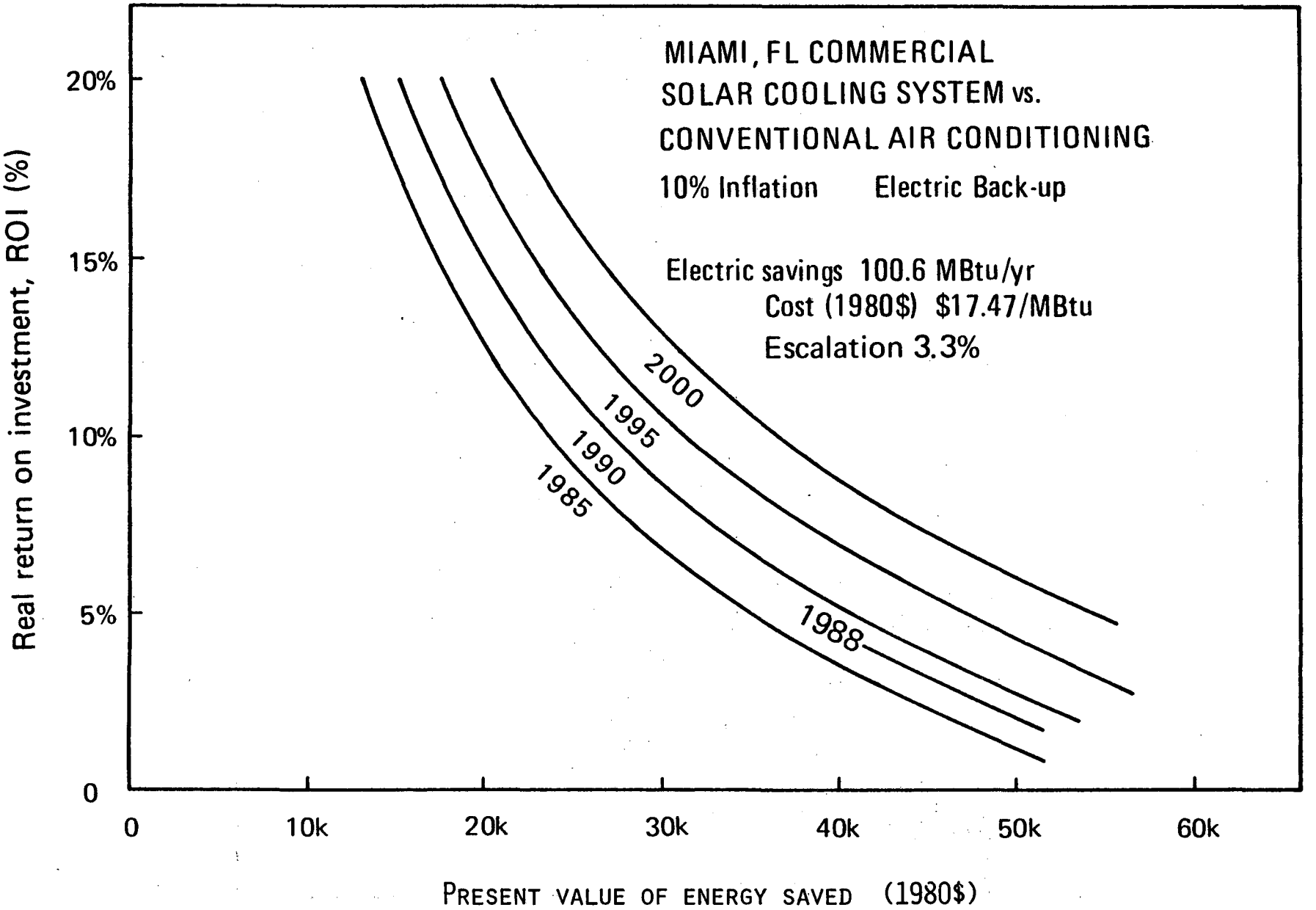


Figure 11. Real return on investment as a function of the present value of the energy saved by a commercial solar cooling system for several years of purchase in Miami.

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Tables 9A, B, C, D list calculated vales of the 20 year present value of energy saved for different years of purchase and for return on investments corresponding to market penetration goals A, B, C and D (see Fig. 7). The present values of energy savings are calculated from the predicted energy use of both an active solar system and a conventional heat pump system for residential and commercial solar cooling systems.

Notes: The 20 year present values of fuel savings in Tables 9A-9D are based on simulation results taken from two studies:

P. L. Versteegen and J. H. Morehouse, "A Thermal And Economic Comparative Analysis of Absorption and Rankine Solar Cooling Systems for Commercial Buildings," Science Applications, Inc., Draft Final Report, May 1979,
[TBL 4-2] Table 4-2. Rankine Coolers #1 and #2 Annual Energy Consumption (GJ) Versus Collector Area(m^2), and
[TBL 4-3] Table 4-3. Absorption Coolers #1 and #2 Annual Energy Consumption (GJ) Versus Collector Area(m^2);

and P. J. Hughes, et. al., "Evaluation of Thermal Storage Concepts for Solar Cooling Applications", Science Applications, Inc., Final Report, January 1981,
[FIG 6-1] Figure 6-1. Residential Absorption System Purchased Energy Requirement vs. Collector Area,
[FIG 6-2] Figure 6-2. Commercial Absorption System Purchased Energy Requirement vs. Collector Area,
[FIG 6-3] Figure 6-3. Commercial Rankine System Purchased Energy Requirement vs. Collector Area, and
[TBL I-5 to I-7] Tables I-5 to I-7. Summary Comparison of Thermal Performance of Each System at the Optimum Collector and Storage Size.

HOT SENSIBLE indicates that only cases using hot sensible storage were considered.

Table 9A. 20 Year present value of fuel savings for return on investment goal A (10 % market penetration in the year 2000) for different systems and cities assuming CONAES A fuel escalation rates (gas 5.7%, electricity 3.3%), a general inflation rate of 10% and a system life of 20 years.

YEAR										1980	1985	1986	1988	1990	1995	2000
PENETRATION GOAL %										0.	0.	0.	1.4	2.9	6.4	10.0
ROI GOAL %										0.	0.	0.	1.2	2.7	5.6	7.5
PAYBACK GOAL YEARS										20.0	20.0	20.0	18.2	16.3	13.0	11.3
	ENERGY UNITS GJ/YR				1980 ANNUAL COST			20 YEAR PRESENT VALUE OF FUEL SAVINGS								
	GSOLAR	ESOLAR	GCONV	ECONV	$SOLAR	$CONV	$SAVE	1980	1985	1986	1988	1990	1995	2000
PHOENIX, AZ RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	47.0	13.5	0.	61.3	$ 388.	$1122.	$ 734.	19217.	21637.	22146.	20561.	18649.	16154.	15433.
WASHINGTON, DC RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 3.74 $/MBTU 1980 ELECTRIC COST 15.88 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	28.0	12.0	0.	61.8	$ 280.	$ 931.	$ 651.	17244.	19539.	20026.	18637.	16945.	14781.	14245.
FORT WORTH RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	28.0	13.0	0.	59.7	$ 242.	$ 798.	$ 555.	14827.	16876.	17314.	16140.	14699.	12884.	12491.
MIAMI, FL RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	44.0	15.5	0.	55.8	$ 412.	$ 925.	$ 513.	12982.	14344.	14620.	13474.	12132.	10281.	9547.
MIAMI, FL COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU														
FIG I-5 150 M2 HOT SENSIBLE	0.	87.0	0.	192.7	$1442.	$3194.	$1752.	48490.	56213.	57900.	54339.	49815.	44504.	44143.
TBL 4-2 150 M2 RANKINE #2	0.	77.5	0.	192.7	$1285.	$3194.	$1910.	52848.	61266.	63104.	59222.	54292.	48504.	48110.
PHOENIX, AZ COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU														
TBL I-6 150 M2 HOT SENSIBLE	0.	47.0	0.	133.0	$ 860.	$2434.	$1574.	43563.	50501.	52016.	48817.	44753.	39982.	39657.
FORT WORTH COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU														
TBL I-7 150 M2 HOT SENSIBLE	0.	48.0	0.	118.0	$ 641.	$1576.	$ 935.	25881.	30004.	30904.	29003.	26589.	23754.	23561.
FIG 6-3 150 M2 HOT SENSIBLE	0.	49.0	0.	118.0	$ 655.	$1576.	$ 922.	25512.	29575.	30462.	28589.	26209.	23414.	23224.
TBL 4-2 150 M2 RANKINE #1	0.	50.0	0.	118.0	$ 668.	$1576.	$ 908.	25142.	29146.	30021.	28174.	25829.	23075.	22888.
MIAMI, FL COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU														
TBL 4-3 150 M2 ABSORPTION #1	178.0	42.7	0.	192.7	$1336.	$3194.	$1858.	46538.	51097.	52004.	47811.	42938.	36103.	33178.
PHOENIX, AZ COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU														
TBL 4-3 150 M2 ABSORPTION #1	21.0	32.9	0.	133.0	$ 665.	$2434.	$1769.	48473.	55907.	57522.	53884.	49309.	43826.	43206.
FORT WORTH COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU														
TBL 4-3 150 M2 ABSORPTION #1	59.0	29.2	0.	118.0	$ 535.	$1576.	$1041.	27692.	31444.	32243.	30030.	27324.	23890.	23089.

Table 9B. 20 Year present value of fuel savings for return on investment goal B (20 % market penetration in the year 2000) for different systems and cities assuming CONAES A fuel escalation rates (gas 5.7%, electricity 3.3%), a general inflation rate of 10% and a system life of 20 years.

	1980	1985	1986	1988	1990	1995	2000
YEAR	1980	1985	1986	1988	1990	1995	2000
PENETRATION GOAL %	0.	0.	0.	2.8	5.9	12.8	20.0
ROI GOAL %	0.	0.	0.	2.7	5.2	8.8	11.4
PAYBACK GOAL YEARS	20.0	20.0	20.0	16.3	13.4	10.5	8.9

ENERGY UNITS GJ/YR				1980 ANNUAL COST			20 YEAR PRESENT VALUE OF FUEL SAVINGS						
GSOLAR	ESOLAR	GCONV	ECONV	$SOLAR	$CONV	$SAVE	1980	1985	1986	1988	1990	1995	2000
PHOENIX, AZ RESIDENTIAL AGAINST HEAT PUMP													
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU													
FIG 6-1 50 M2 HOT SENSIBLE	47.0	13.5	0.	61.3	$ 388.	$1122.	$ 734.	19217.	21637.	22146.	17819.	14948.	12589.	11693.
WASHINGTON, DC RESIDENTIAL AGAINST HEAT PUMP													
1980 GAS COST 3.74 $/MBTU 1980 ELECTRIC COST 15.88 $/MBTU													
FIG 6-1 50 M2 HOT SENSIBLE	28.0	12.0	0.	61.8	$ 280.	$ 931.	$ 651.	17244.	19539.	20026.	16142.	13567.	11500.	10770.
FORT WORTH RESIDENTIAL AGAINST HEAT PUMP													
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU													
FIG 6-1 50 M2 HOT SENSIBLE	28.0	13.0	0.	59.7	$ 242.	$ 798.	$ 555.	14827.	16876.	17314.	13972.	11759.	10014.	9430.
MIAMI, FL RESIDENTIAL AGAINST HEAT PUMP													
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU													
FIG 6-1 50 M2 HOT SENSIBLE	44.0	15.5	0.	55.8	$ 412.	$ 925.	$ 513.	12982.	14344.	14620.	11701.	9758.	8052.	7285.
MIAMI, FL COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)													
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU													
FIG I-5 150 M2 HOT SENSIBLE	0.	87.0	0.	192.7	$1442.	$3194.	$1752.	48490.	56213.	57900.	46956.	39729.	34441.	33138.
TBL 4-2 150 M2 RANKINE #2	0.	77.5	0.	192.7	$1285.	$3194.	$1910.	52848.	61266.	63104.	51176.	43299.	37536.	36117.
PHOENIX, AZ COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)													
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU													
TBL I-6 150 M2 HOT SENSIBLE	0.	47.0	0.	133.0	$ 860.	$2434.	$1574.	43563.	50501.	52016.	42184.	35692.	30941.	29771.
FORT WORTH COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)													
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU													
TBL I-7 150 M2 HOT SENSIBLE	0.	48.0	0.	118.0	$ 641.	$1576.	$ 935.	25881.	30004.	30904.	25062.	21205.	18383.	17687.
FIG 6-3 150 M2 HOT SENSIBLE	0.	49.0	0.	118.0	$ 655.	$1576.	$ 922.	25512.	29575.	30462.	24704.	20902.	18120.	17435.
TBL 4-2 150 M2 RANKINE #1	0.	50.0	0.	118.0	$ 668.	$1576.	$ 908.	25142.	29146.	30021.	24346.	20599.	17857.	17182.
MIAMI, FL COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)													
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU													
TBL 4-3 150 M2 ABSORPTION #1	178.0	42.7	0.	192.7	$1336.	$3194.	$1858.	46538.	51097.	52004.	41547.	34579.	28329.	25387.
PHOENIX, AZ COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)													
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU													
TBL 4-3 150 M2 ABSORPTION #1	21.0	32.9	0.	133.0	$ 665.	$2434.	$1769.	48473.	55907.	57522.	46586.	39359.	33955.	32483.
FORT WORTH COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)													
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU													
TBL 4-3 150 M2 ABSORPTION #1	59.0	29.2	0.	118.0	$ 535.	$1576.	$1041.	27692.	31444.	32243.	26004.	21869.	18578.	17444.

