Natural Gas Heat Pump Implementations and Development

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ABSTRACT

The following paper discusses the demands on the supplies of natural gas in the United States and the necessity to develop energy conserving appliances such as the gas heat pump. An evaluation of various approaches to implementing a gas heat pump is discussed. The result of this evaluation is the selection of a Stirling engine driving a Rankine vapor-compression refrigeration cycle. The development activity associated with a program jointly sponsored by the American Gas Association, U.S. Department of Energy, Gas Research Institute and General Electric Co., is discussed. The current status as well as expected performance and configuration trends are also presented.

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INTRODUCTION

The elements of future gas supply can be catalogued under three main headings:

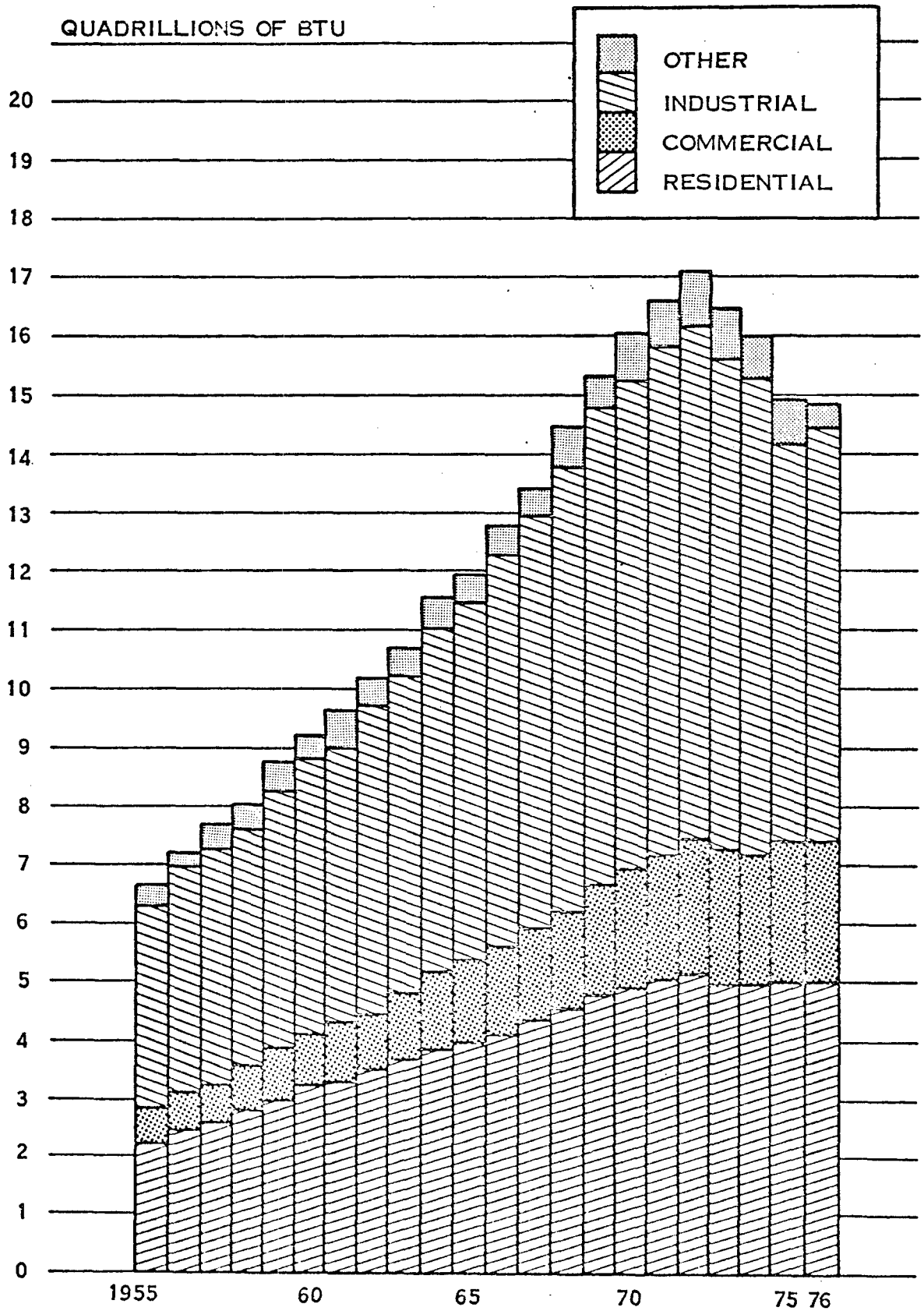
1. Production from conventional natural sources, both onshore and offshore.
2. Development of supplemental gas supplies, including gas from Canada and Mexico, SNG from petroleum-based feedstocks, imported LNG, and Alaskan gas.
3. Gas from unconventional or exotic sources resulting from an aggressive research, development, and demonstration program.

The first two categories are the only near-term options available. The long lead times required to research and develop new technologies make it unlikely that significant supplies from unconventional sources will become available much before the end of this century.

Paradoxically, the limits of conventional sources are finite, and it is the unconventional which may, in the long run, be the sustaining source of gaseous energy available to the industry and the nation.

A close look at gas sold, by class of service (Figure 1), shows that nationally the industry is experiencing a near zero growth in the residential and commercial sectors and a definite negative growth in the industrial area. This decline, which has totaled nearly 2 trillion cubic feet (Tcf) since 1972, has recently shown signs of leveling off. For the immediate future, increased production from conventional sources is the only means of reversing this trend. Over the next five to ten years a lot also depends on Federal energy policies which will encourage new exploration and production both on and offshore.

FIGURE 1 GAS UTILITY INDUSTRY SALES BY CLASS OF SERVICE


QUADRILLIONS OF BTU
OTHER
INDUSTRIAL
COMMERCIAL
RESIDENTIAL
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
1955
60
65
70
75 76

Even though the annual production of natural gas has declined since 1972, there is still a significant resource base of conventional gas. All the major estimates (Table 1) of remaining recoverable gas in the U.S. agree that there is approximately 700 - 1300 Tcf of gas that could be produced. At a consumption rate of 20 Tcf/yr., there are between 35 - 65 years of conventional gas supply remaining to be produced. The judicious use of this supply will give sufficient lead time to validate the potentially vast supplies from unconventional sources.

Table 1

NATURAL GAS:
REMAINING RECOVERABLE U.S. RESOURCES (TCF)

	Year of Estimate	1976 Estimated Proved Reserves	Total Remaining Resources
U.S. Coast Guard	1974	228	752-1085
National Academy of Sciences	1974	228	876
Exxon-Base	1974	228	651-1371
Mobil	1973	228	736
Potential Gas Committee	1972	228	1374

The potential supply of unconventional gas far exceeds proven reserves and even potential resources of conventional gas (Table 2). While these estimates are large, the majority of the research efforts being devoted to develop these unconventional supplies are presently small. For this reason, we cannot expect to realize any significant quantities of gas from these sources before 1995.

They all represent high technology areas which require significant investments per unit of net energy output. Until these technologies are proven, we must continue to rely upon the conventional resource base, and quite frankly, this is the only near-term option.

