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ENERGY AND ECONOMIC ANALYSIS OF TOTAL ENERGY SYSTEMS FOR RESIDENTIAL AND COMMERCIAL BUILDINGS

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ABSTRACT

Energy and economic analyses were performed for an on-site powerplant with waste heat recovery. The results show that for any specific application there is a characteristic power conversion efficiency that minimizes fuel consumption and that efficiencies greater than this do not significantly improve fuel consumption. From an economic viewpoint this type of powerplant appears to be a reasonably attractive investment if higher fuel costs continue.

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SUMMARY

On-site powerplants with waste heat recovery can increase the energy utilization of fuel by 25 percent or more. The concept of a modular integrated utility system (MIUS) is part of a program of the Department of Housing and Urban Development to provide community utility services while at the same time conserving energy and other resources and protecting the environment. In conjunction with work being conducted by the Johnson Spacecraft Center on MIUS, the Lewis Research Center has done a preliminary analysis of the powerplant for such a system.

The analysis focused on two aspects, the energy utilization and economics of the powerplant. The first was aimed at determining the prime mover thermal to electrical conversion efficiency that would result in minimum total fuel consumption for a representative community. The powerplant was then sized and estimates of the capital and operating costs were made. The second part of the analysis utilized these costs to examine some of the economic aspects such as rate of return on investment and fuel savings for the powerplant.

The results show that for a specific application there is a characteristic power conversion efficiency that minimizes fuel consumption and that efficiencies greater than this do not significantly improve fuel consumption. From an economic viewpoint this type of powerplant appears to be a reasonably attractive investment particularly if higher fuel costs continue.

INTRODUCTION

Energy conservation is one of the most effective means of reducing fuel consumption and extending the useful life of this nation's fossil energy reserves. One proven method of efficient utilization of energy is the concept of integrated utility systems. The Modular Integrated Utility Systems (MIUS) program under the direction of the Department of Housing and Urban Development (HUD) is directed toward providing complete community utility services while conserving energy and material resources and minimizing pollution through waste heat utilization and material recycling (ref. 1). This report considers the effect of powerplant type on energy utilization.

Residential and commercial buildings require electricity for illumination and power equipment, heating and cooling for temperature and humidity control and heat for domestic hot water. These requirements consume about 28 percent or approximately 20 quadrillion Btu of th' nation's total energy consumption. Electric power from central utility companies is delivered to the consumer at a thermal efficiency of about 30 percent. Heat from conventional boilers and furnaces is supplied at thermal efficiencies between 70 and 80 percent for oil and natural gas fuels. For the typical consumer this type of utility service results in an overall thermal efficiency for electrical generation and heating of 50 to 60 percent. Supplying these same services through the use of decentralized powerplants with waste heat recovery can increase the overall thermal efficiency to a range of 65 to 75 percent. This 25 percent improvement in efficiency represents a potential of about 4 quadrillion Btu of yearly energy savings at current usage or the equivalent of about 2 million barrels per day of petroleum.

NASA's Johnson Spacecraft Center (JSC) is one of the primary participarts in the MIUS program of HUD. In conjunction with JSC the Lewis Research Center conducted a preliminary analysis of the powerplant for MIUS. The purpose of this study was to identify the type of powerplant that might best serve the MIUS concept and examine some of the economic aspects of a typical MIUS powerplant.

POWERPLANT SYSTEMS

The MIUS concept is basically a total energy system that generates on-site electrical power and recovers waste heat to meet the thermal load. Reference 2 lists more than 500 total energy systems throughout the United States that are currently operating at apartment complexes, shopping centers, schools, hospitals, greenhouses, processing plants, etc. The power capacity of these systems ranges from 200 kilowatts to 20 megawatts. A typical total energy system consists of a prime mover that converts fuel energy to rotating shaft energy to drive an electrical generator and possibly couple directly to a compression refrigeration unit. A portion of the waste heat from the prime mover is recovered in the form of low pressure steam or hot water and used directly for heating or indirectly via absorption refrigeration for cooling. An automatic control system is necessary to match the electrical energy output with the required loads and provide safe operation.

