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ON THE ROLE OF EXTERNAL COMBUSTION ENGINES FOR ON-SITE POWER GENERATION

by

Robert E. Holtz and Kenneth L. Uherka

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Robert E. Holtz and Kenneth L. Uherka
Components Technology Division
Argonne National Laboratory
Argonne, Illinois

INTRODUCTION

Stationary external combustion engines are prime movers which have potential for becoming viable power generation machines in both the residential/commercial and industrial sectors. Large stationary external combustion engines are being developed with the capability to employ alternative and/or non-scarce fuels. Energy sources under consideration include coal, coal derived liquids and gases, low-grade petroleum residues, biomass and municipal wastes. Advantages of external combustion engines relative to conventional prime movers are: greater fuel efficiency, reduced environmental impacts (noise and emissions), and a high degree of fuel flexibility.

A projected market for stationary external combustion engines is in the residential/commercial sector. Among the market applications are total energy systems, integrated community energy systems, and rural cooperative utilities. In these market applications, stationary external combustion engines will compete with diesel engines and gas turbines. Market penetration is expected to occur most rapidly in applications where primary fuel (oil, natural gas) costs are high and where fuel flexibility is an important consideration.

Applications and Advantages

Existing internal combustion engine prime movers such as diesel engines, spark ignition engines, and open-cycle gas turbines utilize scarce fuels (i.e., oil and natural gas) as their primary energy source. External combustion engines include steam turbines, Stirling cycle engines and externally-fired Brayton gas turbines. Among the various applications for external combustion engines are the following:

- Total energy plants
- Integrated community energy systems
- Industrial cogeneration
- Small municipal generating plants
- Pumping stations

Using an external combustion engine with an external heat source (i.e., combustor option) requires the use of a heat transport system. The interface between the fuel input, combustor option, heat transport system and external combustion engine is shown schematically in Figure 1 for a Stirling engine based system. Various options of fuels, combustors and heat transport systems are shown in Table 1 along with some projected characteristics of a large stationary Stirling engine for stationary power generation. It is seen by examination of Table 1, that a major advantage of external combustion engines is a fuels flexibility which does not currently exist with internal combustion machines. Along with this fuels flexibility, other advantages of external combustion engines can include higher efficiencies than conventional prime movers, very low emissions, little noise, and good reliability.

Fuel Options

The four fuels which supply the great majority of the energy used in the United States are coal, oil, natural gas, and nuclear fuels. Of these fuels, coal appears to be the most plentiful in the United States. When siting an energy producing plant, it is essential to know that the fuel supply will be available over the lifetime of the plant. Internal combustion machines need to intake primarily oil derived products and natural gas in order to operate. As shown in Figure 1, an external combustion engine needs only heat supplied to it in order to operate -- it does not matter what the heat source is as long as the quantity and temperature of the heat matches the engine needs. Such engines can be used either as topping or bottoming to an industrial process, or can be used to produce electricity for a residential/commercial application with the rejected heat used for space heating and cooling.

Among the candidate coal-using combustors which could be employed are:

- Coal-fired stokers
- Fluidized bed combustors
- Pulverized-coal furnaces
- Coal-fired cyclone furnaces
- Combustors burning coal derived liquids and gaseous fuels

It is not necessary for all the heat supplied an external combustion engine to come from a single source. Various non-coal sources that can be used either independently or integrated with others to supply heat to external combustion engines include solar energy, municipal wastes, biomass and geothermal.

Stirling Engine Based Systems

Although there are several classifications of external combustion engines, the following discussion deals with a specific type of external combustion engine, the Stirling engine. The advantages which appear most significant are the possibility of achieving very high efficiency levels in the 40-45% range, and the ability to use a variety of fuel forms including coal, municipal wastes, and biomass derived fuels (wood chips, biogas, etc.)