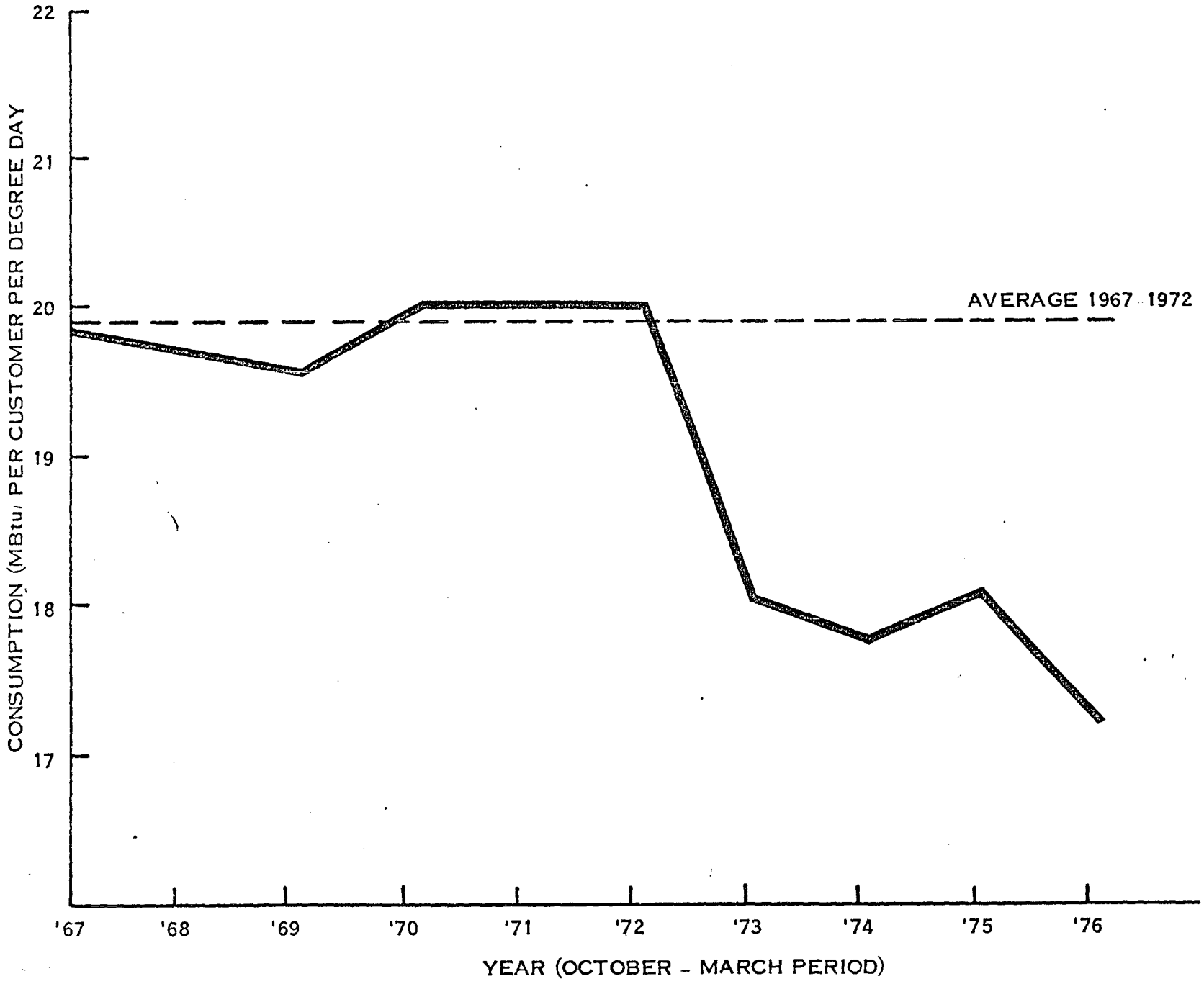
Table 2

FUTURE TECHNOLOGICAL OPTIONS

Resource	Estimated Resource Base (Tcf)
Geopressured Resources	3 - 50,000
Coal Seams	300 - 800
Tight Formations	
- Devonian Shale	500 - 600
- Rocky Mountains	600
Coal Gasification	500
Oil Shale Gasification	464
Biomass (Renewable)	
- Marine	20/Yr.
- Land	7-11/Yr.
Methane from Waste	1/Yr.

The U.S. has had an historic habit for using its inexpensive gas energy resources with a high degree of extravagance. As this resource has become more scarce, its price has risen and consumers have tended to look for ways to either use less, i.e. conversation, or to use it more efficiently. At the same time, higher prices have now encouraged producers to search for more gas.

FIGURE 2 U.S. RESIDENTIAL GAS SPACE HEATING CONSUMPTION PER CUSTOMER PER DEGREE DAY


22
21
20
19
18
17
CONSUMPTION (MBtu) PER CUSTOMER PER DEGREE DAY
AVERAGE 1967 1972
'67
'68
'69
'70
'71
'72
'73
'74
'75
'76
YEAR (OCTOBER - MARCH PERIOD)

Conservation - Conservation has become an important national goal, but conservation implies doing without and there is a limit to the amount of gas energy that can be saved in this manner. A significant level of conservation, however, has been achieved in the residential gas space heating market since 1973[1] through increased insulation, lowering thermostats, etc. Consumption per customer per degree day was about 9 - 10 percent less during the winters of 1973, 1974 and 1975, and 13 percent less in 1976. Figure 2 shows the trend in residential gas space heating consumption during the past ten years, expressed in the form of consumption per customer per degree day. Any significant shift in this "index" is considered to be representative of a change in the non-degree day related consumption pattern or as a relative measure of the amount of conservation achieved.

Natural gas continues to heat more residences in the U.S. than any other fuel.[2] Some 42.3 million house heating units of the over 74 million total used gas at year end 1977. While the rate of growth of gas house heating units has declined since 1973 due to the imposition of restrictions on expanded use of gas, the share of the house heating market represented by gas has continued to grow. Currently gas has a 57 percent share of the house heating market, up slightly from 56 percent in 1973 and 55 percent in 1970.

Efficiency - While the habit of extravagant use of gas in the U.S. has been stemmed and gains made from conservation efforts, substantial energy savings can only be brought about by the use of more efficient equipment. Approximately 40 percent of the total amount of natural gas retailed is sensitive to heating system technology. It is clear that an improvement in heating and cooling technology will have a significant impact nationally on the consumption

of natural gas. The impact of new technological advances in heating/cooling systems will be more than twice as great as technological advances in any other gas market segment.