Table 9C. 20 Year present value of fuel savings for return on investment goal C (40 % market penetration in the year 2000) for different systems and cities assuming CONAES A fuel escalation rates (gas 5.7%, electricity 3.3%), a general inflation rate of 10% and a system life of 20 years.

YEAR	1980	1985	1986	1988	1990	1995	2000
PENETRATION GOAL %	0.	0.	0.	5.7	11.4	25.7	40.0
ROI GOAL %	0.	0.	0.	5.0	8.3	13.0	17.5
PAYBACK GOAL YEARS	20.0	20.0	20.0	13.6	10.9	8.1	6.4

	ENERGY UNITS GJ/YR				1980 ANNUAL COST			20 YEAR PRESENT VALUE OF FUEL SAVINGS						
	GSOLAR	ESOLAR	GCONV	ECONV	$SOLAR	$CONV	$SAVE	1980	1985	1986	1988	1990	1995	2000
PHOENIX, AZ RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	47.0	13.5	0.	61.3	$ 388.	$1122.	$ 734.	19217.	21637.	22146.	14524.	11680.	9478.	8168.
WASHINGTON, DC RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 3.74 $/MBTU 1980 ELECTRIC COST 15.88 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	28.0	12.0	0.	61.8	$ 280.	$ 931.	$ 651.	17244.	19539.	20026.	13143.	10587.	8642.	7501.
FORT WORTH RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	28.0	13.0	0.	59.7	$ 242.	$ 798.	$ 555.	14827.	16876.	17314.	11369.	9168.	7515.	6555.
MIAMI, FL RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	44.0	15.5	0.	55.8	$ 412.	$ 925.	$ 513.	12982.	14344.	14620.	9565.	7656.	6098.	5136.
MIAMI, FL COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU														
FIG I-5 150 M2 HOT SENSIBLE	0.	87.0	0.	192.7	$1442.	$3194.	$1752.	48490.	56213.	57900.	38103.	30860.	25716.	22868.
TBL 4-2 150 M2 RANKINE #2	0.	77.5	0.	192.7	$1285.	$3194.	$1910.	52848.	61266.	63104.	41527.	33634.	28028.	24923.
PHOENIX, AZ COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU														
TBL I-6 150 M2 HOT SENSIBLE	0.	47.0	0.	133.0	$ 860.	$2434.	$1574.	43563.	50501.	52016.	34231.	27725.	23103.	20544.
FORT WORTH COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU														
TBL I-7 150 M2 HOT SENSIBLE	0.	48.0	0.	118.0	$ 641.	$1576.	$ 935.	25881.	30004.	30904.	20337.	16472.	13726.	12206.
FIG 6-3 150 M2 HOT SENSIBLE	0.	49.0	0.	118.0	$ 655.	$1576.	$ 922.	25512.	29575.	30462.	20047.	16236.	13530.	12031.
TBL 4-2 150 M2 RANKINE #1	0.	50.0	0.	118.0	$ 668.	$1576.	$ 908.	25142.	29146.	30021.	19756.	16001.	13334.	11857.
MIAMI, FL COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU														
TBL 4-3 150 M2 ABSORPTION #1	178.0	42.7	0.	192.7	$1336.	$3194.	$1858.	46538.	51097.	52004.	33998.	27168.	21498.	17958.
PHOENIX, AZ COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU														
TBL 4-3 150 M2 ABSORPTION #1	21.0	32.9	0.	133.0	$ 665.	$2434.	$1769.	48473.	55907.	57522.	37832.	30604.	25388.	22460.
FORT WORTH COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU														
TBL 4-3 150 M2 ABSORPTION #1	59.0	29.2	0.	118.0	$ 535.	$1576.	$1041.	27692.	31444.	32243.	21167.	17058.	13952.	12139.

Table 9D. 20 Year present value of fuel savings for return on investment goal D (5 year payback in the year 2000) for different systems and cities assuming CONAES A fuel escalation rates (gas 5.7%, electricity 3.3%), a general inflation rate of 10% and a system life of 20 years.

YEAR	1980	1985	1986	1988	1990	1995	2000
PENETRATION GOAL %	0.	0.	0.	9.4	18.9	42.4	66.0
ROI GOAL %	0.	0.	0.	7.3	11.0	17.7	26.5
PAYBACK GOAL YEARS	20.0	20.0	20.0	11.6	9.1	6.3	5.0

	ENERGY UNITS GJ/YR				1980 ANNUAL COST			20 YEAR PRESENT VALUE OF FUEL SAVINGS						
	GSOLAR	ESOLAR	GCONV	ECONV	$SOLAR	$CONV	$SAVE	1980	1985	1986	1988	1990	1995	2000
PHOENIX, AZ RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	47.0	13.5	0.	61.3	$ 388.	$1122.	$ 734.	19217.	21637.	22146.	12041.	9639.	7248.	5456.
WASHINGTON, DC RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 3.74 $/MBTU 1980 ELECTRIC COST 15.88 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	28.0	12.0	0.	61.8	$ 280.	$ 931.	$ 651.	17244.	19539.	20026.	10887.	8727.	6597.	4996.
FORT WORTH RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	28.0	13.0	0.	59.7	$ 242.	$ 798.	$ 555.	14827.	16876.	17314.	9411.	7552.	5730.	4357.
MIAMI, FL RESIDENTIAL AGAINST HEAT PUMP														
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU														
FIG 6-1 50 M2 HOT SENSIBLE	44.0	15.5	0.	55.8	$ 412.	$ 925.	$ 513.	12982.	14344.	14620.	7953.	6338.	4689.	3464.
MIAMI, FL COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU														
FIG I-5 150 M2 HOT SENSIBLE	0.	87.0	0.	192.7	$1442.	$3194.	$1752.	48490.	56213.	57900.	31457.	25345.	19515.	15081.
TBL 4-2 150 M2 RANKINE #2	0.	77.5	0.	192.7	$1285.	$3194.	$1910.	52848.	61266.	63104.	34284.	27623.	21268.	16437.
PHOENIX, AZ COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU														
TBL I-6 150 M2 HOT SENSIBLE	0.	47.0	0.	133.0	$ 860.	$2434.	$1574.	43563.	50501.	52016.	28260.	22769.	17532.	13549.
FORT WORTH COMMERCIAL RANKINE AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU														
TBL I-7 150 M2 HOT SENSIBLE	0.	48.0	0.	118.0	$ 641.	$1576.	$ 935.	25881.	30004.	30904.	16790.	13528.	10416.	8049.
FIG 6-3 150 M2 HOT SENSIBLE	0.	49.0	0.	118.0	$ 655.	$1576.	$ 922.	25512.	29575.	30462.	16550.	13334.	10267.	7935.
TBL 4-2 150 M2 RANKINE #1	0.	50.0	0.	118.0	$ 668.	$1576.	$ 908.	25142.	29146.	30021.	16310.	13141.	10118.	7820.
MIAMI, FL COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.72 $/MBTU 1980 ELECTRIC COST 17.47 $/MBTU														
TBL 4-3 150 M2 ABSORPTION #1	178.0	42.7	0.	192.7	$1336.	$3194.	$1858.	46538.	51097.	52004.	28294.	22517.	16565.	12155.
PHOENIX, AZ COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 3.16 $/MBTU 1980 ELECTRIC COST 19.29 $/MBTU														
TBL 4-3 150 M2 ABSORPTION #1	21.0	32.9	0.	133.0	$ 665.	$2434.	$1769.	48473.	55907.	57522.	31255.	25155.	19291.	14843.
FORT WORTH COMMERCIAL ABSORPTION AGAINST ELECTRIC-AC(3.0)														
1980 GAS COST 2.59 $/MBTU 1980 ELECTRIC COST 14.08 $/MBTU														
TBL 4-3 150 M2 ABSORPTION #1	59.0	29.2	0.	118.0	$ 535.	$1576.	$1041.	27692.	31444.	32243.	17527.	14057.	10645.	8077.

To be cost effective, we set as a cost goal that the incremental solar system cost be equal to the present value of energy saved for each case corresponding to the various ROI and market penetration goals, years of purchase and locations. Figure 12 then shows the incremental cost goals for residential solar energy systems in four cities for market penetration goal B (a 20% market penetration in the year 2000). The allowable incremental cost depends on the location of the solar system because of climate, insolation, and fuel cost variation. Applications with both heating and cooling requirements make better use of the equipment and are more cost effective. The performance in Washington, DC is typical of these residential systems. Figure 13 shows the effect of varying market penetration goals on the allowable incremental solar system cost (cost goals) for the same typical application. The year 2000 cost goal drops by about a factor of 3 as the final payback period drops from about 11 years (Goal A) to 5 years (Goal D). The numbers being plotted here can all be found in Table 9.

Figure 14 shows the incremental solar system cost goals for commercial systems in three cities for a 20% market penetration in the year 2000 (Goal B). The allowable incremental cost again depends on the location of the solar system because of climate, insolation, and fuel cost variation. The commercial cases were analyzed for cooling only. Washington, DC does not have a large cooling load and has been dropped from the analysis. The performance of the Rankine system in Phoenix is typical of these commercial systems. Figure 15 shows the effect of varying market penetration goals on the allowable incremental solar system cost for the same typical application. The year 2000 cost goal drops by about a factor of 3 as the payback period drops from about 11 years

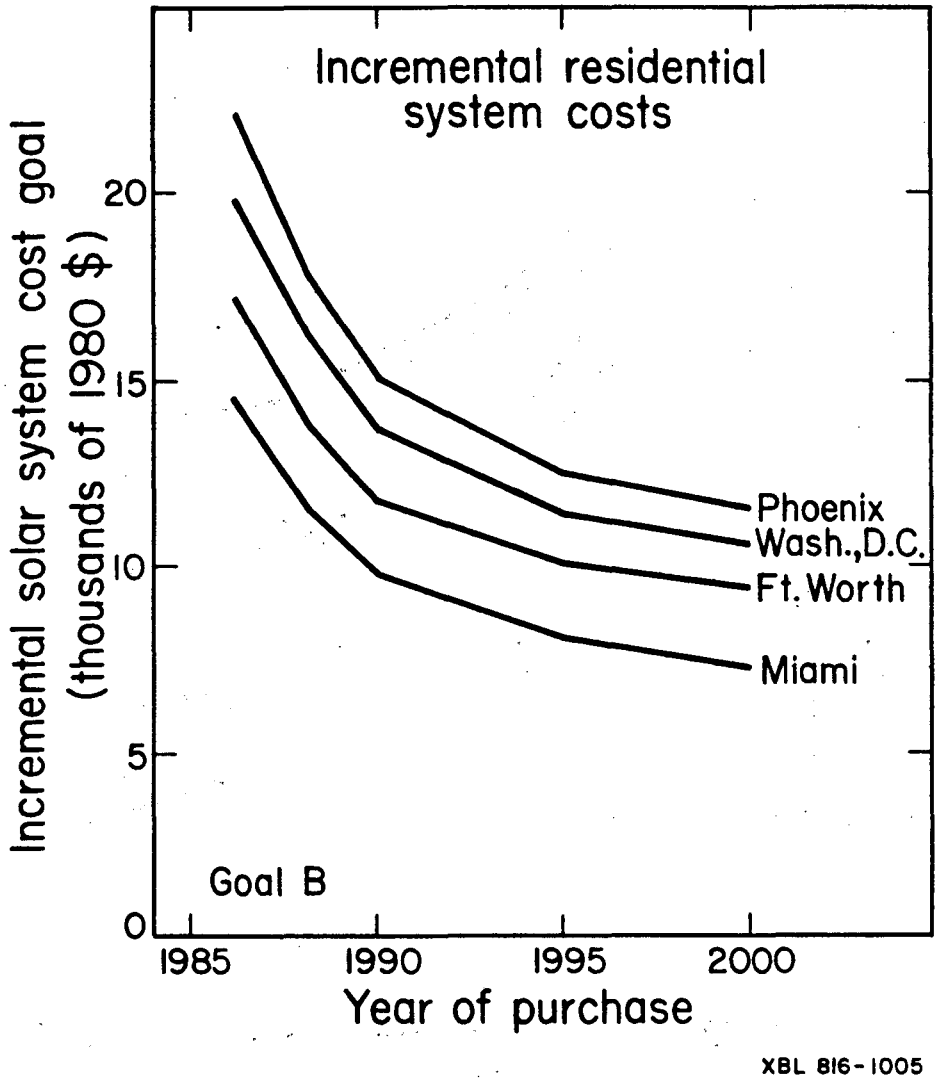

Figure 12. Residential incremental solar system cost goals for representative systems in four cities to achieve goal B, 20% penetration in the year 2000.

