DEVELOPMENT OF A STIRLING ENGINE POWERED HEAT ACTIVATED HEAT PUMP

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ABSTRACT

A 3-ton heat pump, which employs a natural gas-fired Stirling engine to drive the vapor compressor, is presently being developed by the American Gas Association, ERDA, and the General Electric Company. The concept of a heat activated heat pump (HAHP) has the potential of reducing the amount of gas required for space heating. The Stirling engine/Rankine cycle refrigeration loop concept being developed would consume about one-half the gas required by conventional space heating equipment. As a result, this gas could be made available for new residential customers or for alternate applications. The Stirling/Rankine concept offers an efficient and competitive means of providing summer cooling, thereby tending to equalize the summer-winter gas loads.

This paper describes the Stirling/Rankine HAHP, discussing the system and component level constraints, and it presents the predicted performance of the heat pump.

INTRODUCTION

The American Gas Association and the General Electric Company embarked on a four phase program in January, 1975 to develop a heat pump fired by natural gas; ERDA support in the program began in 1976. The four phases include Preliminary Design, Prototype Development, Preproduction Development and Production. If commercialized, such a product will not only conserve our nation's energy resources, but it will also reduce the cost to the consumer for the space conditioning function. The operating savings becomes more significant as energy costs continue to escalate.

The heat activated heat pump is envisioned as a unitary heating and cooling product competing with the same market as the gas year-round and the gas furnace/electric air conditioning systems. As with its competitors, the HAHP could serve the residential and commercial markets including both new and replacement segments of each.

The Preliminary Design, Phase I, was completed in 1975. During this phase, several technical approaches to the implementation of a HAHP were evaluated. In addition, market cost and business evaluations were carried out to aid in evaluating the feasibility and viability of the concept as a product. As a result of Phase I, a Stirling/Rankine prime mover/refrigeration cycle was selected as the most attractive of several approaches.

Currently, the program is in the Prototype Development Phase, Phase II. The objectives of this phase are to demonstrate that the performance projected in Phase I can be attained. To accomplish these goals, a prototype of the gas heat pump is being designed, fabricated and tested. This first prototype will serve to demonstrate component and system interactions. Following evaluation of test data, a second prototype will be fabricated. The performance characteristics of this prototype and the results of concurrent marketing and business evaluations will be used to assess the attractiveness of the present concept.

PRODUCT DESCRIPTION

Functional Description. The operation of the Stirling/Rankine heat activated heat pump is analogous to a conventional Rankine cycle heat pump if the electric motor used to drive the vapor compressor is replaced by a prime mover. Provision must be made, however, to reject the engine's waste heat, i.e., the energy which is not converted into mechanical power. This energy can be utilized advantageously in the space heating mode to improve the heat pump performance by increasing both the coefficient of performance (COP) and the capacity of the heat pump product. The enhanced capacity over the heating mode operating range reduces the need for make-up heat below the system balance point. This enhanced capacity capability then will further improve the seasonal performance factor(1) of the HAHP.

The total heating capacity of the HAHP, which is illustrated in Figure 1, is derived from three sources:

1. Heat pump effect
2. Engine waste energy
3. Recovery of energy from the exhaust products

In the cooling mode of operation, this engine waste heat must be rejected to the ambient. The cooling capacity of the HAHP is derived solely from the heat pump effect, as is the conventional air conditioner. A desirable feature of the HAHP design is that its energy consumption in the cooling mode be no more than that of a competitive system. This necessitates that $\eta_{\text{prime mover}} \times \eta_{\text{combustion}} \geq \eta_{\text{motor}} \times \eta_{\text{electrical conversion}}$ or that the prime mover cycle efficiency must be on the order of 32%.

The components that comprise the heat activated heat pump system are shown schematically in Figure 2. The prime mover is a free piston type of Stirling engine which

(1) Product performance, whether it be COP or seasonal performance factor (SPF), will be based upon the fossil fuel energy consumed to perform the space conditioning function. Electrical energy when taken back to the power plant converts, on the average, only 30% of the energy available in the fossil fuel into electricity by the time it reaches the use point.