Three types of prime movers are used, i.e., high pressure boiler with steam turbine, gas turbine, and reciprocating engine. Figure 1 shows a total energy system with a boiler-steam turbine driving the generator and the compression refrigeration unit either directly or electrically. Steam extracted from the condensing turbine at a pressure corresponding to some temperature requirement supplies the thermal load. The power generating efficiency for this type of steam Rankine system is about 30 percent. However, the high operating pressures require that the powerplants be attended and this added labor cost usually limits this system to large installations where the labor burden is economically feasible.

Figure 2 shows a gas turbine as the prime mover with the waste heat being recovered by heat exchange between the hot exhaust gases and water to produce hot water or low pressure steam. Standard, commercial gas turbines used for aircraft propulsion and other applications have proven to be reliable and economical. For stationary power generation the thermal efficiency of current gas turbines is usually less than 20 percent but with advanced high temperature technology a power generation efficiency near 40 percent appears possible (refs. 3 and 4). The reciprocating prime mover system, typically a diesel engine, is illustrated by figure 3. Waste heat is recovered from the engine jacket, exhaust manifold, lube oil, and exhaust gases in the form of hot water or low pressure steam. These engines convert between 20 and 40 percent of the fuel energy to electrical energy (ref. 4) and have a long history of dependable service as standby power units and total energy prime movers. The wide operating range is a function of engine design such as two-cycle or four cycle and the effect of supercharging.

ENERGY ANALYSIS

The primary purpose of a MIUS powerplant will be to generate sufficient on-site electrical power and heat to meet the load requirements with minimum consumption of fossil fuel. This is achieved when the required electrical and thermal energy is matched by the powerplant output less some nonrecoverable fraction of waste heat. The factor that determines the closeness of this match is the power conversion efficiency. This analysis will attempt to determine the power conversion efficiency that will produce the best match and therefore consume the minimum amount of fuel.

The basis for this analysis will be a 648-unit garden apartment located in a climate corresponding to the east coast region of the United States. Hourly energy requirements based on load profiles presented in reference 5 for typical summer and winter days are presented in table I. The on-site powerplant supplying this community is assumed to lose 22 percent of its total fuel energy as nonrecoverable waste heat in the form of stack losses, hot surface losses, and generator losses. With a fixed nonrecoverable loss the power conversion efficiency will then determine, by difference, the amount of recoverable waste heat that is available for the thermal load. Figure 4 shows the effect of power conversion efficiency on fuel consumption for both summer and winter operation. These curves were generated by making a series of energy balances, based on the summer and winter hourly energy requirements given in table I, at various power conversion efficiencies. Recoverable heat was stored during those hours of excess production and used later to make up any deficits. The total fuel consumption and storage requirements, defined in energy units, for the typical summer and winter days were then determined as a function of power conversion efficiency.

For winter operation, the minimum fuel consumption corresponds to about 31 percent power conversion efficiency with storage required for about 25 million Btu. Assuming hot water storage and a 20° F temperature drop, the required storage volume is approximately 150 000 gallons. At power conversion efficiencies below 31 percent there is excess recoverable heat available. This reduces the storage requirements, but fuel requirements become increasingly greater and additional heat must be dumped to the atmosphere. At power conversion efficiencies greater than 31 percent, there is a shortage of recoverable heat. This shortage must be made up by either generating additional electrical power and converting it back into heat via resistance heating or a heat pump, or by adding a boiler to the system and generating the heat directly. In either case the total fuel consumption will remain at approximately the minimum value.

For summer operation the minimum fuel consumption corresponds to about 36 percent power conversion efficiency with about 10 million Btu of storage required. The energy requirements for summer operation are determined by first meeting the base electrical load and using the available waste heat to satisfy the domestic hot water load and part f the cooling load through operation of absorption refrigeration units. Any additional cooling load is provided by generating additional power to operate compression chillers and utilizing the additional waste heat in more absorption capacity. The power conversion efficiency of the prime mover determines the amount of waste heat available for absorption cooling and hence, the split between absorption and compression refrigeration capacities, as shown in figure 5.