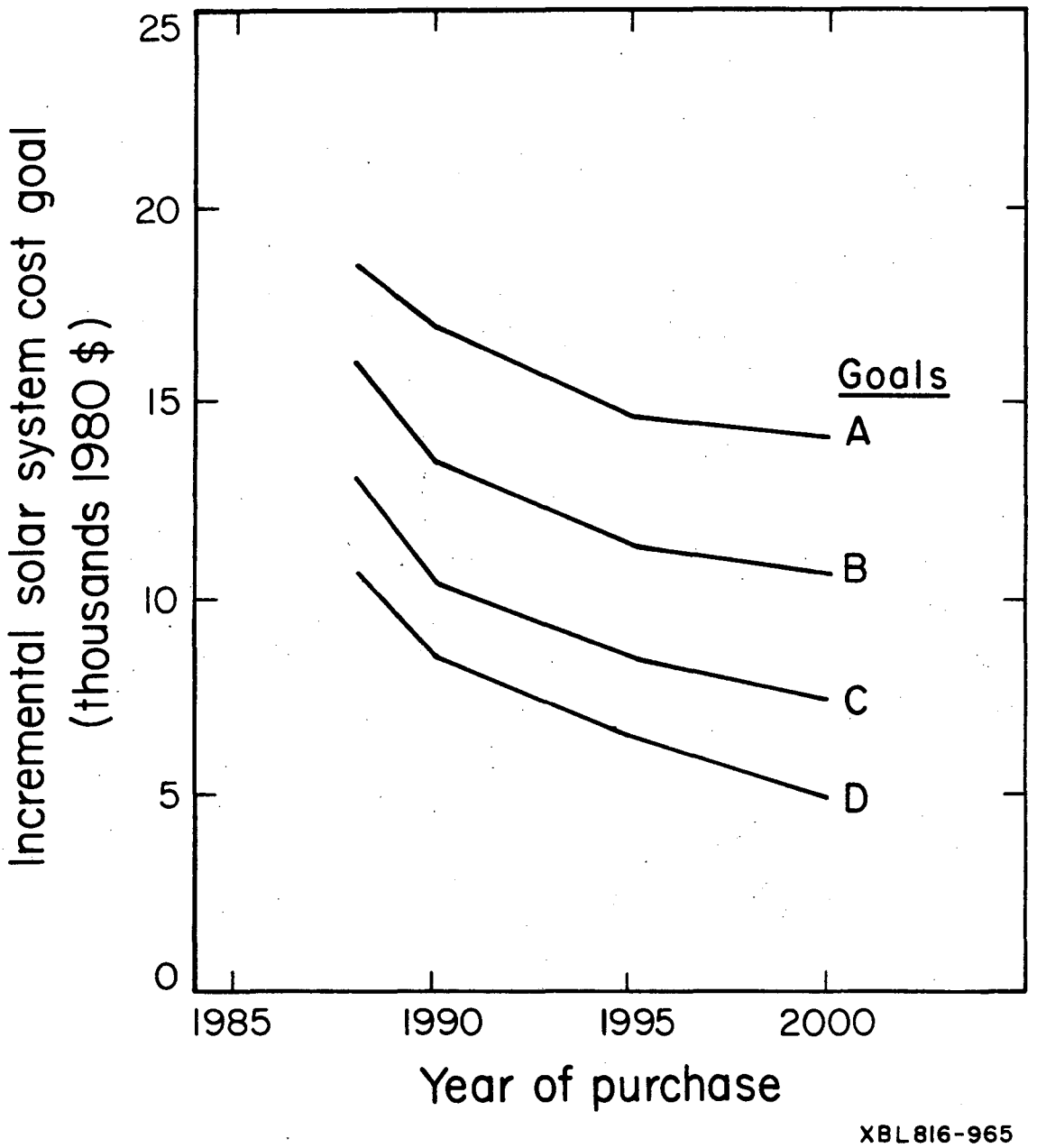

Figure 13. Typical residential incremental solar system cost goals (for Washington, D.C.) for different market penetration goal scenarios.

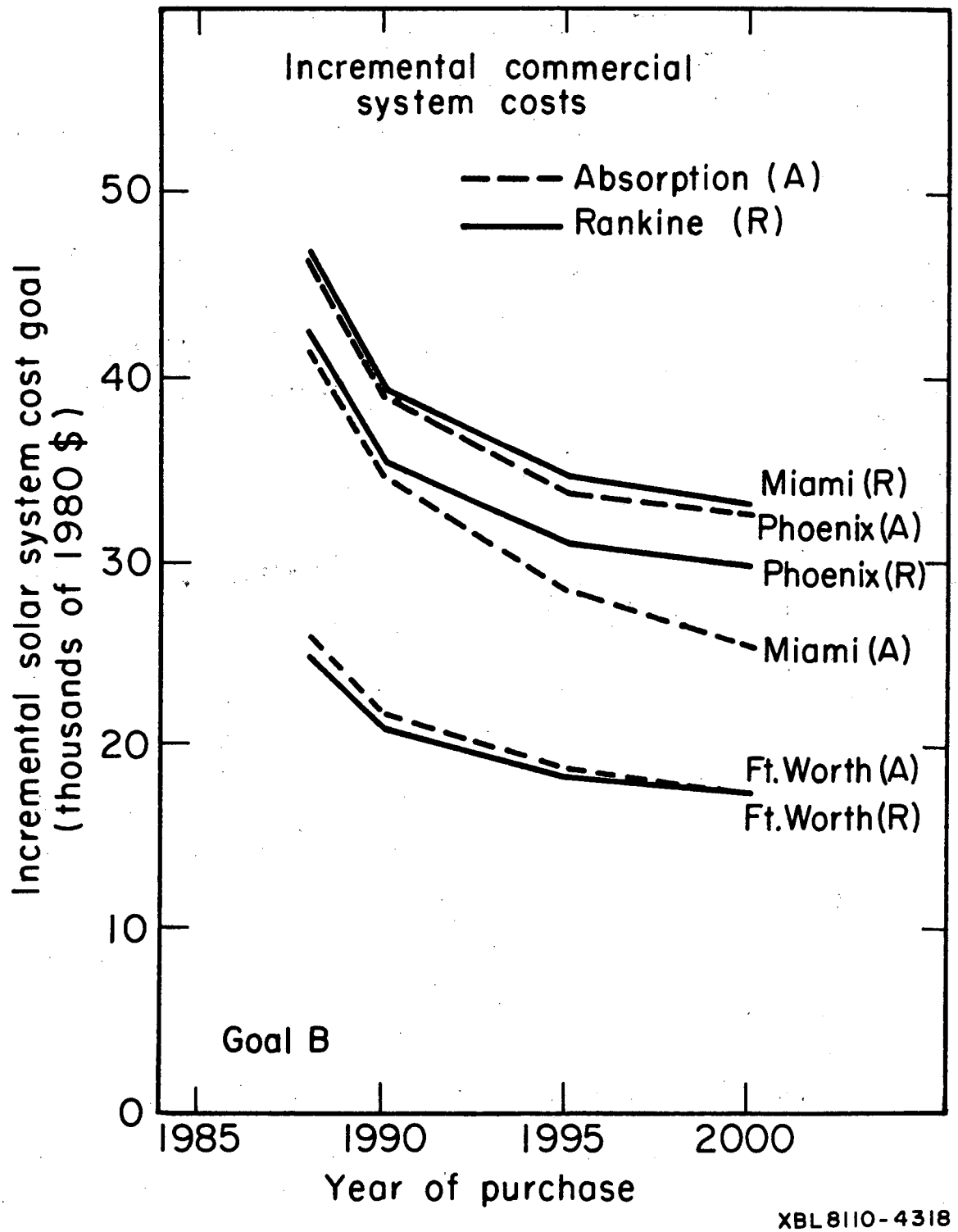

Figure 14. Rankine and absorption commercial incremental solar system cost goals for representative systems in three cities to achieve goal B, 20% market penetration in the year 2000.

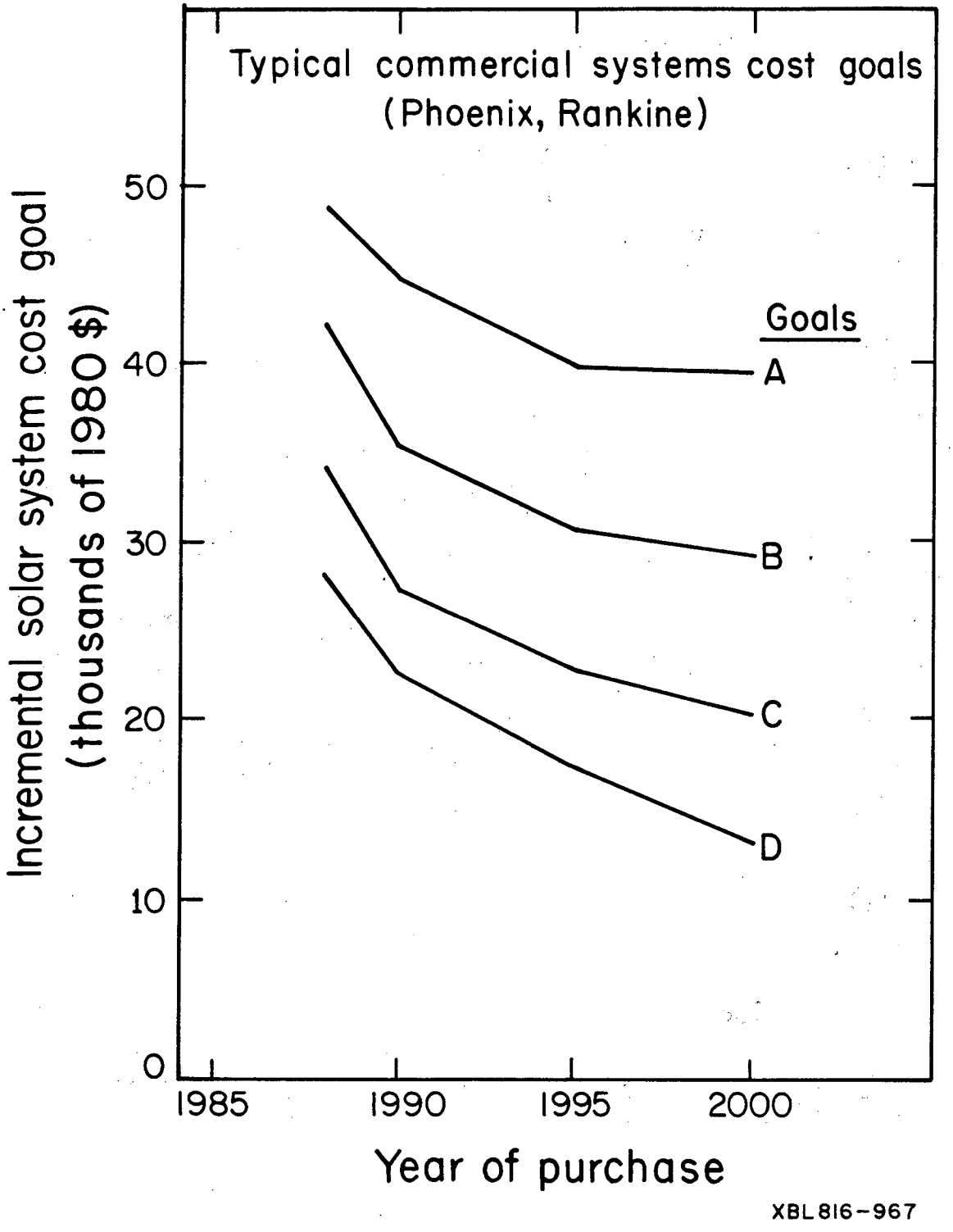

Figure 15. Typical commercial incremental solar system cost goals (for Phoenix, Rankine) for different market penetration goal scenarios.

(Goal A) to 5 years (Goal D).

Table 10 summarizes incremental solar system cost goals for the typical residential and commercial applications displayed in Figures 13 and 15.

Table 10. Incremental solar system cost goals (1980$) for typical residential and commercial applications.

		1986	1988	1990	1995	2000
Residential	Goal A	20.0k	18.6k	16.9k	14.7k	14.2k
	Goal B	20.0k	16.1k	13.6k	11.5k	10.8k
Commercial	Goal A	52.0k	48.8k	44.8k	40.0k	39.7k
	Goal B	52.0k	42.2k	35.7k	30.9k	29.8k

Cost Goal Measures.

The solar system cost, the annual energy saved, the collector area, and the system cooling capacity have similar, although not identical, scaling properties as a function of size of the solar system. Therefore certain ratios of these quantities are roughly independent of the solar system size, and are useful common measures of solar system cost. Accordingly we have evaluated several of these ratios as measures of the solar system cost goals: 1) Incremental Solar System Cost/annual energy saved (MBtu/yr); 2) Incremental Solar System Cost/first year energy cost saved (1980$); and 3) Incremental Solar System Cost/per unit area of collector or per unit of solar cooling capacity.

1) Incremental Solar System Cost/annual energy saved (MBtu/yr).

If only a single fuel such as electricity is used in both the solar and conventional system, calculation of the incremental solar system

cost per unit energy saved is simple. Figure 16 shows the present value of saving one million Btu per year (1 MBtu/yr) of electricity or gas for 20 years as a function of return on investment and starting year, assuming CONAES A fuel escalation rates. The effect of fuel escalation rates is shown in Figures 17 and 18. As the fuel escalation rate increases, the present value of future energy savings also increases. Table 11 shows the 20 year present value of 1 MBtu/year of electricity and gas fuel savings for Washington, DC.