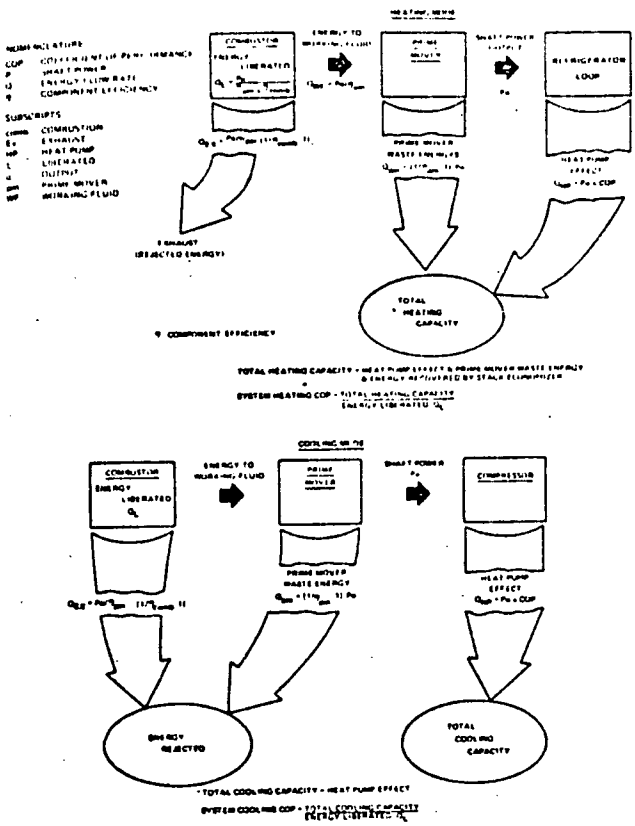

Figure 1. Heat Activated Heat Pump Functional Diagram

has been developed for the American Gas Association for a cooling application by Sunpower Incorporated (Ref. 1). The engine provides linear motion to directly drive a double-acting, inertia type of Rankine cycle vapor compressor. Incorporating an inertia compressor with the free piston Stirling engine (FPSE) permits complete isolation of the Stirling engine working fluid from the ambient and from the refrigeration loop without the use of dynamic seals.

The energy source for the prototype HAHP is the combustion of a premixed air/natural gas mixture; a radiation cooled transpiration burner is employed to perform this function. The liberated energy is transferred to the Stirling engine working fluid, which is helium, via a finned tube heat exchanger. The temperature of the exhaust products exiting the heat exchanger is approximately 1300°F; the combustion air is preheated in order to extract this high grade energy from these exhaust products.

A hydronic loop employing an ethylene glycol/water mixture is employed to transfer the engine waste heat to the appropriate heat rejection zone. A three-way valve directs the fluid flow to the hydronic coil located in the air handler for the heating mode operation and to the outdoor hydronic coil for the cooling mode operation. Other components comprising the hydronic loop include a circulation pump and an expansion tank. The components comprising the refrigeration loop are identical to those employed in a conventional heat pump.

The outdoor package concept is shown in Figure 3 for the mature HAHP product. The combustor/engine/compressor assembly is mounted horizontally in this rendition. In the initial prototype units, the assembly will be mounted