At lower than optimum power conversion efficiencies, the available waste heat is high, thereby requiring a larger fraction of absorption refrigeration capacity and also requiring greater storage capacity, as shown in figure 4. As conversion efficiency increases, the available waste heat becomes less and total fuel consumption is reduced by generating additional power to operate compression chillers. The reason for this is the much higher coefficient of performance for compression chillers compared to absorption chillers; specifically, 4.6 compared to 0.67, which are the values used in this analysis. An additional saving is realized in reduced cooling tower capacity since the heat rejection load from a compression chiller is only about one-half that of an absorption chiller.

At the minimum fuel consumption point which corresponds to 36 percent conversion efficiency, the refrigeration split is approximately 80 percent compression and 20 percent absorption. About 11 percent represents the recoverable waste heat from generating the base electrical load. The other 9 percent represents the waste heat available from generating the additional power necessary to provide the remaining 80 percent compression refrigeration capacity. For power conversion efficiencies greater than 36 percent, the hot water storage requirements approach zero and the system possesses very little operating flexibility. Furthermore, the lack of waste heat would require generating additional heat either from an electric hot water heater or a boiler to meet the domestic hot water demand. Therefore, the 36 percent power conversion efficiency appears to be a practical maximum based on the assumptions used herein.

Currently the diesel engine is the only prime mover that can achieve the range of 31 to 36 percent power conversion efficiencies that appears optimum for the winter and summer operation described. The analysis shows that the optimum power conversion efficiency for minimum fuel consumption is determined by the energy distribution between electrical and thermal load and therefore it will be different for various types of communities and climatological conditions. A conversion efficiency greater than the optimum is never detrimental to fuel consumption, but it is important to realize that it is not necessary to strive for higher efficiencies to conserve fuel.

ECONOMIC ANALYSIS

Capital and operating costs of an on-site diesel powerplant capable of supplying the aforementioned energy requirements were determined and a rate of return on investment using the discounted cash flow method was calculated.

Capital Costs

Capital costs used for this analysis consist of the total installed cost of the powerplant and the building to house it. It does not include any of the common equipment that must be supplied regardless of the source of the energy that operates it.

The required electrical generating capacity consists of the peak base load of about 2000 kilowatts plus the chiller load of about 800 kilowatts for a total peak load of 2800 kilowatts. For operating flexibility, the manufacturers of total energy equipment recommend that between three and five prime mover-generating units, including a spare, be installed, and that all units shall be of equal capacity. Therefore, the peak load will be provided by four 700-kilowatt diesel engine generator units plus one 700-kilowatt unit to serve as a spare, for a total installed capacity of 3500 kilowatts. Each engine would have its own heat recovery system to remove usable heat from the lube oil, engine jacket and exhaust, and its own muffler. Each engine-generator would have its own automatic control switchgear in conjunction with one master control for automatic load sensing, starting and stopping, synchronizing and load sharing. Piping, pumps and storage tanks for 150 000 gallons are required to collect the heat and distribute it to the common equipment. The common equipment for this installation includes a 2.5 million Btu heat exchanger for domestic hot water, 5 million Btu heat exchanger for space heating, 300 ton absorption chiller, and 1000 ton compression chiller for air conditioning, and a 1600 ton cooling water tower.

The total installed cost of the diesel powerplant heat recovery equipment and the building to house it in is estimated to be $260 per kilowatt or about $900 000. This cost includes storage but does not include any of the common equipment.

Operating Costs

The energy analysis considered only two seasonal days representing average summer and winter conditions. To determine operating costs it was necessary to estimate the energy consumption for the whole year. It was assumed that the electrical load and the domestic hot water load remained constant throughout the year while the winter heat load and the summer air conditioning load were each in effect four months of the year with the four remaining months requiring no space heating or cooling. The seasonal and yearly energy requirements based on these assumptions are summarized in table II.

Operating cost consists of the cost of labor, maintenance and fuel. Total energy systems normally operate unattended so the labor cost is nil. Maintenance and repair costs historically (ref. 5) are valued at about 0.4 cent per kilowatt-hour per year. Fuel prices vary widely so the economic analysis will consider a range of fuel costs to determine their effect.