Table 11. 20 Year Present Value (1980$) of 1 MBtu per year ($10^6$ Btu/yr) of fuel savings, assuming Washington, D.C. fuel costs (electricity $15.88/MBtu, gas $3.74/MBtu), 3% discount rate, 10 % inflation rate, CONAES A escalation rates, and different initial years.

Initial Year	1980	1985	1990	1995	2000
Electricity (1980$)	322	379	439	509	590
Natural Gas (1980$)	97	125	160	206	266

Again setting the incremental solar system cost goal as equal to the 20 year present value of energy saved, the present values in Figures 16, 17 and 18, and Table 11 can be interpreted as values of incremental solar system cost goals per annual energy saved in MBtu/yr.

When two fuels are used, the energy quantities are weighted and considered as a single fuel. Typically, as a resource, one unit of electricity is equivalent to about four units of natural gas. The incremental solar system cost goals per MBtu/yr of equivalent gas and electricity for a representative system in Phoenix, and for national average prices are shown in Table 12. The cost of fuel is escalating and the required rate of return is also increasing to stimulate market acceptance.

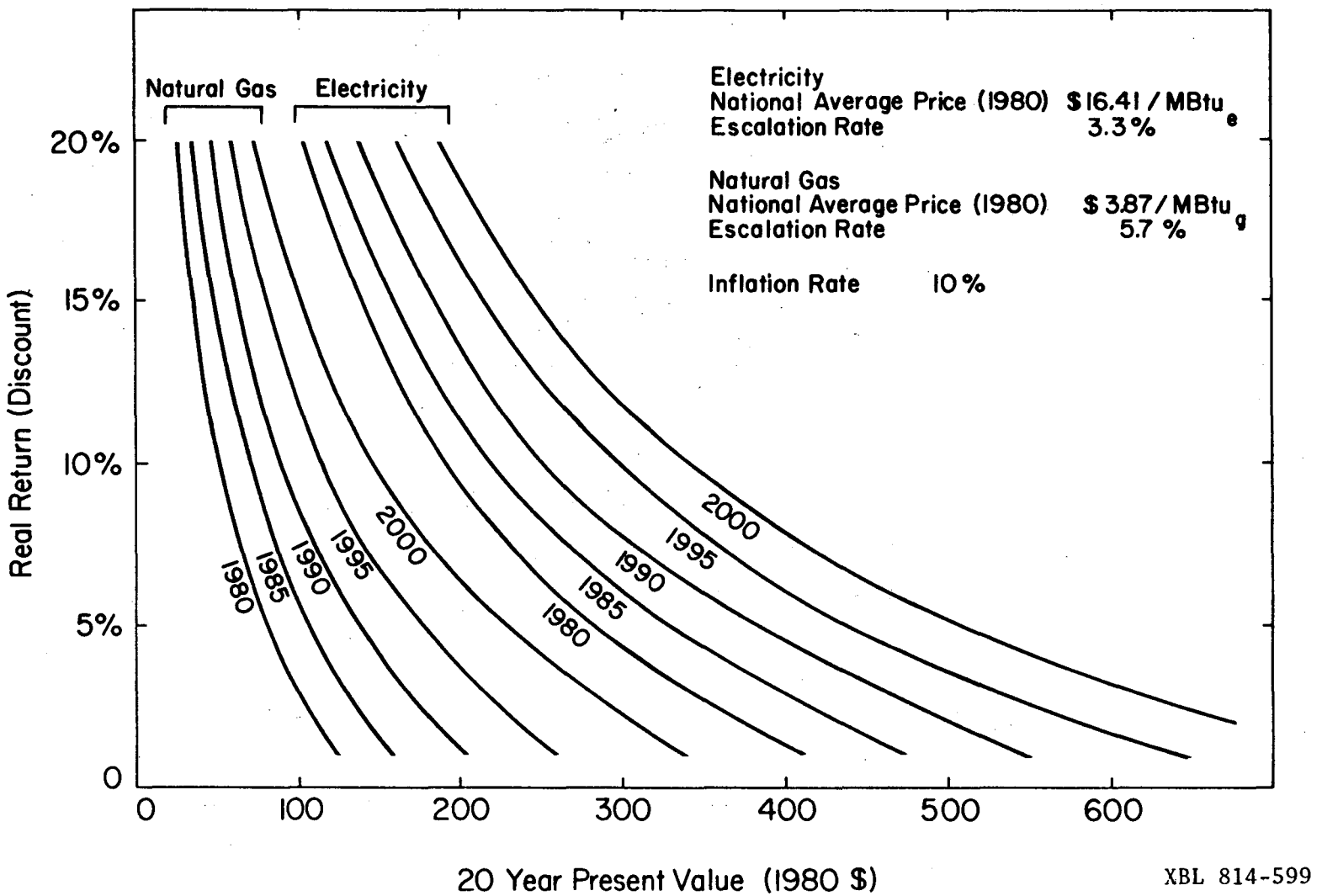

Figure 16. 20 year present value of 1 MBtu/yr (10^6 Btu/yr) fuel savings as a function of real return on investment and starting year using CONAES A fuel escalation rates and 10% inflation rate.

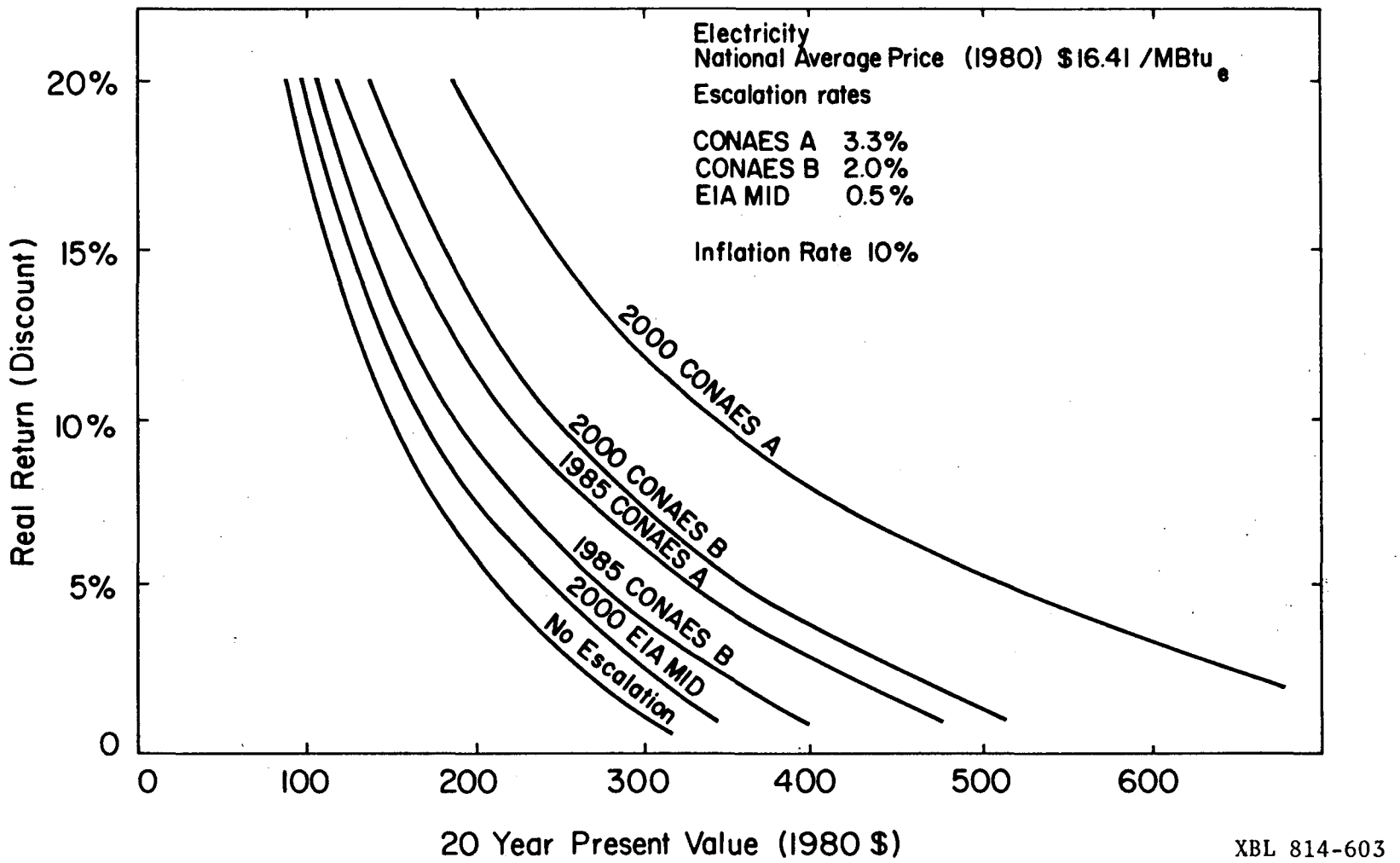

Figure 17. 20 year present value of 1 MBtu/yr (10^6 Btu/yr) electricity savings as a function of real return on investment, electricity escalation rate, and starting year.

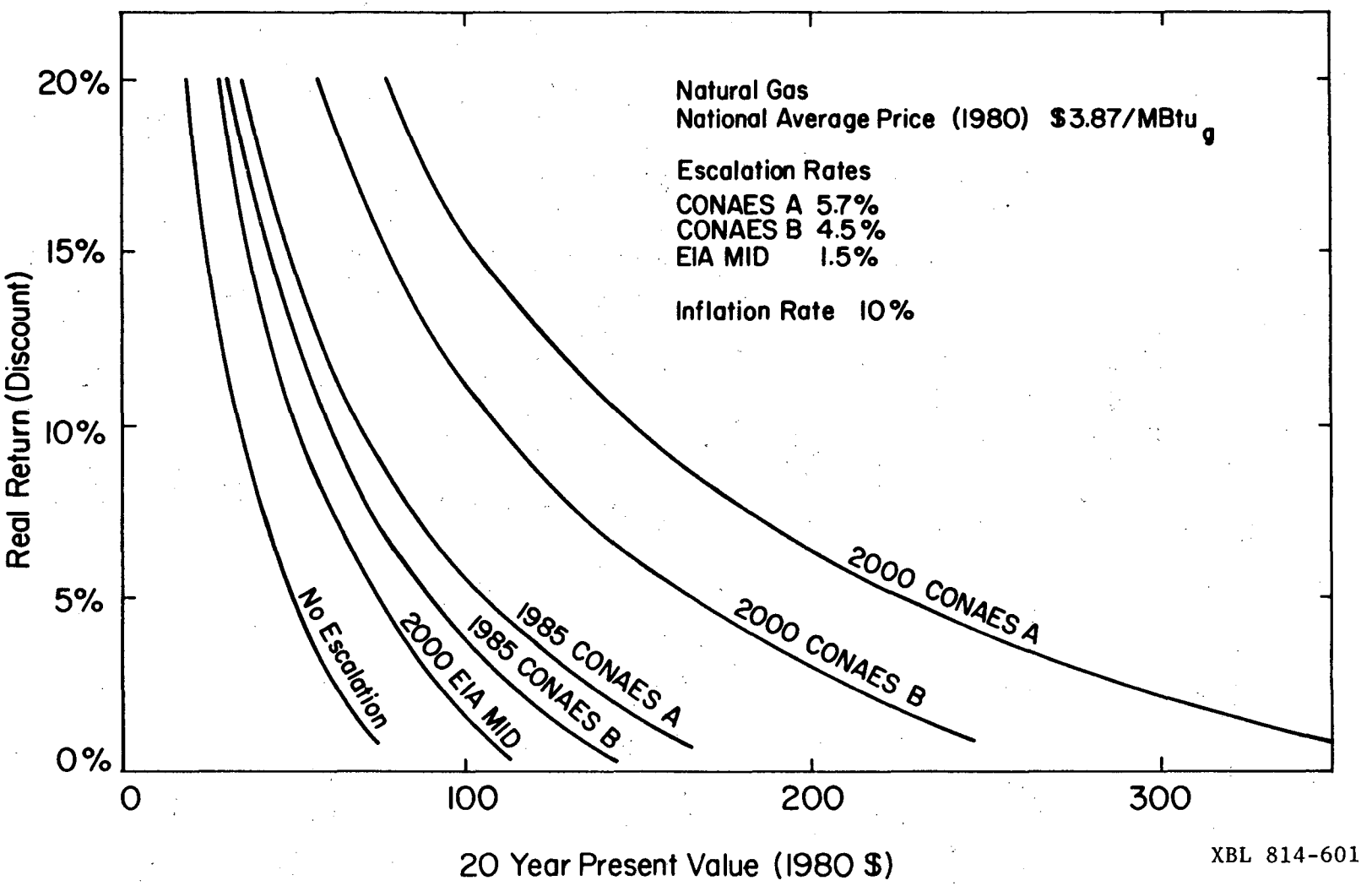

Figure 18. 20 year present value of 1 MBtu/yr (10^6 Btu/yr) natural gas savings as a function of real return on investment, natural gas escalation rate, and starting year.

Table 12. Cost Goal measures for representative systems assuming CONAES A fuel escalation rates (Gas 5.7 %, Electricity 3.3 %), an inflation rate of 10 % and a system life of 20 years. National average gas 3.87 $/MBtu. National average electricity 16.41 $/MBtu. Represenative system performance based on Phoenix (gas 3.16 $/MBtu, electricity 19.29 $/MBtu).