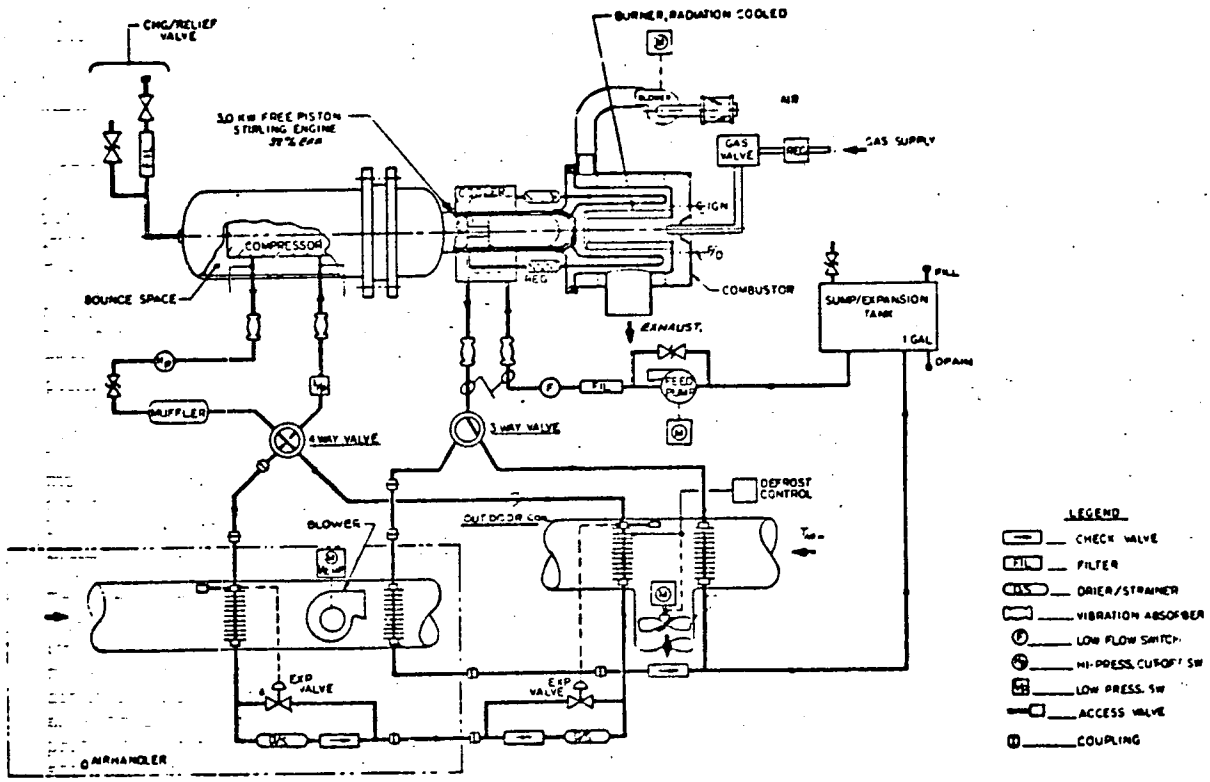

Figure 2. HAHP Component Definition

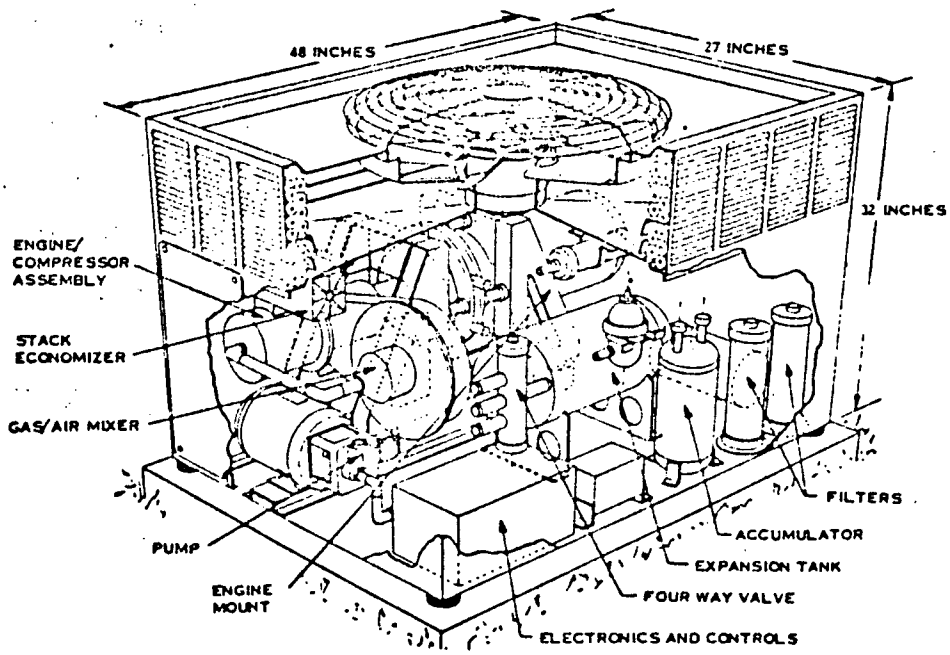

Figure 3. 3-Ton Stirling/Rankine Heat Pump Product Concept

vertically, which will result in a higher profile package. The indoor package employs conventional HVAC hardware which has been modified to accept the hydronic coil.

Requirements and Goals. The system-level requirements and goals that were placed on the HAHP system evolve from several sources. First, the HVAC industry places constraints on the system in the form of standards - ARI, ASHRAE, UL, AGA, etc. For example, these standards specify safety requirements for the electrical, piping, combustion and refrigeration system; they define the procedure to rate the heat pump system; and they specify installation and servicing requirements. General Electric also imposes requirements and constraints on the system-level design as a result of the engineering and marketing practices that have evolved; these inputs, which include reliability, performance, physical characteristics, interface, and power input requirements are partially a result of the competitive nature of the HVAC industry. Finally, the system annual operating performance and manufacturing cost goals evolved from the Phase I assessment of the viability of the heat activated heat pump product. These requirements are presented in Table I for the eventual product.

The performance goals presented in Table I are rated in accordance with ARI Standard 240. Another approach to measure how well the system performance goals are being met is presented in Figure 4. Here, annual HAHP operating cost savings, as compared to the conventional but improved system (a 75% effective combustion efficiency gas fired furnace and a 10.0 EER electric air conditioner), take into account the performance of the HAHP over the entire operating range; Philadelphia was used as the reference city.