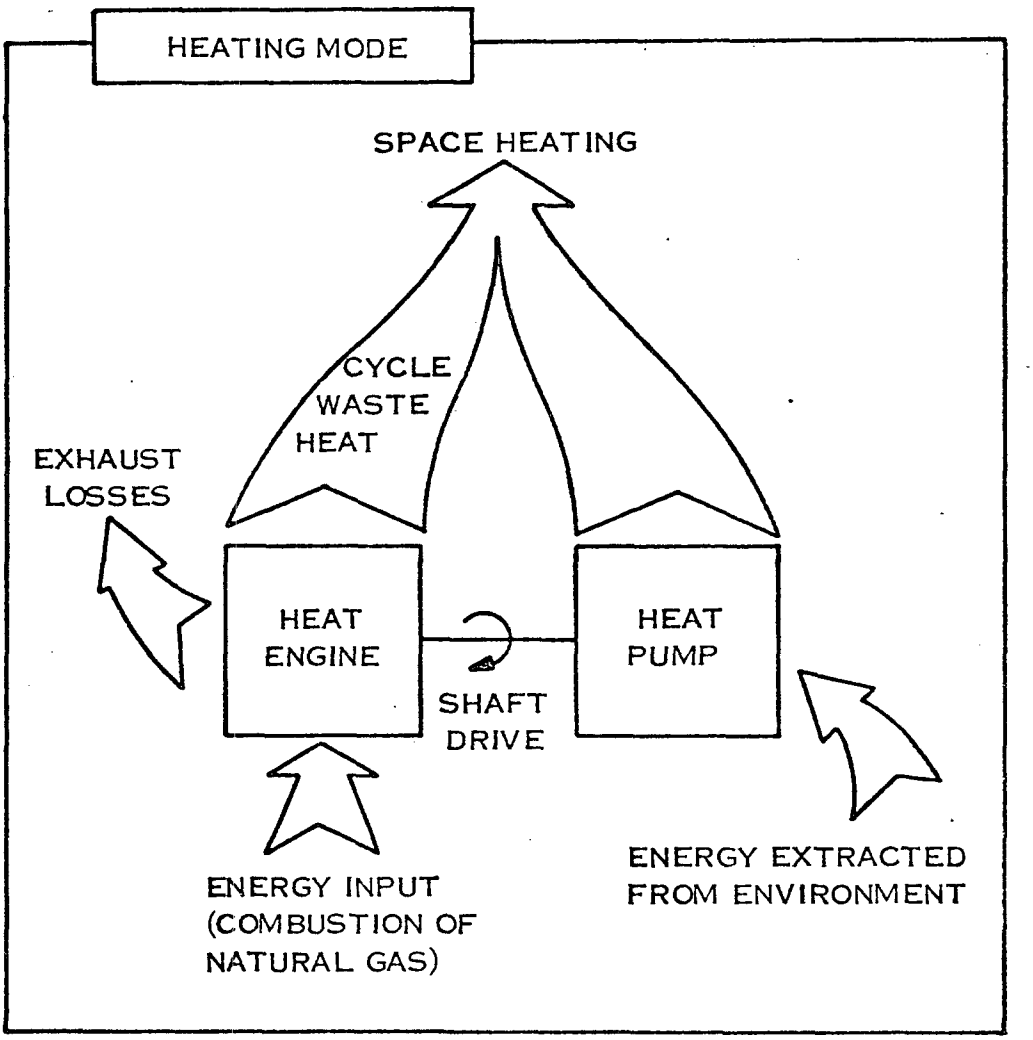
The seasonal efficiency of a properly sized, properly installed conventional gas furnace is about 65 percent and the COP of electric air conditioners is about 0.6 to 0.8 (referred to primary source efficiency). As compared to a contemporary gas furnace/electric air conditioner system, it is estimated that gas heat pumps can improve the overall seasonal gas utilization by a factor of 2.0. The development of gas heat pump technology is, therefore, considered essential and has been accorded high priority by the U.S. gas industry.

The following sections of this paper discuss some possible gas heat pump implementations and describe the status of the Stirling/Rankine heat pump development.

CONCEPT

The concept of a natural gas driven heat pump is most commonly characterized by replacing the electric motor of a conventional heat pump with a heat engine. The concept is shown schematically in Figure 3. In the heating mode, the energy extracted from the environment by the heat pump cycle can be supplemented by the waste heat from the heat engine. This enhances the performance of the unit over conventional, on-site heating equipment and allows use of waste heat otherwise lost in the central station generation of electricity. In the cooling season, the relative performance of the unit depends upon the efficiency of the drive implementation. The engine waste heat may be rejected to the environment or used to provide such ancillary services as hot water heating. Furthermore, as in the case of electrically driven equipment,

FIGURE 3 GAS HEAT PUMP CONCEPT


HEATING MODE
SPACE HEATING
CYCLE
WASTE
HEAT
EXHAUST
LOSSES
HEAT
ENGINE
HEAT
PUMP
SHAFT
DRIVE
ENERGY INPUT
(COMBUSTION OF
NATURAL GAS)
ENERGY EXTRACTED
FROM ENVIRONMENT

the concept lends itself to future integration with solar energy.

The activity discussed in this paper concerns the development of a natural gas fired heat pump to provide heating and cooling services. Integration with hot water heating and solar heating will be considered in the future.

Requirements - In 1975, General Electric in conjunction with the American Gas Association (AGA) undertook an evaluation of the potential of a natural gas heat pump product. It was judged that the product should provide heating and cooling capability consistent with the U.S. market for gas year-'round equipment. In addition, the product was envisioned as a unitary product, assembled and delivered to the installation site, as opposed to a unit specifically engineered for a given application.

In order to maximize the market potential of the product, the unit was targeted to be applicable to most climatic regions of the United States. This implies the capability to accommodate a wide range of heating/cooling ratios consistent with the conditions encountered over the range of conditions from the southern to northern portions of the U.S. An initial goal of a heating-to-cooling ratio of 2.0:1 was envisioned.

In terms of market segment, the product was envisioned to be applicable to both residential and small commercial applications. As a consequence, large high-rise buildings such as office buildings, hotels and auditoriums were excluded as possible applications. The range of possible model sizes, as characterized by the cooling capacity, is specified to be in the range of 2 to 30 tons (24,000 to 360,000 BTU/Hr).

In order to facilitate the introduction of the product into the Heating,

Ventilating and Air Conditioning (HVAC) market, several qualitative requirements were imposed on the concept. The useful life of the unit is required to be 15 years or more, consistent with current electrically driven product goals. Maximum use of currently available refrigeration equipment was envisioned to maximize the availability of replacement parts and provide the maximum of familiarity with possible service operations. This requirement also impacts the overall goal of minimizing additional service training which is of considerable impact to overall product feasibility and acceptability.

As a goal, the size of the unit was specified to be similar to currently available electrically powered HVAC products. It was recognized that, with the incorporation of power generation equipment, additional size and volume was likely to be required. However, in light of the emphasis on more energy efficient equipment, the size requirement was considered realistic when compared to electrically driven equipment of the future.

Similarly, the noise and emissions associated with operation of the equipment was required to be consistent with current industry practice as well as the increased stringency of anticipated regulations.

Implementation - In order to implement the concept previously described, a variety of drives are feasible. An extensive matrix of possible combinations of heat engines and refrigeration cycle-implementations was generated and evaluated. In terms of heat engine options, the selections include Rankine, Brayton and Stirling cycles as well as Internal Combustion engines such as Diesel and Otto cycles. The most commonly used refrigeration cycle is the Rankine vapor compression cycle which was deemed applicable to all heat engines considered. The Brayton cycle was considered as being uniquely compatible with

the Brayton heat engine. The Stirling refrigeration cycle was deemed to require excessive development in order to be considered compatible with the requirements of the envisioned product development.