PHOENIX SYSTEM ENERGY SAVINGS

	Natural Gas	Electricity	Equivalent Gas	Equivalent Electricity
	$MBtu_g$/yr	$MBtu_e$/yr	$MBtu_g$/yr	$MBtu_e$/yr
Phoenix 150 m^2 Rankine 12.5 ton solar	0.	81.6	326.	81.6
Phoenix 150 m^2 Absorption 12.5 ton solar	-20.	95.	360.	90.
Phoenix 50 m^2 Absorption 3.0 ton	-44.6	45.4	137.	34.3

		1980	1985	1986	1988	1990	1995	2000
PENETRATION GOAL	%	0.	0.	0.	2.8	5.9	12.8	20.
ROI GOAL B	%	0.	0.	0.	2.7	5.2	8.8	11.4
PAYBACK GOAL	YEARS	20.	20.	20.	16.3	13.4	10.5	8.9

PHOENIX INCREMENTAL SYSTEM COST GOALS (1980$)

	1980	1985	1986	1988	1990	1995	2000
Phoenix 150 m^2 Rankine 12.5 ton solar	43600.	50500.	52000.	42200.	35700.	30900.	29800.
Phoenix 150 m^2 Absorption 12.5 ton solar	48500.	55900.	57500.	46600.	39400.	34000.	32500.
Phoenix 50 m^2 Absorption 3.0 ton	19200.	21600.	22100.	17800.	14900.	12600.	11700.

INCREMENTAL COST GOAL/ MBTU/yr (10^6BTU/yr) NATURAL GAS SAVED

	1980	1985	1986	1988	1990	1995	2000
Phoenix 150 m^2 Rankine Equivalent Gas	134.	155.	159.	129.	109.	95.	91.
Phoenix 150 m^2 Absorption Equivalent Gas	135.	155.	160.	129.	109.	94.	90.
Phoenix 50 m^2 Absorption Equivalent Gas	140.	158.	162.	130.	109.	92.	85.
Phoenix Average Natural Gas	112.	144.	152.	126.	110.	103.	109.
National Average Natural Gas	137.	177.	186.	155.	134.	127.	133.

INCREMENTAL COST GOAL/ MBTU/yr (10^6BTU/yr) ELECTRICITY SAVED

	1980	1985	1986	1988	1990	1995	2000
Phoenix 150 m^2 Rankine Equivalent Electricity	534.	619.	638.	517.	437.	379.	365.
Phoenix 150 m^2 Absorption Equivalent Electricity	539.	621.	639.	518.	437.	378.	361.
Phoenix 50 m^2 Absorption Equivalent Electricity	562.	633.	648.	521.	437.	368.	342.
Phoenix Average Electricity	534.	619.	638.	517.	437.	379.	365.
National Average Electricity	454.	527.	542.	440.	372.	323.	310.

PHOENIX FIRST YEAR SYSTEM COST SAVINGS (1980$)

	1980	1985	1986	1988	1990	1995	2000
Phoenix 150 m^2 Rankine 12.5 ton solar	1574.	1825.	1879.	1994.	2115.	2452.	2843.
Phoenix 150 m^2 Absorption 12.5 ton solar	1769.	2043.	2102.	2227.	2358.	2720.	3136.
Phoenix 50 m^2 Absorption 3.0 ton	734.	833.	854.	897.	942.	1062.	1193.

INCREMENTAL SYSTEM COST GOAL/FIRST YEAR ENERGY COST SAVINGS

	1980	1985	1986	1988	1990	1995	2000
Phoenix 150 m^2 Rankine	27.7	27.7	27.7	21.2	16.9	12.6	10.5
Phoenix 150 m^2 Absorption	27.4	27.4	27.4	20.9	16.7	12.5	10.4
Phoenix 50 m^2 Absorption	26.2	26.0	25.9	19.9	15.9	11.9	9.8
Natural Gas Modified Present Worth Factor	35.5	35.5	35.5	26.7	20.9	15.3	12.5
Electricity Modified Present Worth Factor	27.7	27.7	27.7	21.2	16.9	12.6	10.5

2) Incremental Solar System Cost/first year energy cost saved.

The ratio of allowable incremental solar system cost to first year cost saving is another important measure. If a single fuel is used then the incremental solar system cost goal per first year energy cost saving is given by the modified uniform present worth factor for that fuel escalation rate and expected rate of return on investment. Figure 19 shows the uniform present worth factor for gas and electricity for system life of 20 years assuming CONAES A escalation rates. The first year energy cost savings depends on the year of purchase of the system because of the escalation in fuel costs. If the expected rate of return is equal to the fuel escalation rate then the uniform present worth factor is equal to the system life, in this case 20 years. As the expected return on investment increases with time and maturity of the market, the incremental solar system cost goal per first year energy cost saved decreases, as shown in Table 12. If two fuels with different escalation rates are used, then the relative importance of each fuel will change with time.

3) Other measures.

Inasmuch as the collector area determines the amount of solar energy collected and the collectors constitute the single largest cost item in a solar cooling/heating system, the incremental solar system cost per unit collector area is a commonly used measure of the cost goal. Similarly, the incremental solar system cost per ton of cooling is also sometimes used as a cost goal measure.

Considerable care must be taken in extrapolating these representa-

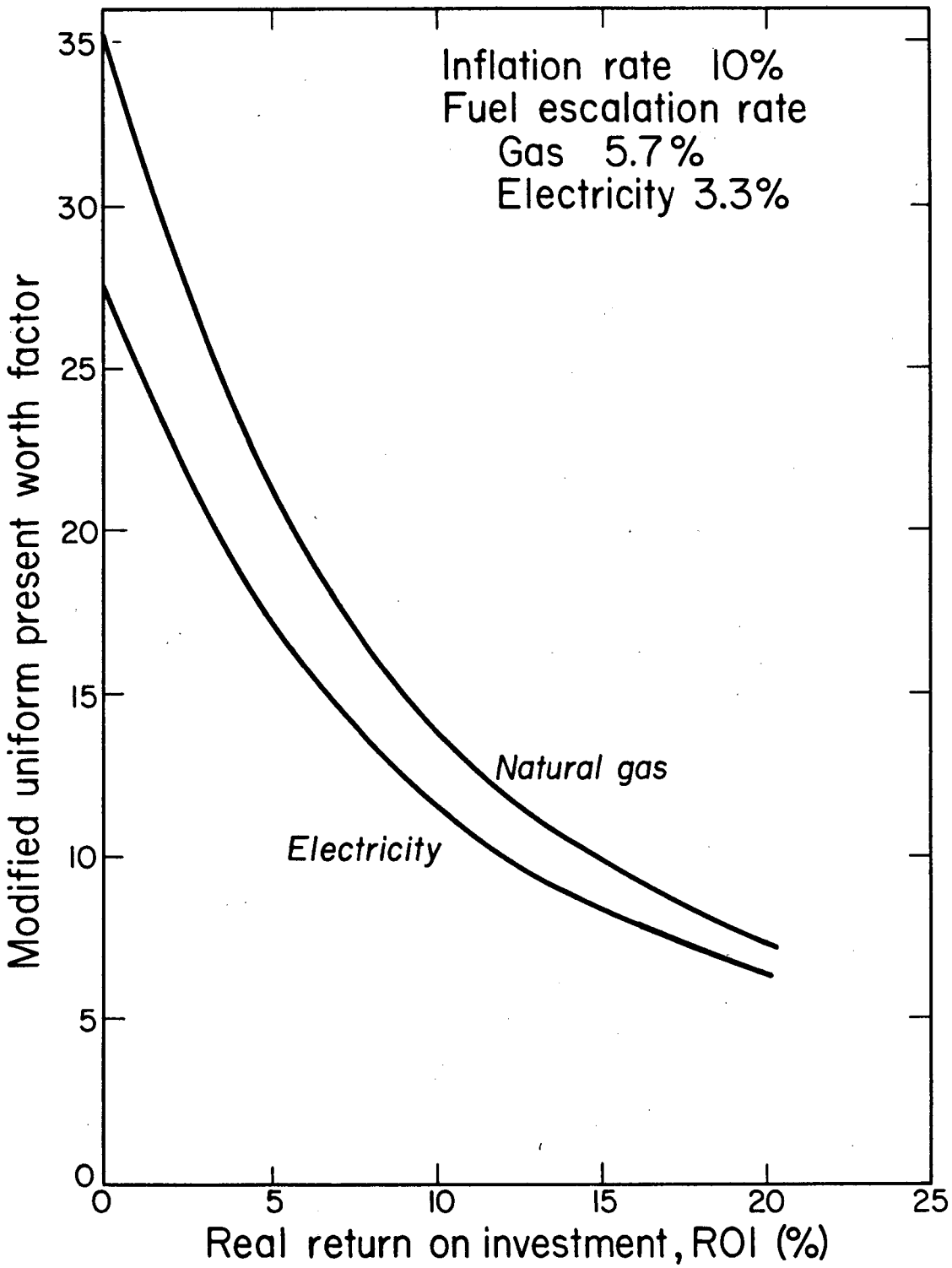

Figure 19. 20 year modified uniform present worth factors for electricity and natural gas as a function of real rate of return on investment, for CONAES A escalation rates and 10% inflation rate.

tive system costs to other systems. These incremental cost goals have been developed for specific systems and buildings in representative geographic locations. For example, two commercial systems (absorption and Rankine) with a 25-ton chiller servicing a building with a 25 ton peak cooling load have been modeled in Phoenix, AZ. The collector array has been sized to 150 m^2 (1614 ft^2) in each case, an area that made sense economically for these configurations. Using as a rule of thumb for driving a chiller a figure of 12 m^2 (130 ft^2) of collector area per ton of cooling, the collector array might appear to have been sized for approximately a 12.5 ton solar chiller. This array will certainly not be able to run the chiller at peak capacity. But the average chiller load will be 50% of the peak capacity or less for a large part of the cooling season, so the lower collector area makes economic sense in this situation.

The peak building load of 25 tons could be met in various ways: for example, by driving the solar chiller to 25 tons capacity with auxiliary energy input (a gas boiler for the absorption system and purchased electricity for the Rankine system), or by using a 12.5 ton solar chiller in parallel with a conventional electric or gas-fired chiller, with or without cold storage. The commercial analysis has been performed for cooling only. The additional economic benefit derived from using the same solar collection to provide heating has not been included in this preliminary analysis.

For the 3 ton residential system analyzed here, which includes cooling, heating, and hot water loads, economic considerations resulted in a collector area of 50 m^2 (538 ft^2), or 17 m^2/ton (179 ft^2/ton).

Thus this collector array should be capable of operating the chiller at full capacity.

Table 13 presents the incremental solar system cost goals, the cost goals per unit collector area and the cost goals per ton of cooling based on simulation analysis in Phoenix, Arizona.

Table 13. Incremental system cost goals (1980$), cost goals per unit collector area, and cost goals per ton of cooling. Analysis assumed CONAES A fuel escalation rates (Gas 5.7 %, Electricity 3.3 %), an inflation rate of 10 %, and a system life of 20 years. Represenative system performance based on Phoenix (gas 3.16 $/MBtu, electricity 19.29 $/MBtu).

		1980	1985	1986	1988	1990	1995	2000
PENETRATION GOAL	%	0.	0.	0.	2.8	5.9	12.8	20.
ROI GOAL B	%	0.	0.	0.	2.7	5.2	8.8	11.4
PAYBACK GOAL	YEARS	20.	20.	20.	16.3	13.4	10.5	8.9

INCREMENTAL SYSTEM COST GOALS

	1980	1985	1986	1988	1990	1995	2000
Phoenix 150 m^2 Rankine 12.5 ton solar	43600.	50500.	52000.	42200.	35700.	30900.	29800.
Phoenix 150 m^2 Absorption 12.5 ton solar	48500.	55900.	57500.	46600.	39400.	34000.	32500.
Phoenix 50 m^2 Absorption 3.0 ton	19200.	21600.	22100.	17800.	14900.	12600.	11700.

INCREMENTAL SYSTEM COST GOALS PER UNIT COLLECTOR AREA (ft^2)

	1980	1985	1986	1988	1990	1995	2000
Phoenix 150 m^2 Rankine 12.5 ton solar	27.0	31.3	32.2	26.1	26.1	22.1	18.5
Phoenix 150 m^2 Absorption 12.5 ton solar	30.0	34.6	35.6	28.9	24.4	21.1	20.1
Phoenix 50 m^2 Absorption 3.0 ton	35.7	40.1	41.1	33.1	27.7	23.4	21.7

INCREMENTAL SYSTEM COST GOALS PER UNIT COLLECTOR AREA (m^2)

	1980	1985	1986	1988	1990	1995	2000
Phoenix 150 m^2 Rankine 12.5 ton solar	291.	337.	347	281.	281.	238.	199.
Phoenix 150 m^2 Absorption 12.5 ton solar	323.	373.	383.	310.	262.	227.	217.
Phoenix 50 m^2 Absorption 3.0 ton	384.	432.	442.	356.	298.	252.	234.

INCREMENTAL SYSTEM COST GOALS PER UNIT SOLAR COOLING (tons)

	1980	1985	1986	1988	1990	1995	2000
Phoenix 150 m^2 Rankine 12.5 ton solar	3490.	4040.	4160.	3380.	3380.	2860.	2380.
Phoenix 150 m^2 Absorption 12.5 ton solar	3880.	4470.	4600.	3730.	3150.	2720.	2600.
Phoenix 50 m^2 Absorption 3.0 ton	6400.	7200.	7470.	5930.	4970.	4200.	3900.