The system-level performance requirement can be specified in terms of three HAHP subsystems - the combustor, the engine, and the refrigeration loop. The sensitivity of the system performance in terms of annual operating savings is presented in Figure 5 as a function of engine cycle and refrigeration loop efficiencies ($\eta_c \times COP_R$) and in terms of an effective combustion efficiency. Free piston Stirling engine cycle efficiencies in the range of 32% have been demonstrated (Ref. 2), and efficiencies approaching 40% are achievable for Stirling engines providing less than 5 hp; a conservative estimate of an achievable cycle efficiency is 29%.

Present unitary systems have a COP_R (2) of less than 3.2. The refrigeration loop COP is not only a function of the compressor performance but is also a strong function of condenser and evaporator temperaures. Mechanical improvements can be made to the compressor, but only small gains in compressor performance can be realized at considerable R&D expense. Improvements in COP_R will be obtained by employing larger heat exchangers and/or air flow rates in order to reduce the condenser temperature

Table I. System Level Requirements and Goals

	Eventual Product
Performance	
Cooling Capacity Btu/hr	36,000
Heating Capacity Btu/hr	64,000
COP (H/C)	1.7/1.0
Electrical Parasitics, Watts	1500
Sound Rating Number	18
Physical Characteristics	
Size	48 x 32 x 29
Weight	TBD 77
Reliability	
Design Life	15 years
Service Call Rate	1 per year
Design	Satisfy ARI, UL, & AGA Requirements
Power Input	115/230V, 60 Hz 1 Phase

(2) $COP_R = \frac{\text{Refrigeration Capacity}}{\text{Compressor Input Power}}$