In addition to the conventional approaches already described, the use of an absorption pair implementation was considered.

While evaluating each of the possible approaches, both centrifugal and positive displacement equipment was evaluated for the heat engine and refrigeration equipment. Evaluation of the absorption pair implementations included both the aqua-ammonia pair and advanced organic fluids under development by AGA.

Performance - Evaluation of the candidate implementations against the established requirements yielded the four options shown in Table 3. These concepts were considered the most attractive potential implementations of the Gas Heat Pump.

Table 3

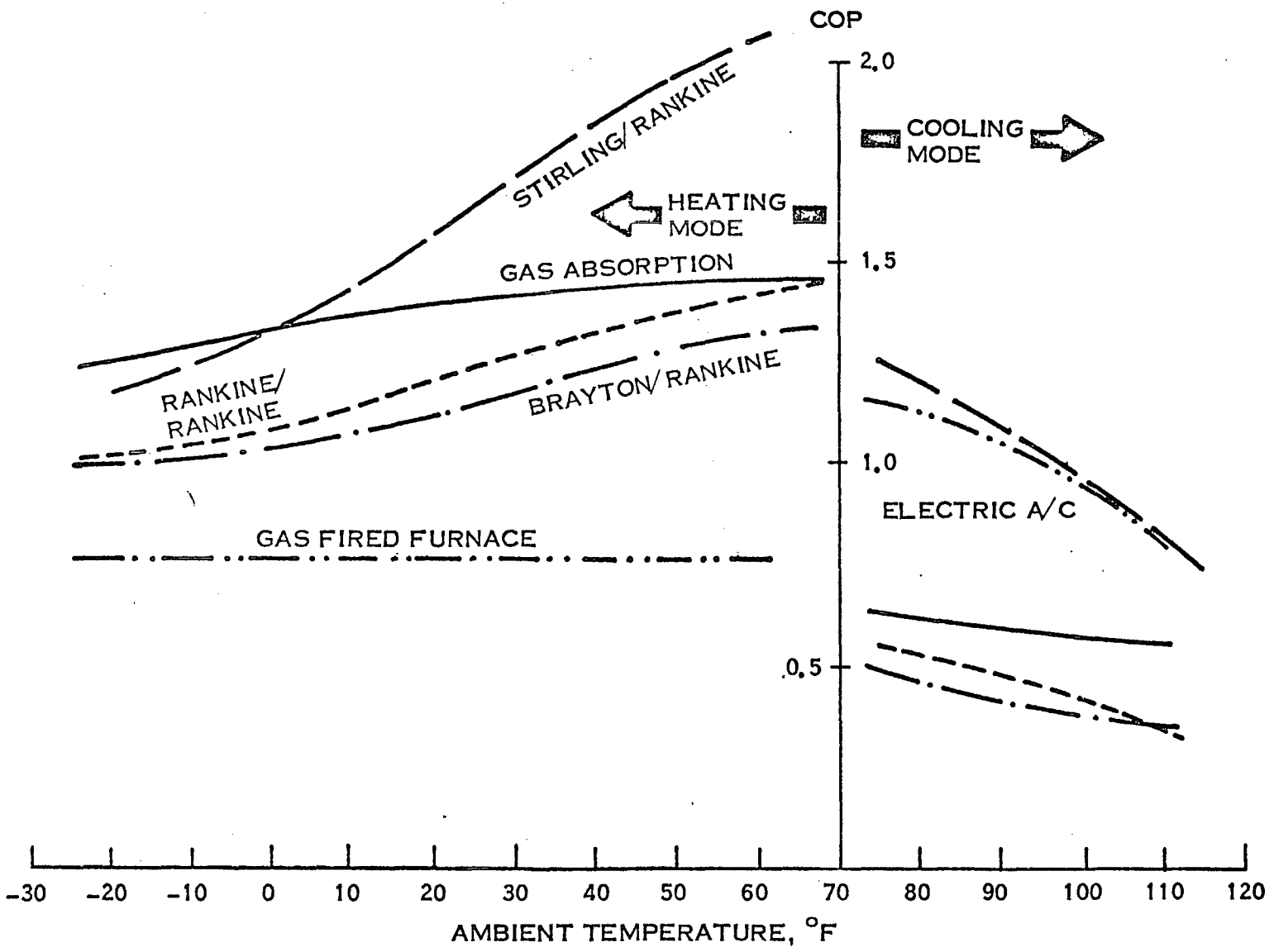
PRELIMINARY IMPLEMENTATION SELECTION

Heat Engine	Refrigeration Loop
Brayton Engine	Rankine Vapor Compression
Rankine Engine	Rankine Vapor Compression
Stirling Engine	Rankine Vapor Compression
Absorption Pair	Absorption Pair

Those combinations eliminated from further evaluation were rejected primarily because of qualitative evaluation of the ability to meet noise and servicing criteria as well as performance.

Figure 4 illustrates the relative performance, in heating and cooling, of the selected concepts. Performance is depicted in terms of Coefficient of Performance

FIGURE 4 RELATIVE CONCEPT PERFORMANCE


COP
2.0
1.5
1.0
0.5
COOLING MODE
HEATING MODE
STIRLING/RANKINE
GAS ABSORPTION
RANKINE/ RANKINE
BRAYTON/RANKINE
GAS FIRED FURNACE
ELECTRIC A/C
-30
-20
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
AMBIENT TEMPERATURE, °F

(COP). COP is defined as the product capacity (Heating capability or Cooling capability) divided by the heat energy input required. Parasitic power for fans and pumps is neglected in this calculation. As a measure of relative performance, the performance of an improved gas furnace is shown for the heating mode. Similarly, the performance of an improved electrically powered air conditioner is shown in the cooling season range of ambient temperatures.

These preliminary evaluations of relative performance as compared to the gas furnace/electric air conditioner were instrumental in evaluating the operating cost performance of the respective configurations. Since the gas heat pump is expected to have additional equipment, when compared to a gas furnace/electric air-conditioner implementation, the operating cost saving is an important consideration in off-setting initial cost and, therefore, influences the market application and attraction of this equipment.

Figure 5 illustrates the operating cost savings over the reference system (improved gas furnace/improved electric air-conditioner) for various regions of the United States for each of the four selected concepts. This example is shown for the residential application although similar comparisons were prepared for the commercial application as well. As can be seen, a gas heat pump of 3-ton capacity would be expected to save as much as $240/year in operating costs in the Philadelphia region of the United States.

Application - In evaluating the individual concepts, three items are of prime importance: Performance (as measured by operating cost savings); the applicable market (residential or commercial); and the regional application in the United States. Table 4 illustrates the relative ranking of the concepts considered.