D. SUBSYSTEM AND SYSTEM COSTS

The total solar cooling system cost goals for different locations can, in turn, be subdivided into subsystem cost and performance goals. Such a breakdown is not unique, in that the subsystem cost allocations can be individually varied as long as the overall system cost goal is achieved. It is anticipated that the major reductions in subsystem costs will be achieved by technical improvements in subsystem performance (e.g., increased chiller efficiency resulting in reduced collector subsystem array size), by improved performance through integration of chiller controls with the cooling load being served, by volume production economies, by improved packaging that will reduce system engineering and installation costs, and possibly by use of lower-cost materials.

Preliminary subsystem cost estimates for a residential system are shown in Figure 20 and Table 14. These values are based on estimates of current subsystem costs plus expectations for subsystem cost and performance improvements. Similar analyses have been done for commercial absorption and Rankine systems, as shown in Tables 15 and 16. Solar desiccant cooling systems are not yet well enough defined to allocate this type of detail at the subsystem level. Current costs of representative subsystems are based on the MITRE cost study[13] with adjustments to make the total system cost consistent with other estimates[14].

Principal major subsystems include: the collector subsystem, the energy transport subsystem, the storage subsystem, the heating

[13] "Systems Descriptions and Engineering Costs for Solar Related Technologies," Vol. II. MITRE Technical Report MTR-7485, June 1977
[14] "Evaluation of Thermal Storage Concepts For Solar Cooling Applications," Science Applications, Inc., DRAFT Final Report, January 1981.

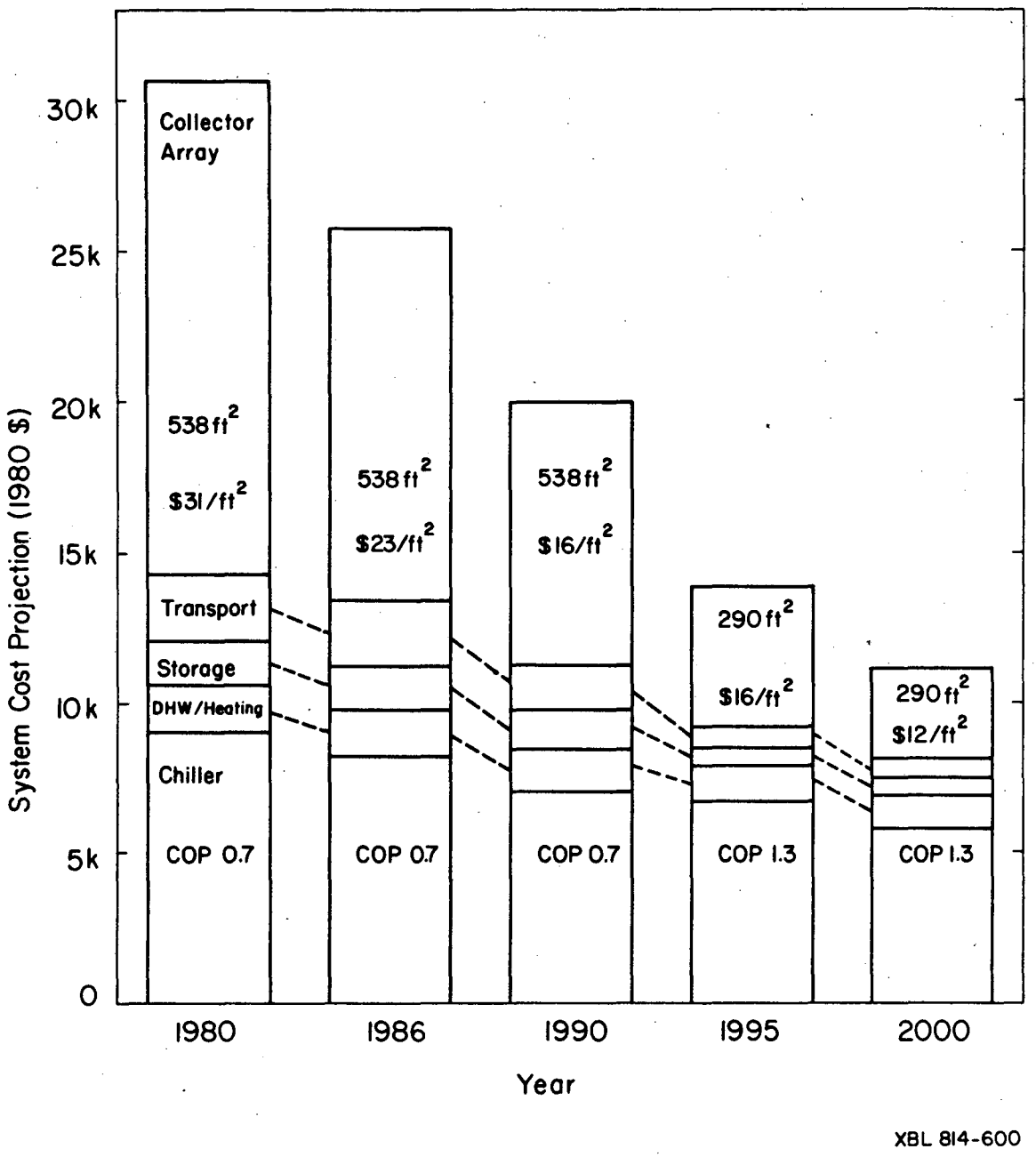

Figure 20. System and subsystem cost projections for a 3 ton residential absorption cooling, heating, and hot water system.

Table 14. Subsystem Costs and Cost Goals for Representative Residential 3-ton Absorption System (cooling, heating, and domestic hot water)

YEAR	1980	1986	1990	1995	2000
Chiller Coefficient of Performance	0.7	0.7	0.7	1.3	1.3
Operating Temperature (^oF)	190.	190.	190.	350.	350.
Collector Area (ft^2)	538.	538.	538.	290.	290.
Area Dependent Costs					
Collector Subsystem					
Collectors (1980 $/ft^2$)	$20.00	$15.00	$10.00	$10.00	$7.00
Installation Labor	3.00	2.00	2.00	2.00	2.00
Energy Transport Subsystem	3.10	3.10	2.00	2.00	2.00
Storage Subsystem	2.10	2.10	1.70	1.50	1.20
Area Dependent Costs	28.20	22.20	15.70	15.50	12.20
Overhead and Profit (35%)	9.80	7.70	5.50	5.40	4.30
Area Dependent Costs (1980 $/ft^2$)	38.00	29.90	21.20	20.90	16.50
Total Area Dependent Costs (1980 $)	20400.	16100.	11400.	6060.	4780.
Fixed Costs					
DHW (80 gal/day) Subsystem (1980 $)	280	280	200	200	200
Heating Subsystem	830	800	800	600	600
Chiller Subsystem	4120	3600	3000	3000	2500
Tower (Air Condensor)	1110	1100	1000	1000	800
Pump and Controls	1410	1400	1200	1000	1000
Total Fixed Costs	7750	7180	6200	5800	5100
Overhead and Profit (35%)	2710	2510	2170	2030	1790
Total Fixed Costs	10460	9690	8370	7830	6890
Total Area Dependent Costs	20400	16100	11400	6060	4780
Total Solar System Cost	30900	25800	19800	13900	11700
Conventional System Cost	3000	3000	3000	3000	3000
Incremental Solar System Cost	27900	22800	16800	10900	8700
Typical Incremental Residential Goal B		20000	13600	11500	10800
Required Solar Cooling Incentives ($)		2800	3200	-600	-2100
Required Solar Cooling Incentives (%)		11%	16%	0%	0%

Table 15. Subsystem Costs and Cost Goals for Representative 25 ton Commercial Absorption System (cooling only)

YEAR	1980	1986	1990	1995	2000
Chiller Coefficient of Performance	0.7	0.7	0.7	1.3	1.3
Operating Temperature (^oF)	190.	190.	190.	350.	350.
Collector Area (ft^2)	1600.	1600.	1600.	860.	860.
Area Dependent Costs					
Collector Subsystem					
Collectors (1980 $/ft^2)	20.00	15.00	10.00	10.00	8.00
Support	5.00	5.00	4.00	4.00	3.00
Installation Labor	3.00	3.00	2.00	2.00	2.00
Energy Transport Subsystem	2.40	2.40	2.40	2.40	2.40
Storage Subsystem	1.60	1.60	1.60	1.60	1.60
Area Dependent Costs	32.00	27.00	20.00	20.00	17.00
Overhead and Profit (35%)	11.20	9.45	7.00	7.00	5.90
Area Dependent Costs (1980 $/ft^2)	43.20	36.45	27.00	27.00	22.90
Total Area Dependent Costs (1980 $)	69100.	58300.	43200.	23200.	19700.
Fixed Costs					
Chiller Subsystem					
Chiller	13300	12000	11000	10500	10000
Tower	4000	4000	3750	3750	3500
Pumps and Controls	9000	9000	8000	8000	7000
Other Fixed Costs	4000	4000	3750	3750	3500
Fixed Costs Subtotal	30300	29000	26500	26000	24000
Overhead and Profit (35%)	10600	10150	9300	9100	8400
Total Fixed Costs	40900	39200	35800	35100	32400
Total Area Dependent Costs	69100	58300	43200	23200	19700
Total Solar System Cost	110000	97500	79000	58300	52100
Conventional System Cost	25000	25000	25000	25000	25000
Incremental Solar System Cost	85000	72500	54000	33300	27100
Typical Incremental Commercial Cost Goal B		52000	35700	30900	29800
Solar Cooling Tax Incentives Required ($)		20500	18300	2400	-2700
Solar Cooling Tax Incentives Required (%)		21%	23%	4%	0%

Table 16. Subsystem Costs and Cost Goals for Representative 25 ton Commercial Rankine System (cooling only).

YEAR	1980	1986	1990	1995	2000
Chiller Coefficient of Performance	0.7	1.0	1.2	1.4	1.5
Operating Temperature (°F)	300.	350.	400.	450.	500.
Collector Area Required (ft^2)	1600.	1130.	940.	800.	750.
Area Dependent Costs					
Collector Subsystem					
Collectors (1980 $/ft^2$)	20.00	20.00	15.00	15.00	10.00
Support	5.00	4.00	4.00	3.00	3.00
Installation Labor	3.00	3.00	2.00	2.00	2.00
Energy Transport Subsystem	2.40	2.40	2.00	2.00	2.00
Storage Subsystem	3.00	3.00	2.00	2.00	2.00
Area Dependent Costs	33.40	32.40	25.00	24.00	19.00
Overhead and Profit (35%)	11.70	11.34	8.75	8.40	6.65
Area Dependent Costs (1980 $/ft^2$)	45.10	43.70	33.75	32.40	25.65
Total Area Dependent Costs (1980 $)	72100.	49400.	31700.	25900.	19200.
Fixed Costs					
Chiller Subsystem					
Chiller	32000	28000	24000	22000	20000
Tower (Air coil)	4000	4000	2000	1500	1000
Pump and Controls	3000	2500	2500	2000	2000
Other Fixed Costs	4000	4000	3500	3000	2500
Fixed Costs Subtotal	43000	38500	32000	28500	25500
Overhead and Profit (35%)	15000	13500	11200	10000	8900
Total Fixed Costs	58000	52000	43200	38500	34400
Total Area Dependent Costs	72100	49400	31700	25900	19200
Total Solar System Cost	130000	101000	74900	64400	53600
Conventional System Cost	25000	25000	25000	25000	25000
Incremental Solar System Cost	105000	76000	49900	39400	28600
Typical Incremental Commercial Cost Goal B		52000	35700	30900	29800
Solar Cooling Tax Incentives Required ($)		24000	14200	8500	-1200
Solar Cooling Tax Incentives Required (%)		24%	19%	13%	0%

subsystem, the domestic hot water subsystem, and the chiller subsystem. The collector subsystem includes the collectors with mounting structure and installation, piping and insulation. The energy transport subsystem includes loop piping, fittings, insulation, pumps, valves, heat exchangers, fluids, electrical work, and controls. The storage subsystem includes hot or cold sensible or latent heat storage. The chiller subsystem could include a Rankine chiller with auxiliary motor and cooling tower, an absorption chiller with auxiliary boiler and cooling tower, or a desiccant chiller subsystem; in each case, the appropriate chiller pumps and controls are included.

Performance Improvements. Technical improvements in subsystem performance are anticipated. For the residential 3 ton absorption chiller and for the commercial 25 ton absorption chiller, the current coefficient of performance (COP) of about 0.7 should stay relatively constant until the development and introduction of double effect absorption chillers in these sizes, at which time the COP should increase to about 1.3. For the commercial 25 ton Rankine chiller, the current coefficient of performance of about 0.7 should increase gradually to about 1.5 if the operating temperature is increased to about 500 ^{o}F.

The size of the collector array is dependent on the COP of the chiller. At a COP of 0.7, a peak heat input of 430 kBtu/hr is needed to operate a chiller at 25 tons. With a solar input of 300 Btu/hr-ft^2, and a collector efficiency of 45%, the collector area required to drive the chiller at full capacity is about 130 ft^2/ton. As the COP of the chiller is increased the required energy collection and collector area will be reduced accordingly. For example, if the COP were increased

from 0.7 to 1.3, and if the collector efficiency could be maintained at 45%, then the required collector area would drop from 130 ft^2/ton to 70 ft^2/ton.