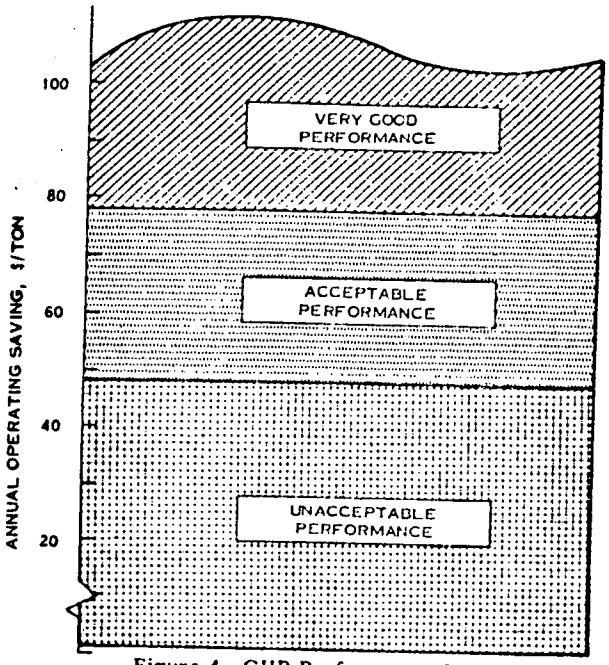

Figure 4. GHP Performance Goals

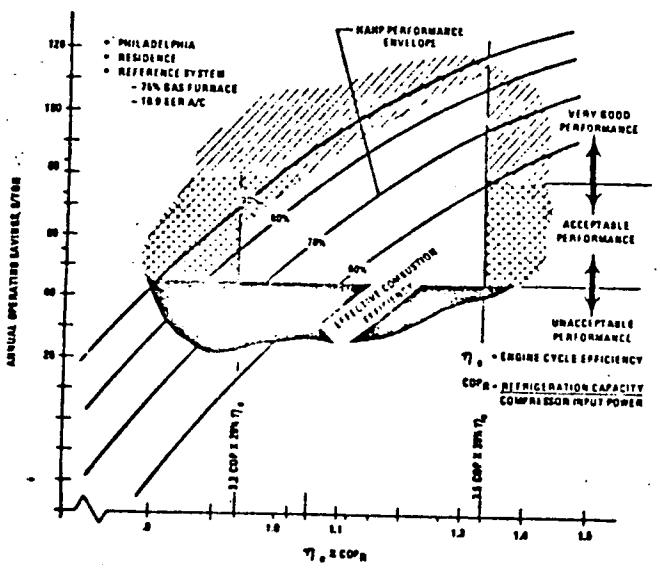

Figure 5. HAHP System Performance

and increase the evaporator temperature (Ref. 3). Figure 6 summarizes the effect of condenser and evaporator temperature on refrigeration loop performance. Since the inertia type of compressor inherently has lower mechanical frictional losses than do the positive displacement compressors, slightly higher performance is anticipated for the HAHP COP_R at equivalent operating conditions. A refrigeration loop COP in the range of 3.2 to 3.5 is feasible for the HAHP if condenser and evaporator temperatures of 120°F and 45°F, respectively, are obtained.

The combustor efficiency is a function of the amount of excess air, the amount of air preheat, and the temperature of the exhaust products at the inlet to the preheater. As shown in Figure 7, an 85% combustor efficiency is the maximum achievable for a 1300°F preheat inlet tempera-

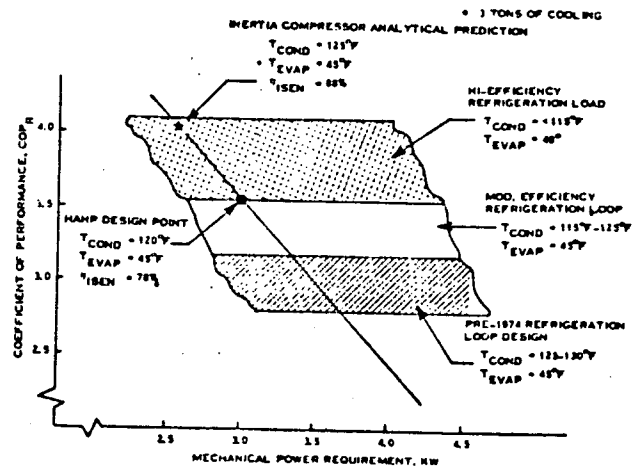

Figure 6. Compresssor Loop Performance

ture of the exhaust products and for a maximum air preheat temperature of 1000°F.