FIGURE 5 OPERATING COST SAVINGS

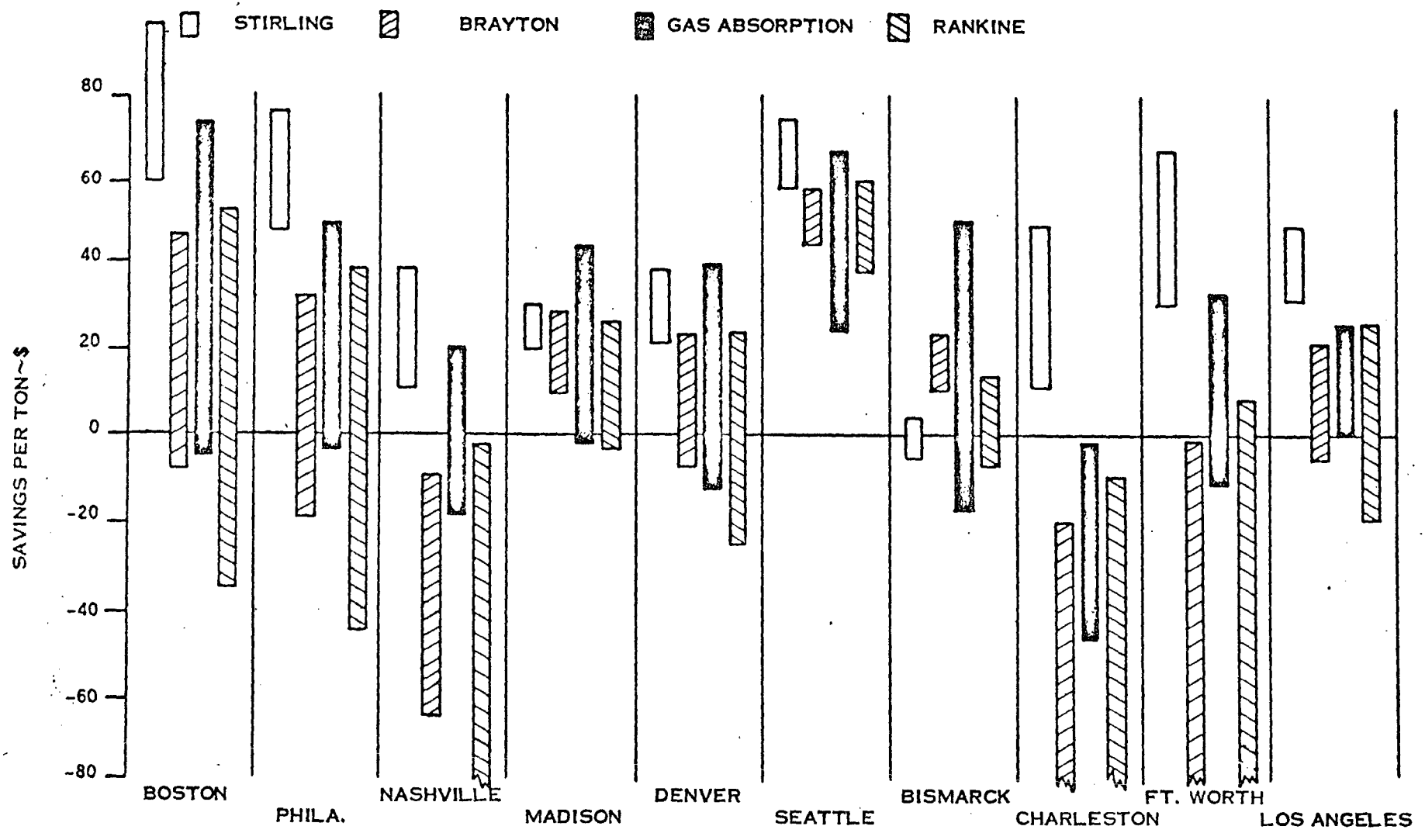

STIRLING
BRAYTON
GAS ABSORPTION
RANKINE
SAVINGS PER TON~$
80
60
40
20
0
-20
-40
-60
-80
BOSTON
PHILA.
NASHVILLE
MADISON
DENVER
SEATTLE
BISMARCK
CHARLESTON
FT. WORTH
LOS ANGELES

Table 4

CONCEPT COMPARISON

CONCEPT	PERFORMANCE	MARKET	REGIONAL APPLICATION
BRAYTON/ RANKINE	3	COMMERCIAL	LOCAL
GAS ABSORPTION	2	RESIDENTIAL	LOCAL
RANKINE/ RANKINE	4 (worst)	RESIDENTIAL	LOCAL
STIRLING/ RANKINE	1 (best)	ALL	ALL

Among the items evaluated in the concepts considered are the following:

- Rankine/Rankine: When considering the residential and commercial applications, this unit has the least attractive performance from an operating cost standpoint. Furthermore, because of its performance in the cooling mode, it is likely to be applicable only to residential applications where cooling loads are relatively small as well as to those regions of the country where cooling loads are low.

- Brayton/Rankine: Although capable of relatively good performance, the Brayton heat engine is not likely to be capable of the performance necessary to make it a competitor in the small model sizes. As a result it, also, is likely to be applicable to the commercial range of installations and in selected geographic areas.

- Absorption Pair: This implementation is likely to be most applicable to the residential segment of the market where cooling loads are relatively low. The same consideration applies to the regional market characteristics.

- Stirling/Rankine: Of the implementations considered, this concept applies to the broadest market and regional application. It competes well in areas requiring significant cooling capacity and promises significant operating cost savings.

Selected Approach - Based on the evaluation of potential applications and further estimates of cost and production requirements, the Stirling/Rankine system was selected as the candidate for further development. Of the possible Stirling engine implementations, a free-piston engine was selected because of its promised reliability and the minimal requirement for Stirling engine seal development with this approach. The prime implementation of the Rankine vapor compression cycle for the refrigeration loop relies on a commonality of parts with existing production equipment.

The current program involves the development of two iterations of heat pump hardware. The first unit (Prototype #1) is currently under fabrication and test. A second unit will be fabricated and is scheduled for test and evaluation in 1979.

GAS HEAT PUMP PROTOTYPE

In 1976, the development of the first prototype unit was initiated. The current program is being sponsored by: The American Gas Association, U. S. Department of Energy, Gas Research Institute, and General Electric. The objective of the program is to demonstrate that those goals originally projected in the evaluation on the concept, can be achieved.

Figure 6 illustrates the prototype configuration. The selection of two compartments for the equipment reflects the anticipated access required during the testing phase of the program.

The forward compartment houses the basically standard refrigeration cycle components as well as the controls for the unit. The rear compartment houses the natural gas interfaces as well as those interfaces required for the indoor air handler. The indoor air handler is currently envisioned as being a standard production unit with the addition of a hydronic coil to allow the utilization of the engine waste energy for heating. The rear housing also includes the equipment requiring the prime development emphasis. This is illustrated by the vertical assembly consisting of the combustor/engine/compressor.

Development Status - The development of the prototype unit has progressed through the stages of an assembly of the air handling equipment and testing of the various assemblies of the combustor/engine/compressor. Most of the developmental efforts have been concentrated on the combustor/engine/compressor assembly shown in Figure 7. This assembly combusts the natural gas providing energy input to the Stirling engine which drives the compressor for the refrigeration circuit. The overall performance of the assembly has been specified to be consistent with the operating cost performance savings shown in Figure 5.