Collector Array Costs.

The collector array is one of the major cost items of any active solar cooling system. The key to cost effective cooling systems is reduced collector array costs. For residential systems with less than about 50 m^2 (500 ft^2) of collector, the collectors are mounted directly on the roof, and no support structure is needed. For commercial systems a support structure is needed. In retrofit situations, where the collector array must be tied to the building's structural members at odd orientations, the cost of the support structure can be as much as the collectors themselves. The collector cost projections for commercial absorption solar cooling systems that were included in Table 15 are broken out separately in Table 17.

Table 17. Collector cost projections for commercial absorption solar cooling systems.

COST	(1980$)/$ft^2$				
YEAR	1980	1986	1990	1995	2000
Collectors	20	15	10	10	8
Support structure	5	5	4	4	3
Installation Labor	3	3	2	2	2
Overhead and profit (35%)	10	8	6	6	5
Total	$38/$ft^2$	$31/$ft^2$	$22/$ft^2$	$22/$ft^2$	$18/$ft^2$

For the high temperature, high COP future scenario, either evacuated tubes with reflectors or cylindrical trough collectors will likely be used. Collector manufacturing costs of $14.27/$ft^2$ (1980$) have been projected [15] for evacuated tube concentrating collectors. A key to

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typical absorption chiller driving temperature of about 185°F. Work underway at Brookhaven National Laboratory[18] is directed toward the development of solar collectors that might possibly meet these types of cost and performance requirements.

A recent study [19] projects that, with volume production by a single manufacturer of greater than 200,000 collector panels per year and automation of the production lines, the manufactured cost of panels could drop to $10.60/ft^2 for flat plates and to $6.50/ft^2 for evacuated tube collectors. This is consistent with the collector costs by the year 2000 assumed in this report.

Chiller Costs.

The absorption chiller subsystem costs reflect recent cost projections by ARKLA, Yazaki, and others. The cost projections for Rankine chillers are based on a recent technical report by Carrier.[20]

[18] Bill Wilhelm, Brookhaven National Laboratory. Private Communication.
[19] A. S. Jacobsen and P. D. Ackerman, "Cost Reduction Projections for Active Solar Systems," Proceedings of the AS/ISES Conference, Philadelphia, PA, 27-30 May 1981, pp. 1291-1295.
[20] "Development of a High Temperature Solar Powered Water Chiller," Carrier Corporation, Energy Systems Division, Phase II, Technical Progress Report, June 1978- March 1979.

Volume Production. Developing packaged and standardized subsystems will reduce system engineering and installation costs. The price history of the residential heat pump shown in Figure 21 indicates that significant price reductions can and did occur with increases in production volume and accumulation of experience ("learning curve" effects). Projections by Westinghouse[17] and others [21,22] have estimated collector and system cost savings that can be achieved through volume production.

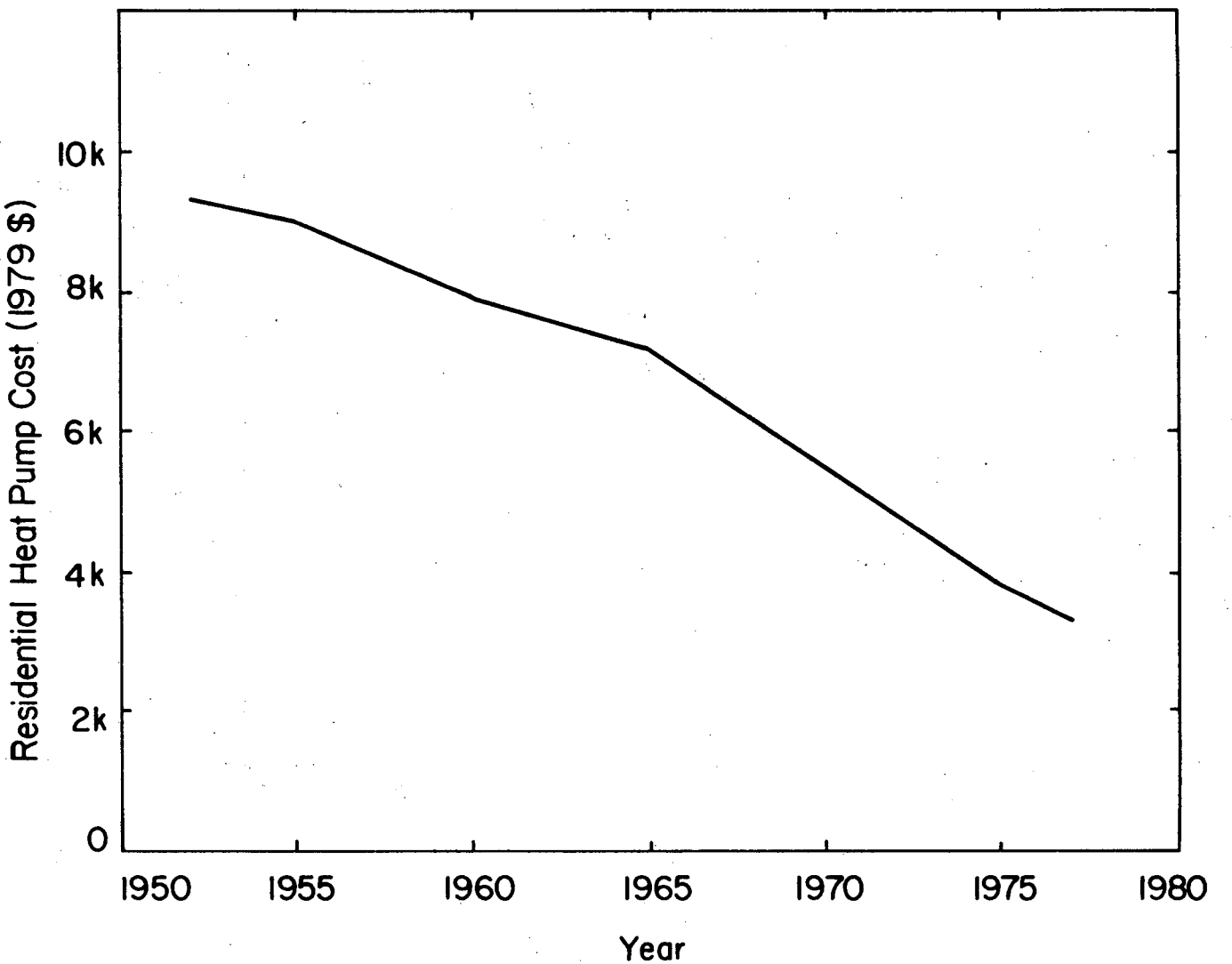
E. COMPARISON OF COSTS WITH COST GOALS

As shown previously in Figure 20, the projected system costs for any given year are obtained from the combined estimates of cost and performance of the subsystems. The projected incremental costs of the solar system are obtained by subtracting the cost of the conventional system from the active solar system that replaces it. The incremental projected solar system costs and the comparison of these costs with cost goals for a residential system are shown in Figure 22. The incremental projected solar system costs and cost goals for commercial systems are plotted in Figures 23 and 24. The data plotted in these three figures are contained in Tables 14, 15, and 16.

For a residential solar cooling and heating system, Figure 22 indicates the approach over time of the projected system cost to the cost goals. The difference between projected cost and cost goal indicates a typical variation over time of the anticipated solar cooling tax

[21] A. S. Jacobsen and P. D. Ackerman, "Cost Reduction Projections for Active Solar Systems," Proceedings of the AS/ISES Conference, Philadelphia, PA, 27-30 May 1981, pp. 1291-1295.
[22] Steven A. Hass and Alan S. Jacobsen, "Evaluation of Residential and Commercial Solar/Gas Heating and Cooling Technologies," Final Report for 1980, Vol. 1 - Program Overview and Vol. 2 - Final Report, Gas Research Institute Report GRI-79/0150, December 1980.

Figure 21. Cost of residential heat pump systems normalized to (1979$) by the Consumers Price Index shows a 64% price reduction from 1952 to 1977. Price data from Planco, Inc.



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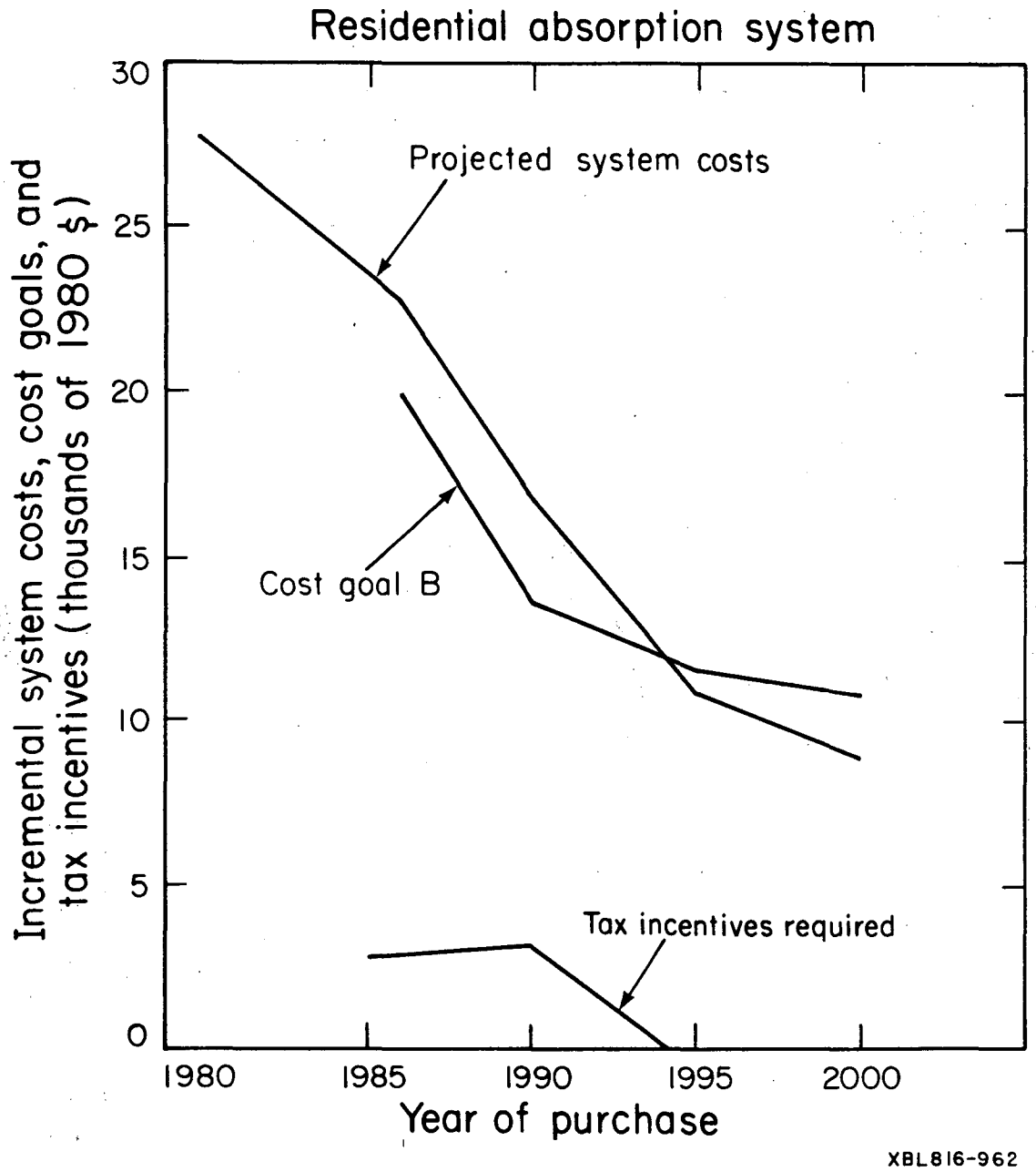

Figure 22. Typical incremental solar system cost goals, projected system costs and required tax incentives for a 3 ton residential system as a function of year of purchase to achieve a 20% market penetration in the year 2000.