Stirling engines with efficiency levels approaching 40% have been built and tested. However, most Stirling engines built to date have efficiency levels in the 32 to 35% range. The ideal efficiency of these engines, which is equal to the Carnot efficiency, is from 60 to 70%. Most present Stirling engines achieve about one half of the Carnot efficiency. This large difference between the actual and ideal efficiencies has been due somewhat to restrictions placed on these engines because the primary development was for use in vehicular propulsion systems. These restrictions do not apply to stationary engine applications which allow for maximizing efficiency consistent with achieving a low life cycle operating cost.

Extrapolations of existing data assuming a heat rejection temperature of 100°F, optimum efficiency operation speeds, and heat input temperatures of 1900°F indicate that Stirling engine efficiencies of about 45% are a realistic goal.

Figure 2 illustrates a Stirling engine based system which allows for a multiplicity of fuels. A possible option in this system is the use of a heat pipe system to transfer the heat to the Stirling engine. This allows for a uniform, high flux, heat input to the engine heater without subjecting the heater tubes to the possible corrosion and fouling associated with the combustion of some solid fuel forms. The heat input to the heat pipe system can be accomplished by employing heat exchanger configurations which are easily cleaned and which have sufficient heat transfer area to keep the heat fluxes and temperature drops low.

The two sources of heat in a Stirling engine based system are the rejected heat from the cycle during the compression process and the exhaust gases from the Stirling engine combustor. The former produces temperatures in the range of 100 to 150°F and the latter produces temperatures in excess of 300°F. These moderate temperature fluids can be used for driving absorption air conditioning units and/or for supplying heated water for space heating and domestic hot water.

Figure 3 shows the variation of shaft work efficiency for current and advanced Stirling engine technology. Current technology Stirling engines can be operated at about 30-34% efficiency. The expected advanced full load efficiency is about 46%, although a highly successful development program could provide a higher efficiency. It is seen in Figure 3 that a large amount of the heat is recoverable.

Stirling engines have considerable potential for application in both industrial cogeneration systems and residential/commercial energy systems. For application in these systems, they will have to compete with diesel engines and gas turbines. The nominal heat balances of these prime movers as a percentage of fuel input is shown in Table 2. It is seen that from an energy savings standpoint, Stirling engines compare favorably with both diesel engines and gas turbines.

Figure 4 shows the cost comparison of Stirling engines with current technology diesel engines. The shaded area for the Stirling engine option shows essentially the range of variation between what is possible in terms of efficiency and capital cost uncertainties. It is seen that the Stirling engine becomes cost competitive with diesel engines when the fuel cost exceeds about 1.75$/$10^6$ Btu, provided that a target efficiency of 46% is reached by the Stirling and that the cost of the Stirling system is only 20% greater than a similar diesel system. The utilization of a larger amount of recoverable heat in the Stirling based systems (see Table 2) will provide cost savings additional to those shown in Figure 4.

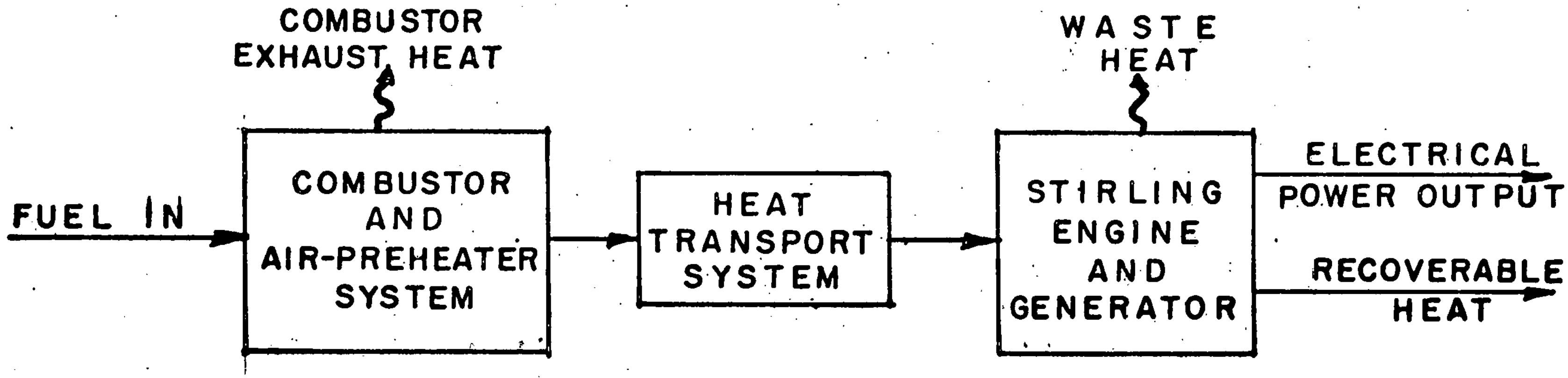
The fuels flexibility of a Stirling engine based system will have significant impact upon the cost comparison with current technologies which employ scarce fuels. Using a non-scarce fuel with a much lower fuel cost (i.e., coal, municipal wastes, biomass, etc.) in a Stirling based system will result in significantly lower electrical generation costs when compared to the generation costs associated with employing oil and natural gas in current technology diesel prime mover systems.