Combustor - Figure 8 illustrates the configuration of the combustor used to drive the free-piston Stirling engine. The unit is of sheet metal construction having been designed with consideration to the eventual product manufacturing techniques.

The overall heat transfer efficiency of the unit had as its goal, 80% (heat into the engine divided by fuel burned in the combustor). The demonstrated performance

FIGURE 6 PROTOTYPE CONFIGURATION

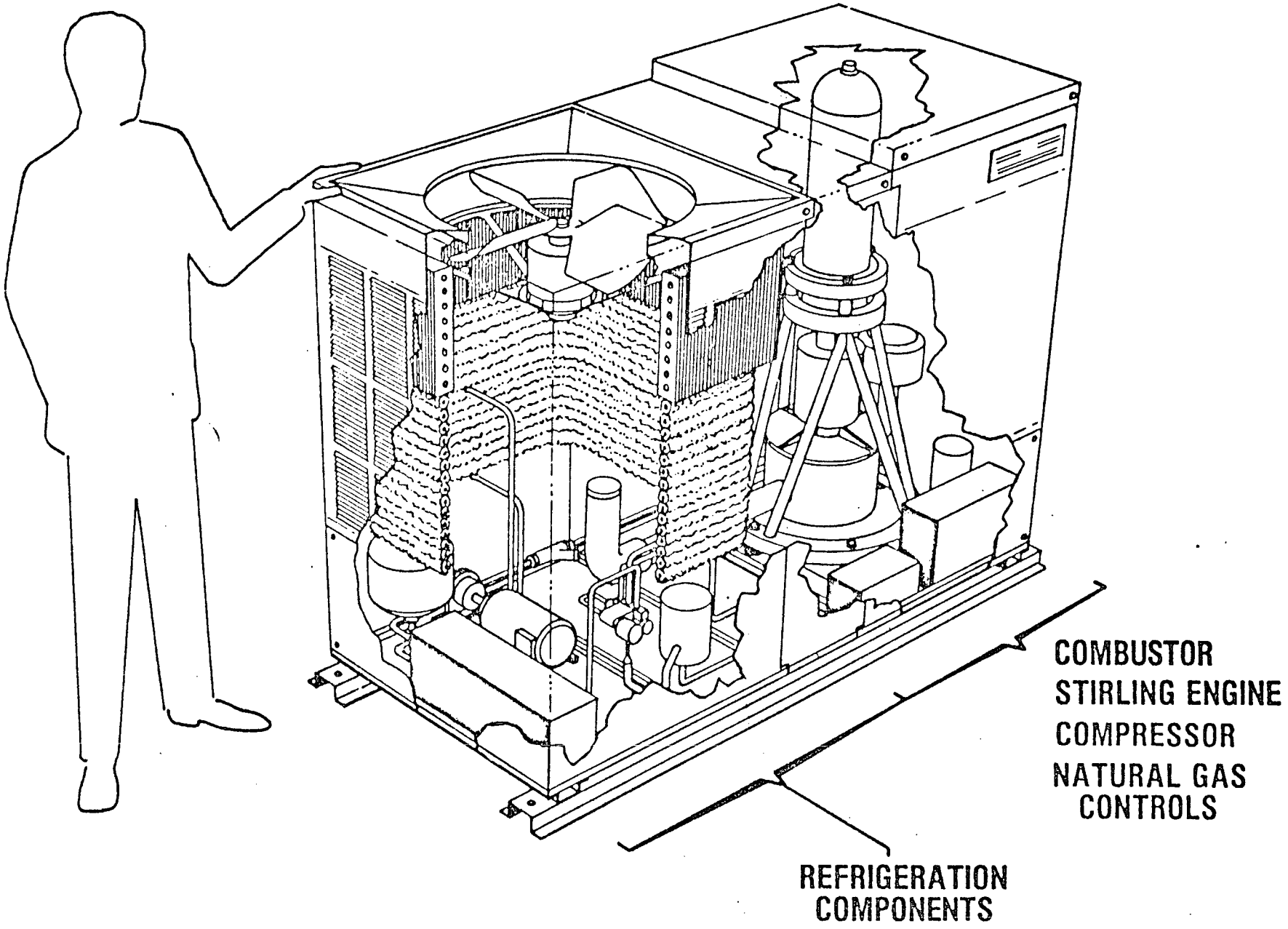

COMBUSTOR
STIRLING ENGINE
COMPRESSOR
NATURAL GAS CONTROLS
REFRIGERATION COMPONENTS

FIGURE 7 POWER UNIT ASSEMBLY

GAS HEAT PUMP

COMBUSTOR/ENGINE/COMPRESSOR ASSEMBLY

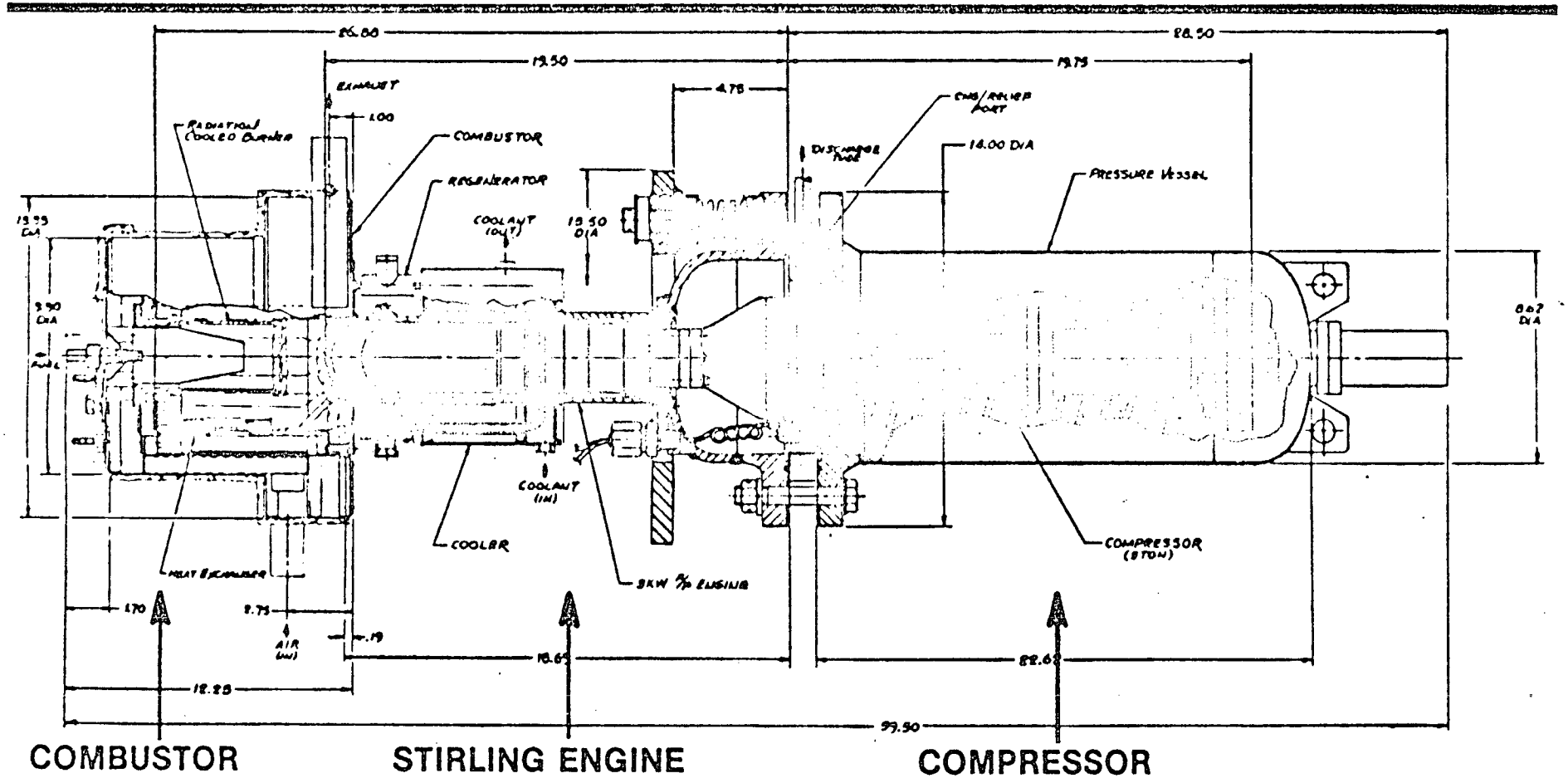


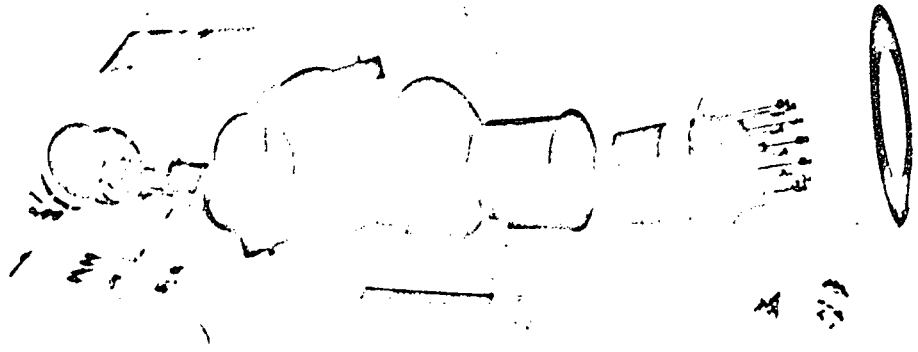
FIGURE 8 COMBUSTOR DEVELOPMENT

GENERAL ELECTRIC

COMBUSTOR CHARACTERISTICS

space division

CONFIGURATION



TRANSPIRATION BURNER

CHARACTERISTICS

- SHEET METAL CONSTRUCTION
- UNIFORM FLAME DISTRIBUTION
- 800^{0}F AIR PREHEAT
- STABLE FIRING-20,000 TO 60,000 BTUH
- HEAT TRANSFER EFFICIENCY - 85%

shows an 85-86% overall heat transfer efficiency, exceeding current design requirements. The heart of the unit is a transpiration burner, accepting a premixed fuel-air charge. The unit operates with preheated air to 430°C (800°F) and 15% excess air. The transpiration burner provides some quenching of the combustion flame limiting NO_x emissions. The burner assembly has been successfully operated utilizing either a metal matrix or ceramic structure for the burner unit.