Investment Analysis

Rate of return on investment using the discounted cash flow method was calculated for the MIUS system. The analysis was performed for an assumed 20-year system life.

To perform the analysis the capital investment, the expected annual revenues, and the expected annual costs were estimated. For all three, both a low and a high value were prepared as shown in table III. By using various combinations of high and low estimates, eight distinct cases can be analyzed. These cases are listed on the left side of table IV. The right side of table IV shows the computed values of rate of return before and after taxes. The after-tax values are shown for three different depreciation schedules. The eight cases are arranged in decreasing order of rate of return with case 1 giving the highest rate of return and case 6 the lowest. It can be seen that over the range of values considered, rate of return is most sensitive to the assumed annual revenues and least sensitive to the capital cost. The method of depreciation employed has little effect on the results. The rates of return shown in table IV are the minimum rates of return to be expected from an investment in a MIUS system depending on the combination of high and low estimates used. Where the minimum rates of return are above the prevailing interest rate, higher rates of return can be realized through financing a substantial portion of the project. The effect of this (and inflation) were further analyzed for cases 1 and 6. The results are shown in table V.

Case 6, marginal to begin with, is affected little by the degree of financing or the interest rate. For case 1 which represents the most favorable investment conditions, a 5-percent annual inflation rate results in rates of return which are approximately 5 percent greater (both before and after taxes) than for the case of no inflation. It may also be seen that the interest rate at which funds are borrowed has a relatively minor effect on rates of return, particularly after taxes. The predominant determinant of rate of return is obviously the degree of financing. With no financing, in the case of 5 percent inflation, the rates of return are 49.2 and 28.6 ercent before and after taxes, respectively. With 80 percent of the capital cost financed at 7.5 percent, the corresponding rates become 188 and 103 percent.

Overall MIUS appears to be economically feasible. Case 4 probably is most representative of current economic conditions with crude oil selling in excess of $10/bbl and utilities requesting electric rate hikes. The analysis shows a rate of return of about 14 percent while more favorable conditions could result in a 25 percent return. However, a more accurate assessment would require better estimates of capital costs, operating costs, and revenues.

FUEL CONSIDERATIONS

The most commonly used fuels for total energy systems have been natural gas and number 2 fuel oil. Both are compatible with gas turbines, diesel engines and fired boilers and both are environmentally acceptable because the exhaust gases meet governmental regulations regarding sulfur dioxide and particulate emissions for residential areas. Until recently these fuels have been abundant and inexpensive but the energy shortage has made them both premium fuels in terms of availability and cost. The fact that energy utilization of any fuel for the generation of electricity is improved by a factor of two or more in a total energy system should be a consideration in any future allocation of natural gas and fuel oil supplies. If cost is the deciding factor, the lower fuel costs for an integrated utility system would be a consideration in deciding between it and a conventional system.

Coal, the most abundant fossil fuel, is currently not acceptable for on-site powerplants because of environmental effects. The development of a clean, compact and efficient coal-fired powerplant for on-site application would be a significant contribution to energy conservation. Research and development on coal conversion (ref. 6) has turned up certain processes that might be adapted for this purpose. Various coal liquefaction processes produce a clean fuel that would meet environmental effects. For example, the solvent refined coal process produces a low sulfur and virtually ash-free fuel that melts at about 350° F and has a heating value of 16 000 Btu per pound regardless of the coal feed stock. Other processes that might apply include atmospheric pressure fluidized or fixed-bed boilers and gasifiers with hot gas cleanup systems to remove sulfur and particulates.

Table VI summarizes the quantities of these three fuels that could produce the electricity and heat requirements stated in table II by either a conventional system or an integrated utility system. The conventional system provides electricity to the site at an overall power conversion efficiency of 30 percent and heat at a thermal efficiency of 75 percent. The fuel savings indicate the energy conservation possible with an on-site powerplant with waste heat recovery.