Figure 5 illustrates the electrical generation cost comparison of the Stirling engine based system and the simple and regenerative gas turbine based systems. In this case the Stirling engine based system has clear cost advantages over the gas turbine based system. The fuels flexibility of the Stirling engine based system makes it appear even more attractive.

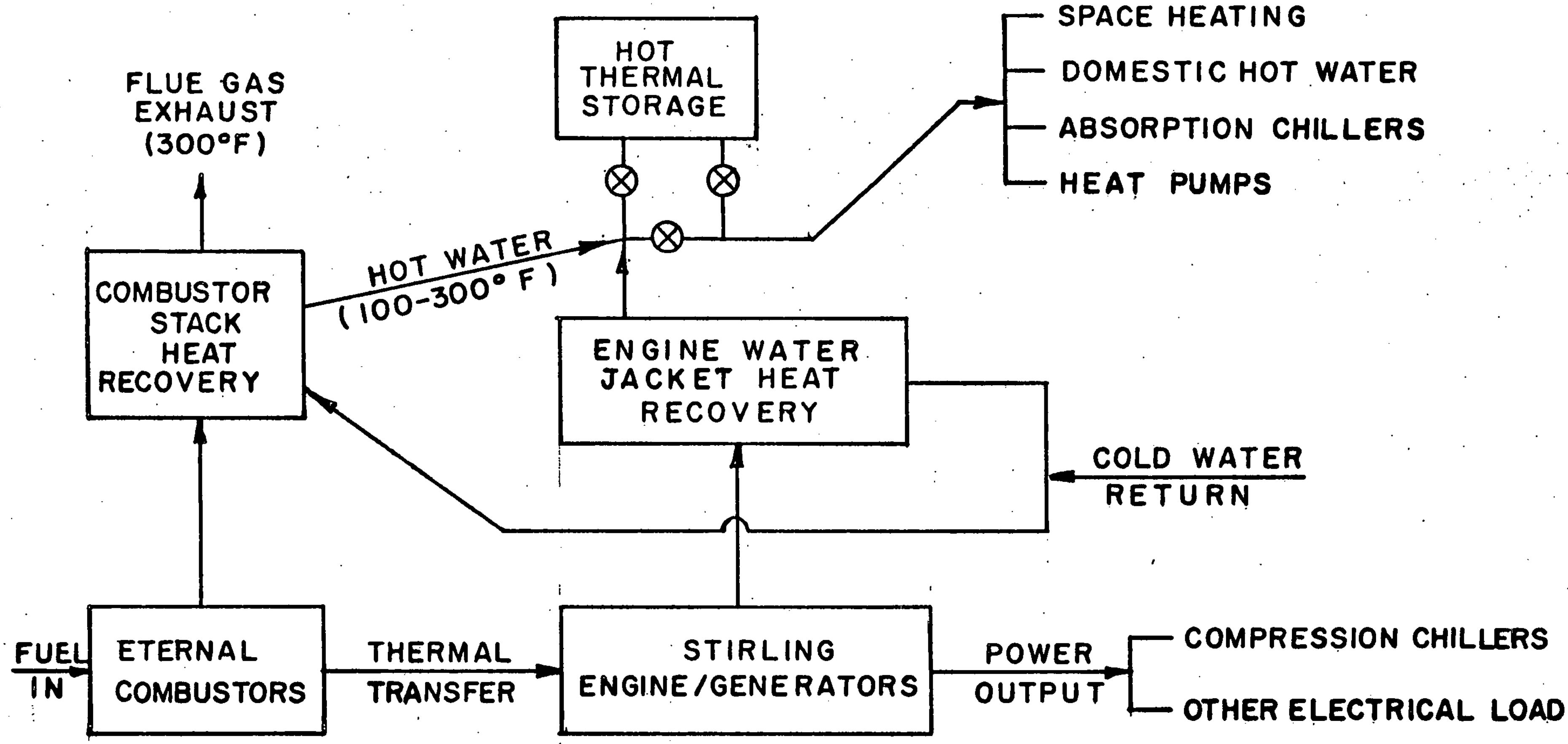
Detailed studies of energy systems for application in the residential/commercial sector have shown considerable energy and cost savings when compared to the energy systems which are based upon the utilization of current technologies. Market penetration is expected to occur most rapidly in applications where primary fuel (oil and natural gas) costs are high and where fuels flexibility is an important consideration.