Engine - The free-piston Stirling engine configuration is shown in Figure 9. The unit is designed to operate at a heat exchanger temperature (heater head) of 650°C (1200°F). At this temperature, stainless steel components can be used rather than more expensive superalloys. Analysis indicates that an efficiency of 30-35% can be achieved at this operating temperature. The working fluid is helium, at a charge pressure of 60 atmospheres. This charge pressure was selected to minimize the material usage to meet existing safety standards.

Due to the fact that the engine employs only two dynamic components, significant reliability is expected. Endurance tests are currently underway to evaluate candidate materials for the engine. Tests initiated in February 1978 have yielded engine efficiencies in excess of 20%.

Compressor - The compressor for the unit is a double-acting inertia compressor. The compressor housing is driven by the power piston of the Stirling engine. Figure 10 illustrates the compressor concept and configurations. A compressor isentropic efficiency of 75% is the goal for the unit. An efficiency of approximately 72% has been demonstrated.

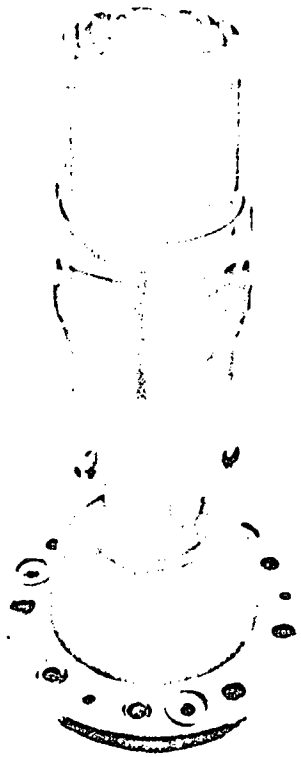
Development of the compressor unit has been facilitated by using production materials and components when practical. The prototype unit incorporates

FIGURE 9 STIRLING ENGINE DEVELOPMENT

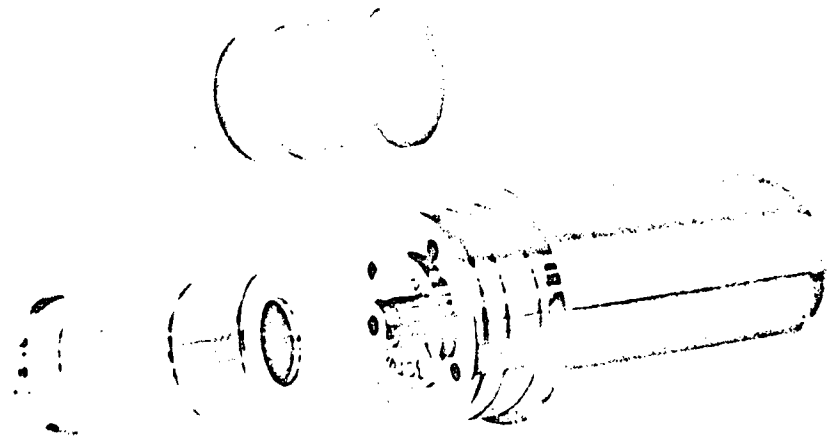
GAS HEAT PUMP

PROTOTYPE STIRLING ENGINE

ENGINE HOUSING



DYNAMIC COMPONENTS



DESIGN CHARACTERISTICS

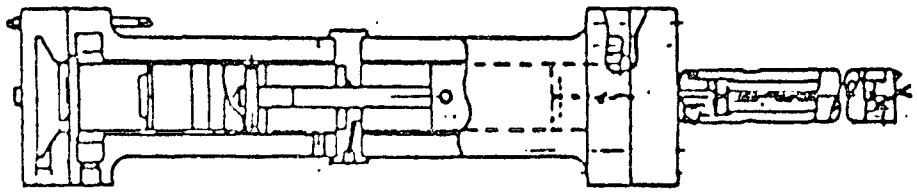
OPERATING TEMPERATURE	-	1200°F
POWER OUTPUT	-	3 KW
EFFICIENCY	-	30%
FREQUENCY	-	25-30 Hz