A performance envelope for the HAHP is defined in Figure 5 for the range of subsystem performances which have been specified. This envelope shows that the system performance requirement is achievable.

PREDICTED SYSTEM PERFORMANCE

The predicted performance - COP and capacity - of the HAHP is presented in Figures 8 and 9 for the cooling and heating modes, respectively. This performance evolved from a constant firing rate assumption over the range of operation. The COP characteristic does not include the electrical power requirements to operate the blowers, fans and pumps.

The energy and operating cost savings that the HAHP provides is presented in Figure 10 for various climatic regions across the U.S. The reference system was an advanced gas fired furnace having a 75% overall

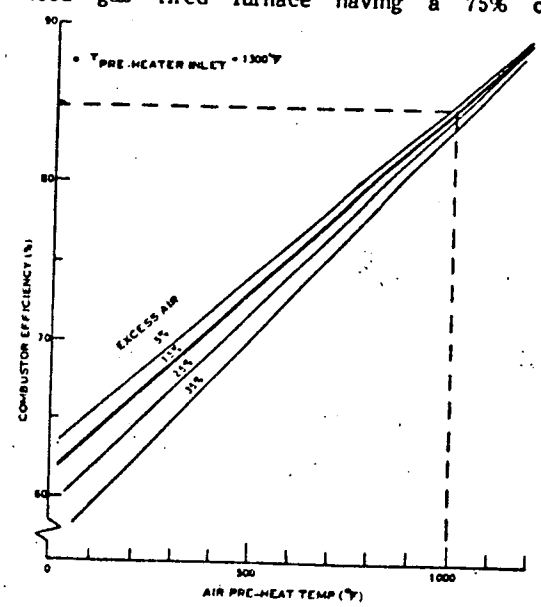

Figure 7. Overall Combustor Efficiency

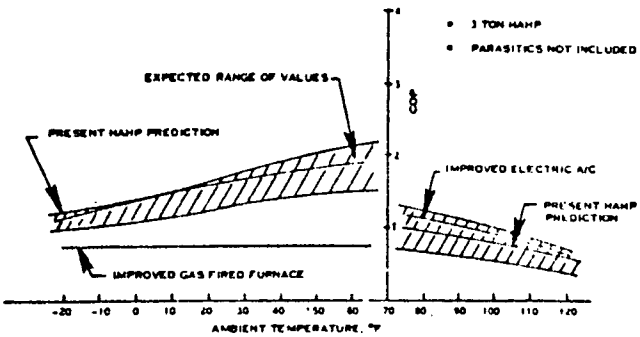

Figure 8. Predicted System Performance (COP)

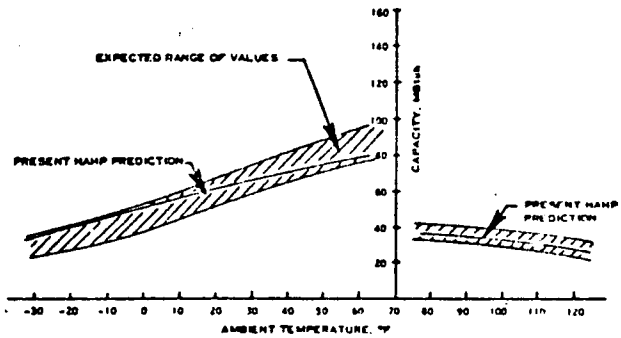

Figure 9. Predicted System Performance (Capacity)

combustion efficiency and a unitary air conditioner with a 10.0 EER. The energy costs were based upon an up-date of a 1974 A.D. Little Study, which projected energy costs for the various forms of energy, applications and regions. The building was a 1800 sq ft residence which employed energy conserving design features. The ASHRAE bin method was used to calculate the building load requirements. Make-up heat, where needed, was provided by an auxiliary gas fired hydronic boiler. The size of the unit was based upon the cooling season design point.