Development of Stirling Engines

Stirling engines show promise to produce both energy and cost savings in both the residential/commercial and industrial sectors of the economy. In order for Stirling engines to become a mature technology a number of research and development areas must be addressed. These areas include the investigation of working fluids, seal designs, engine configuration, heater designs, combustion system design, air preheater design, regenerator design, and the design of novel concepts. Goals for the large, stationary Stirling engine must include the development of engines with the minimum efficiency in the 38 to 40% range, which employ low cost fuels (such as coal, industrial wastes and municipal wastes), and that achieve a capital cost of the non-scarce fueled Stirling engine which is not more than twice that of a comparably sized medium speed diesel engine. It is anticipated that this Stirling engine development activity will take in the range of 6 to 8 years from initiation to the full demonstration of at least one engine. After a successful demonstration, a commercialization program should be implemented in order to fully utilize the engine to conserve scarce fuels and use alternate fuel supplies.

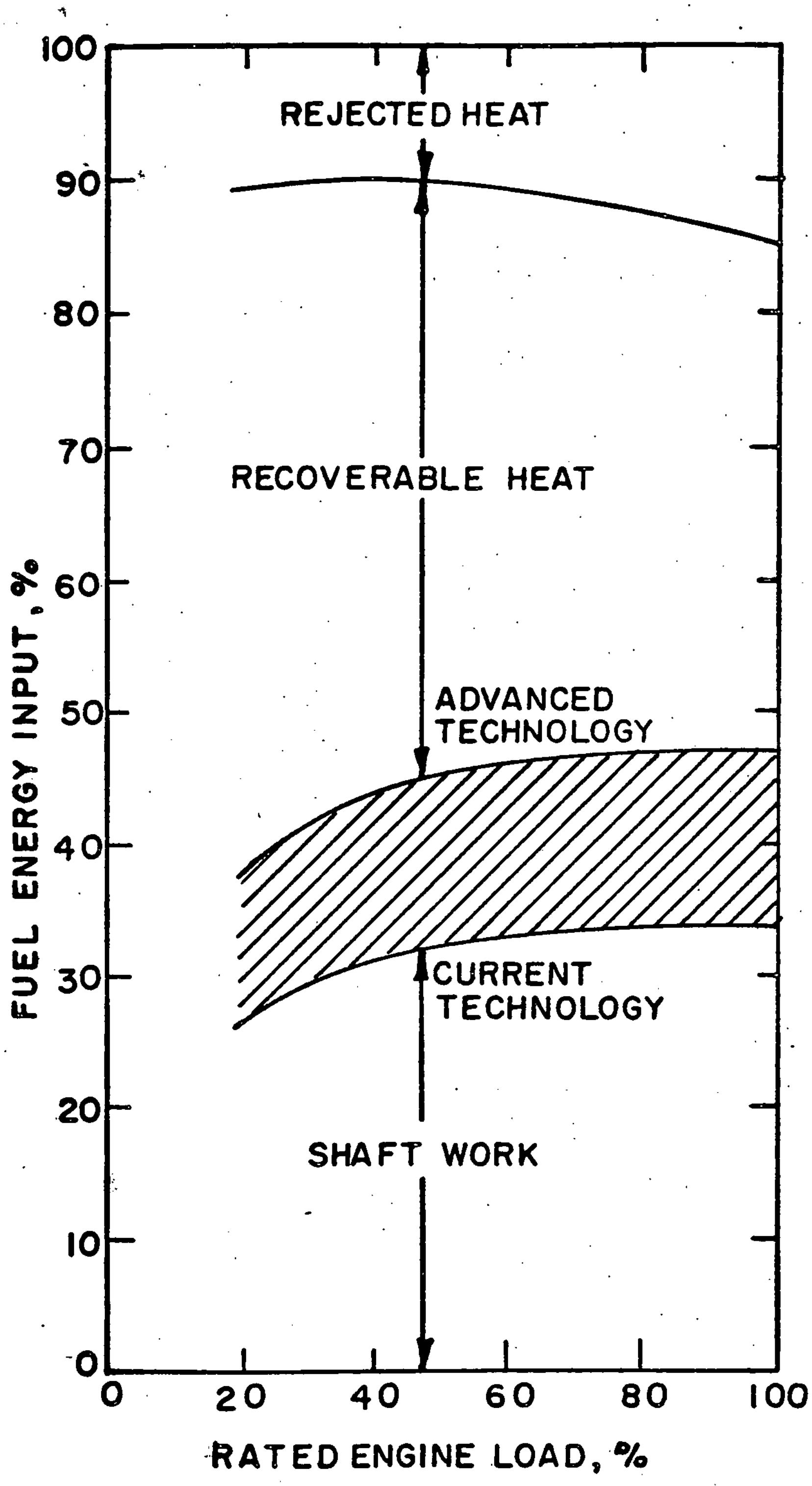


STATIONARY STIRLING ENGINE POWER SYSTEM



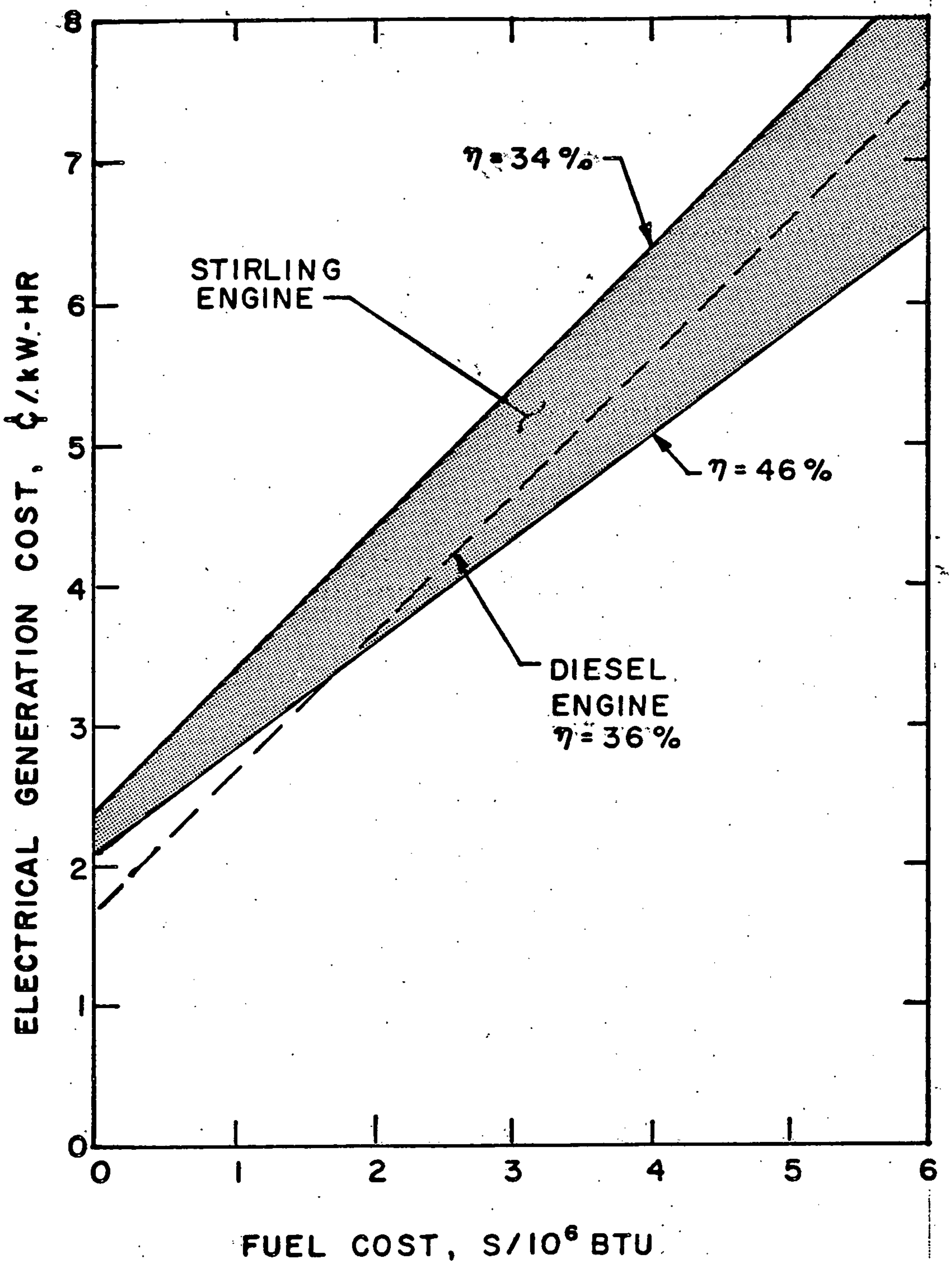
STERLING ENGINE TOTAL ENERGY SYSTEM

Figure 2