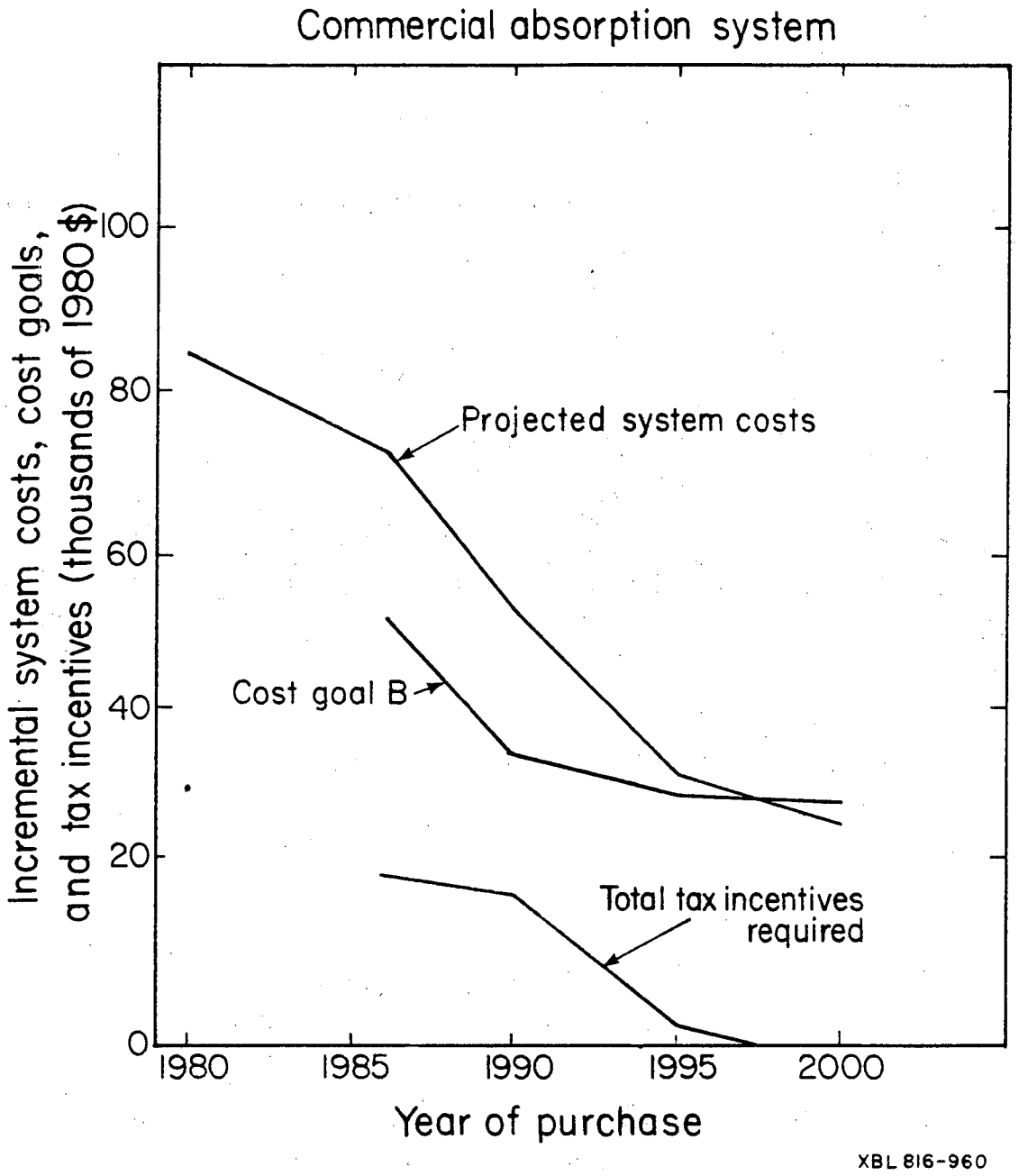

Figure 23. Typical incremental solar system cost goals, projected system costs, and required tax incentives for a 25 ton commercial system (absorption) as a function of year of purchase to achieve a 20% market penetration in the year 2000.

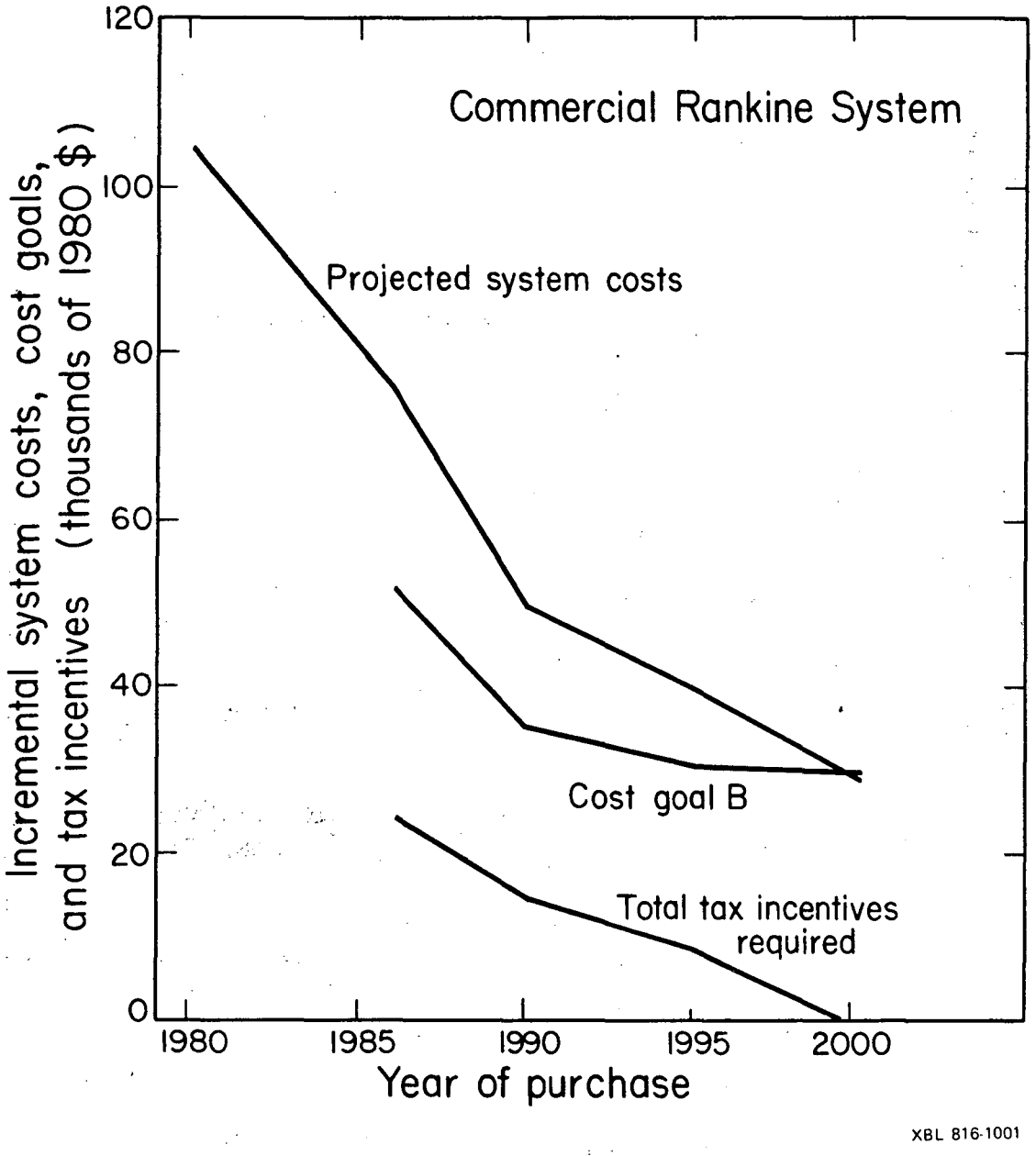

Figure 24. Typical incremental solar system cost goals, projected system costs, and tax incentives for a 25 ton commercial system (Rankine) as a function of year of purchase to achieve a 20% market penetration in the year 2000.

incentive that would be needed to achieve the desired residential consumer cost goals and market penetration. Quantitatively, this projected tax incentive must be considered very preliminary at this time. The total incentive would consist of a combination of incentives by federal and state governments and by utility companies.

Figures 23 and 24 describe similar costs, cost goals, and resulting tax incentives over time required for commercial solar absorption and Rankine systems, respectively. Energy property as defined by the tax code[23] may qualify for both the 10% Investment Tax Credit, and for the Business Energy Investment Credit. For solar and wind energy property the business energy investment credit is 15% through 1985. To qualify for the investment tax credit, however, the investment must be in "tangible personal property other than an air conditioning or space heating unit." Thus solar cooling/heating systems are explicity excluded from benefitting from the investment tax credit. The required solar cooling system tax incentive would decrease to zero by about 1997.

As the solar cooling technology progresses toward its cost and performance goals between now and the year 2000, incentives (tax credits or similar methods) will be necessary to bridge the gap between current costs and cost goals. It is important to note that present business energy investment credits are scheduled to expire before they can benefit the introduction of solar cooling systems in the marketplace and that cooling and heating systems are excluded from the investment tax credit. An extension of the energy and investment tax credits specifically to assist solar cooling would be necessary. Such solar cooling

[23] IRS Publication 572, "Investment Tax Credit."

system tax credits would be expected to decrease over time, and would reflect the difference between the value of solar cooling to the private sector (the individual purchaser) and its value to the public sector (reduction of dependence on non-renewable energy resources).

F. NON-ECONOMIC FACTORS.

Factors other than economics have assisted in the early market development and penetration of new technologies; e.g., heat pumps were marketed in the early 1950's and achieved a sizeable penetration of the market with only a small, 3-6%, return on investment. For solar these factors might include the belief that use of renewable solar energy will help the nation achieve energy independence and that solar energy will protect against rationing and interruption of energy supplies. Attitudes about solar's long and short term social acceptability are also important. "Consumers need to hear that there is a 'band wagon' for them to get on; they need to be convinced that though solar is not widespread now, it will be used on more and more homes as the years go by."[24]

[24] Gary L. Lilian and Paul E. Johnston, "A Market Assessment for Active Solar Heating and Cooling Products, Category B: A Survey of Decision Makers in the HVAC Market Place," Final Report OR/MS Dialogue, Inc. Contract AC03-79CS-30209, September 1980. Page 3-123.

G. PRODUCTION REQUIREMENTS

Meeting the year 2000 market penetration goal of 20% of the air conditioning market will require substantial production capacity. However, this production capacity represents a relatively small portion of the total air conditioning market and can be provided by the same well-developed HVAC industry. Production need not be a significant limitation to industry growth. The production of solar components for active solar cooling, such as the collector arrays, will be stimulated by the solar domestic hot water and solar space heating industry.

The total residential market for active solar cooling systems includes new single family construction, new multiple-family construction, as well as existing residential replacement and retrofitting. Estimated residential air conditioning shipments from 1980 to 2000 for the south and west are about 1 925 000 units per year [25]. Assuming the average residential air conditioning market of 1 925 000 units/yr, one can project the production volumes required to meet a 20% market penetration in the year 2000. We assume that the market begins with zero penetration in 1986, increasing uniformly to the postulated value of 20% in the year 2000. The estimated production capacity required to meet this market is shown in Table 18.

[25] "Assessment of Active Solar Air Conditioning 1980-2000," Draft Report, Planco, Inc., January 1981.

Table 18. Residential unit production requirements to meet market penetration goals.

Production of residential units to meet 10 % market penetration by 2000.

Year	UNITS	1986	1988	1990	1995	2000
Penetration	%	0	1.4	2.9	6.4	10
Production Required	units	0	27 000	55 800	123 000	192 500

Production of residential units to meet 20 % market penetration by 2000.

Year	UNITS	1986	1988	1990	1995	2000
Penetration	%	0	2.8	5.7	12.9	20
Production Required	units	0	53 900	109 700	248 000	385 000

The total commercial market for active solar cooling systems can be estimated from the Planco "Survey of the HVAC market [26]." The breakdown by capacity range in the commercial market is shown in Table 19. Based on projections of historical trends, the total annual commercial air conditioning shipments for 1985 will be about 394 000 units. The market is expected to be relatively constant through the year 2000.

[26] "Survey of the HVAC Market," Draft Report, Planco, Inc., August 1980.

Table 19. Production of commercial units required to achieve a 20 % penetration of the commercial market in the year 2000 is shown by capacity range. This assumes constant production from 1985 to 2000. The table is based on Table 2-7,"Projections of 1985 cooling shipments by unit capacity ranges," from "Survey of the HVAC Market," Planco, Inc., August 1980, adjusted to remove residential units from the 2.3 - 5.4 ton range.

Production Required to meet 20% market penetration by 2000.

Year				1986	1988	1990	1995	2000
Market Share(%)			100.	0	2.8	5.7	12.9	20
Capacity (tons)	Total cap. (ktons)	Total No. of Units	Average cap. (tons)	Number of Units				
2.3 - 5.4	826	265 000	3.1	0	7 400	15 100	34 200	53 000
5.5 - 15.4	819	109 000	7.5	0	3 000	6 200	14 000	21 800
15.5 - 31.6	181	10 000	18	0	300	600	1 300	2 000
31.7 - 53.3	125	4 000	31	0	110	230	520	800
53.4 - over	1 112	6 000	185	0	170	340	770	1 200
Total	3 063	394 000			10 980	22 470	50 790	78 800

H. SUMMARY

A consistent methodology has been presented here by which general solar cooling market penetration goals can be and have been translated into specific cost and performance goals for solar cooling systems and subsystems.

The preliminary figures shown in this paper indicate that realistic cost/performance goals can be established for active solar cooling systems. Moreover, the preliminary estimates of projected subsystem cost and performance indicate that these goals can be approached before the year 2000. In the meantime, tax incentives would be required to bridge the gap between the actual costs and the cost goals, so that an ever-increasing share of market penetration can be achieved over the 1986 to 2000 time period. These tax incentives would gradually decrease over time, being phased out completely by the year 2000.

It must be emphasized that the data used in this paper, although the best available at this time, are nonetheless still only preliminary. Efforts are currently underway to acquire better estimates of the market penetration vs. payback relationship, better estimates of cost and performance projections, and more realistic models of the thermal performance of the cooling systems.

Finally, this methodology for establishing cost goals and identifying cost and performance improvements necessary to reach these goals is not limited to active solar cooling applications, but can equally well be used for other technologies such as passive cooling and heating.

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