Sensitivity of the operating cost savings to variations in component performance is shown in Figure 11. The two performance parameters which impact system performance most significantly are engine and efficiency and the refrigeration loop COP. This result is an obvious one, but the important fact is that there is sufficient latitude

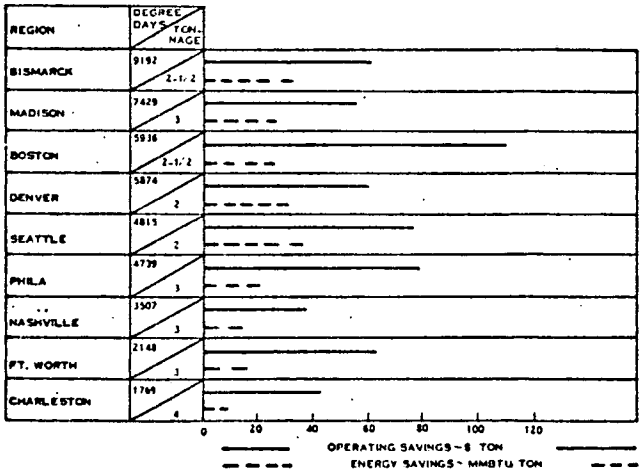

Figure 10. Single Family Residence HAHP Savings

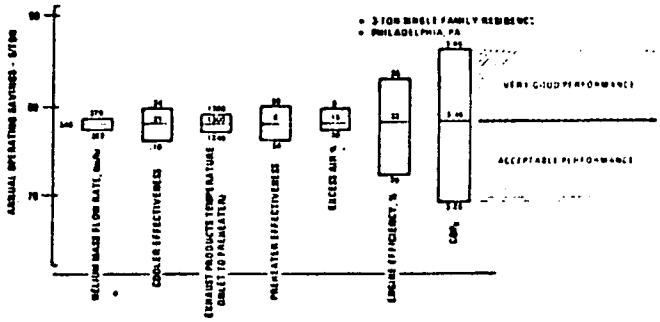

Figure 11. Sensivity of Operating Cost Savings to Component Performance

allowable in these component performances that will still yield an acceptable performance. For instance, if the Prototype 1 Stirling engine results in an engine efficiency of 29% instead of 32% (the design goal), the system performance goal is still achievable.

SUMMARY

The previous discussion of product concept development provides an overview of the heat activated heat pump, its description, performance and potential energy savings.

As highlighted throughout this paper, it is the inherent overall improvement in efficiency of this system that translates into operating cost savings and makes it attractive to a full range of market segments. The product attractiveness extends further to include the utilities since, the supply limited commodity of natural gas can be stretched further because of the higher HAHP efficiency. Also, the total potential energy savings represent a positive step in addressing the national emphasis for energy conservation.

The Stirling/Rankine heat activated heat pump, therefore, has the potential of becoming a viable HVAC product. The predicted operating cost savings upon which product expectations were based are consistent with the results that are presently being obtained from the subsystem level testing. These subsystems will be integrated into a system, and testing of the system will begin fourth quarter of 1977.

A second cycle of prototype hardware will be developed in 1978. This hardware will be employed in an HAHP demonstration program to obtain performance information of prototoype configured hardware in various climatic regions of the U.S. and to provide visibility of the Stirling/Rankine HAHP in the HVAC industry and in the consumer market.

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