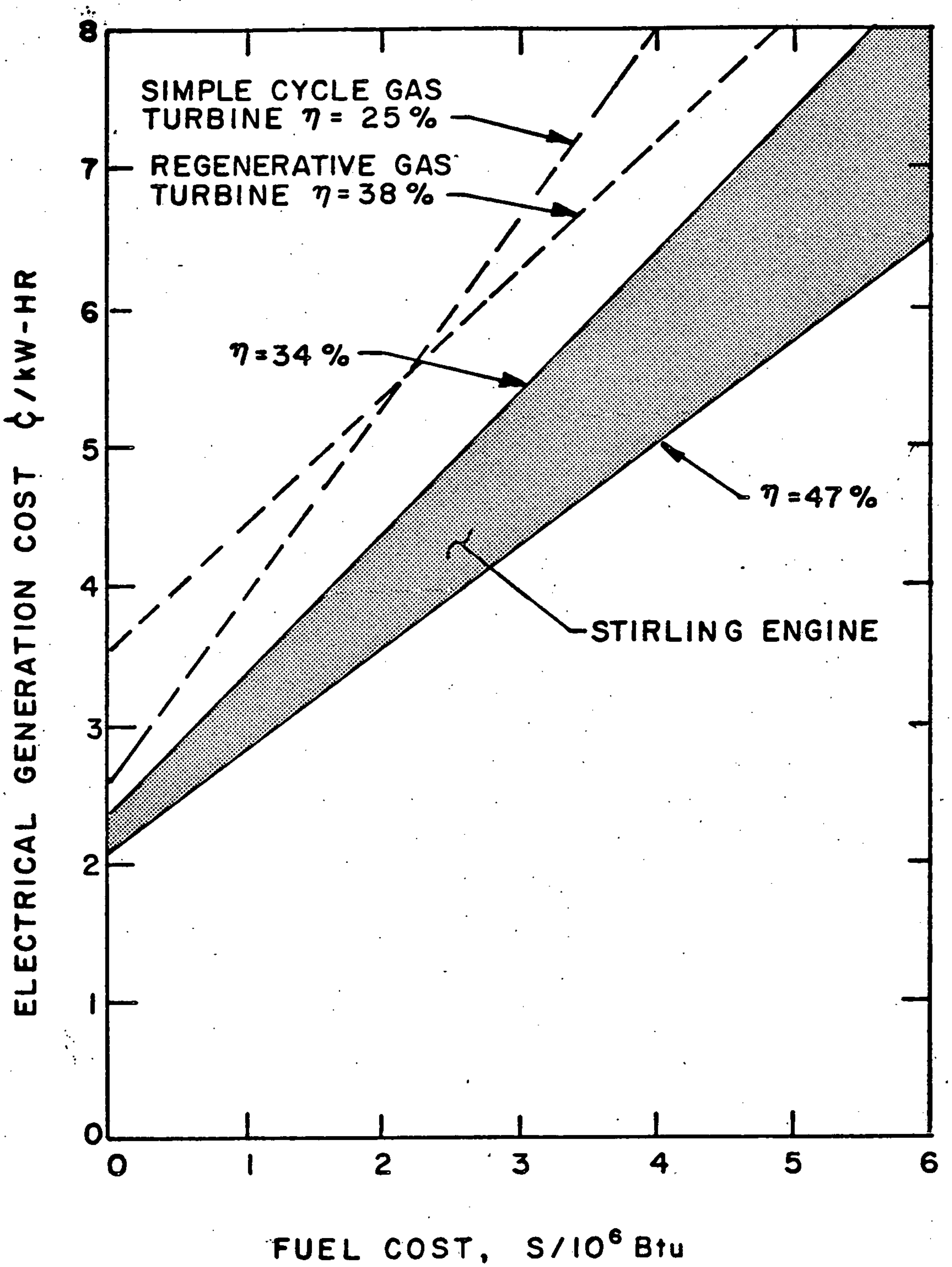
GENERALIZED STIRLING ENGINE HEAT BALANCE

Figure 3



COMPARISON OF FIRST GENERATION STIRLING ENGINE TO CURRENT DIESEL GENERATION COSTS (1000 kW)

Figure 4



ELECTRIC GENERATION COST COMPARISON OF FIRST GENERATION STIRLING ENGINES AND SIMPLE AND REGENERATIVE GAS TURBINES (1000 kW)

Figure 5

TABLE 1

DESIGN OPTIONS FOR STIRLING ENGINE SYSTEMS USED FOR STATIONARY POWER GENERATION

Fuels	Combustors	Heat Transport Systems	Stirling Engine Interface Factors
Solid Coal Coal-Derived Products Municipal Wastes Biomass Products Solar and Geothermal Nuclear Oil and Natural Gas	Coal Combustors • Fluidized Bed Combustors • Stoker Furnaces • Pulverized Coal Burners • Cyclone Furnaces Coal/Oil Slurry Combustors Solid Waste Incinerators Wood and Other Biomass Combustors Solar Collector Devices Nuclear Reactors Oil/Gas Furnaces	Direct-Fired Systems Indirect-Fired Systems • Liquid Metal Loops • Heat Pipes • High Pressure Gas Loops • Other Fluids	500 - 3000 Hp Heater Head Design Working Fluid Characteristics Hot End Temperature Dead Volume Constraints Heat Flux Requirements Heater Tube Configuration

Table 2

NOMINAL HEAT BALANCES OF PRIME-MOVERS

	PERCENT OF FUEL INPUT		
	WORK	RECOVERABLE HEAT	REJECTED HEAT
DIESEL	36	42	22
GAS TURBINE (SIMPLE)	25	45	30
GAS TURBINE (REGENERATIVE)	38	22	40
STIRLING (CURRENT)	34	54	12
STIRLING (ADVANCED)	46	41	13

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(MCW)