STATUS - TEST INITIATED

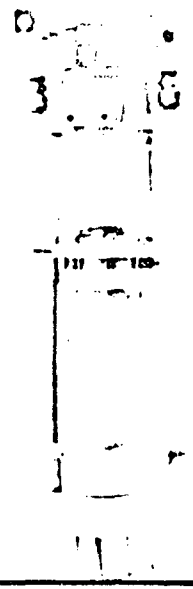
FIGURE 10 COMPRESSOR DEVELOPMENT

GAS HEAT PUMP

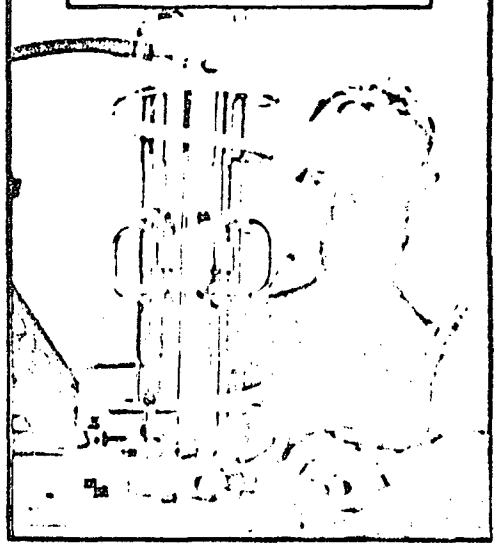
COMPRESSOR CONFIGURATION



PROTOTYPE COMPRESSOR



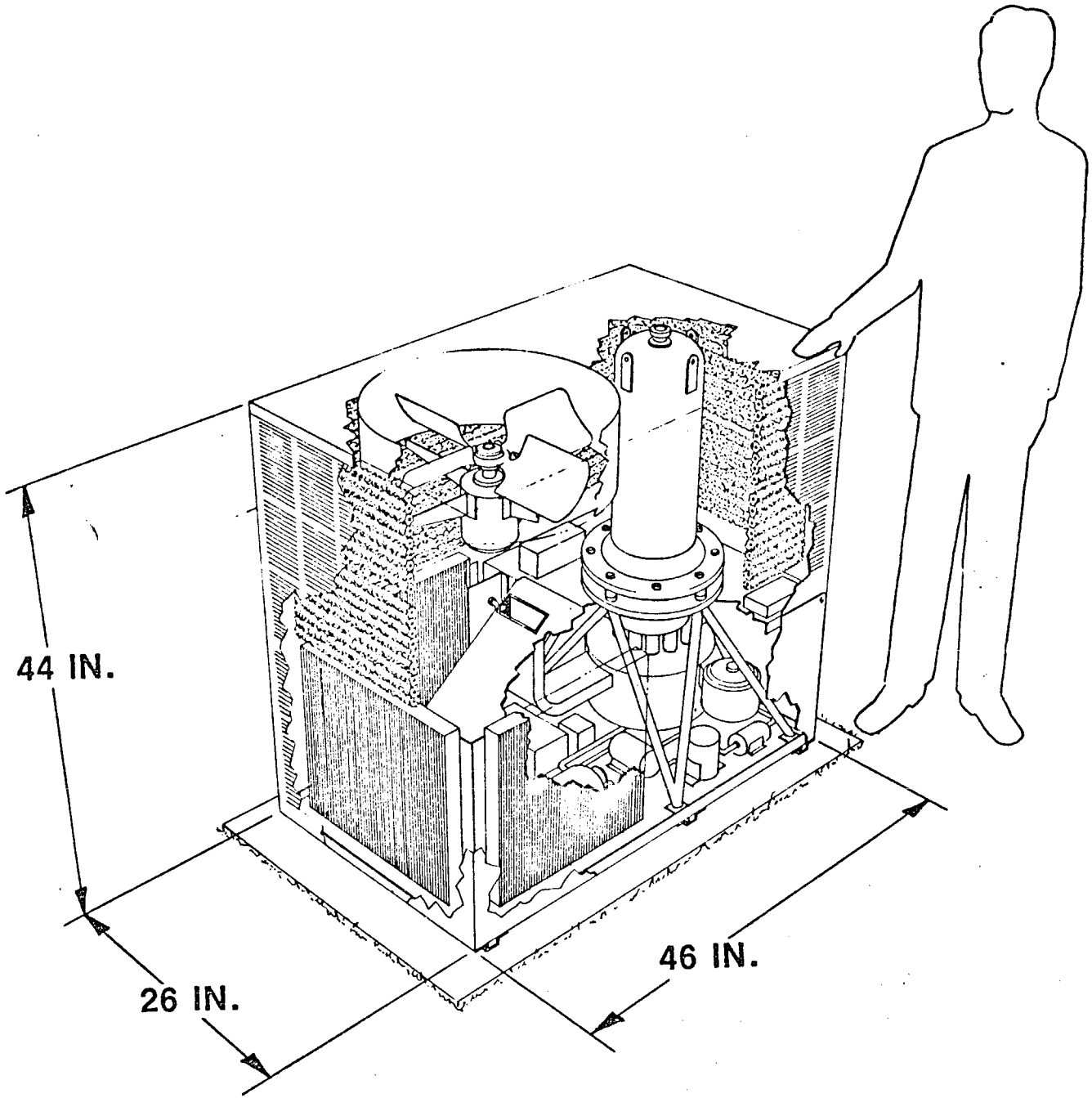
RESEARCH COMPRESSOR



CHARACTERISTICS

- DOUBLE ACTING
- WEATHERTRON MATERIALS/ VALVES
- 3-TON COOLING CAPACITY
- MEASURED EFFICIENCY - 72%

FIGURE 11 PRODUCT CONCEPT


44 IN.
26 IN.
46 IN.

materials and refrigerant valving from General Electric compressors currently in production.

The first prototype compressor incorporates internal porting of the refrigerant passages between the two pistons. This configuration is adaptable to casting implementation in production models. Early research compressors utilized external feed lines.

Product Configuration - As the product concept matures, it is expected that a unit similar to that shown in Figure 11 will evolve. This unit consolidates the compartmented version of the prototype shown in Figure 6, while retaining removable access panels for servicing of the product.

SUMMARY

The gas heat pump product is expected to reach the general marketplace in the mid-1980's. The operating cost savings are expected to allow pricing in excess of competitive units to be paid back in less than 3 years. During the first decade of availability, the product is expected to realize a cumulative energy saving of from .10 to .25 quads.

REFERENCES

1. American Gas Association Energy Analysis, "An Evaluation of Energy Conservation in the Residential Gas Space Heating Market," February 3, 1978.

2. American Gas Association Energy Analysis, "An Evaluation of Trends in the House Heating Market," April 24, 1978.