CONCLUDING REMARKS

The results of this study of on-site powerplants with waste heat recovery are:

1. Minimum fuel consumption is achieved at some characteristic thermal to electric conversion efficiency that is determined by the energy distribution between electrical and thermal loads and therefore is different for each type of community and climatological region. For the apartment used in this analysis this efficiency ranged between 31 and 36 percent which corresponds to a diesel engine-generator powerplant. A conversion efficiency greater than this would not significantly improve the fuel consumption.

2. From an economic viewpoint, this system appears to be a reasonably attractive investment. Based on a total capital investment of about $1 million and assuming high energy costs and revenues, the effective rate of return after taxes can be in the range of 14 to 25 percent.

3. The energy shortage emphasizes the benefits of energy conservation and reduced fuel costs that are characteristics of these systems. The development of a clean, coal-fired, on-site powerplant would further enhance the MIUS concept because it would use the most abundant fuel and use it most efficiently.

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TABLE I. - HOURLY ENERGY REQUIREMENTS

Time	Year-round electrical load, kW	Year-round domestic hot water, 10^3 Btu/hr	Winter heat load, 10^3 Btu/hr	Summer air conditioning load, 10^3 Btu/hr
12 Mid.	360	1 109	4 328	15 600
1 a.m.		778		
2		444		
3		334		
4		334		
5	460	444	4 106	
6	560	556		
7	990	666		
8	1420	1 997	4 328	
9	1300	1 553	4 106	
10	1180	1 775	4 106	
11	1300	1 553	4 328	
12 Noon	1400	1 444	4 328	
1 p.m.	1300	1 222	3 884	
2	1140	1 444		
3	1300	1 109		
4	1400	1 222		
5	1500	1 109		
6	1700	1 222		
7	1940	1 775	4 328	
8	1600	2 109	4 328	
9	1200	1 887	4 993	
10	900	1 444		
11	500	1 109		
Daily total	1055 kW-hr	28 639 10^3 Btu	102 093 10^3 Btu	374 400 10^3 Btu

TABLE II. - YEARLY ENERGY REQUIREMENTS

	Heat, billion Btu	Electric, million kWh	Fuel, billion Btu
Winter	16	3.1	34
Summer	19	5.4	51
Spring/fall	4	3.1	29
Year	39	11.6	114

TABLE III. - COST AND REVENUE ESTIMATES

	High estimate		Low estimate	
	Unit cost	Cost	Unit cost	Cost
Capital cost (3500 kW plant)	$300/kW	$1 050 000	$260/kW	$910 000
Annual operating cost				
Fuel cost	$2.50/$10^6$ Btu	$ 285 000	$1.25/$10^6$ Btu	[illegible] 500
Maintenance cost	0.4¢/kW-hr	50 000	0.4¢/kW-hr	[illegible] 000
Total		$ 335 000		[illegible]92 500
Annual revenues				
Sale of electric power	4¢/kW-hr	$ 460 000	2¢/kW-hr	$230 000
Sale of heat	$3.50/$10^6$ Btu	135 000	$1.70/$10^6$ Btu	66 000
Total		$ 595 000		$296 000

TABLE IV. - RATES OF RETURN FOR VARIOUS

COST AND REVENUE ESTIMATES

Case	Assumed values			Rate of return, percent			
	Revenue	Costs	Capital investment (c)	Before tax	After tax (b)		
					S.L.	1.5 DB	S.D.
1	High	Low	Low	44.2	24.0	24.7	25.3
2	High	Low	High	38.3	20.9	21.5	22.2
3	High	High	Low	28.4	15.6	16.1	16.7
4	High	High	High	24.5	13.5	13.9	14.5
5	Low	Low	Low	9.5	4.9	4.8	5.4
6	Low	Low	High	7.6	3.7	3.6	4.2
[a]7	Low	High	Low				
[a]8	Low	High	High				

[a]Not feasible since costs exceed revenues.

[b]50 percent tax rate assumed. Depreciation assumes 10 percent salvage value, 20 year life. (SL = straight line; 1.5 DB = 1.5 times declining balance; SD = sum-of-the-years digits.)

[c]Assumed financed entirely from equity capital.

TABLE V. - EFFECTS OF FINANCING AND INFLATION

Equity capital, $\$10^3$	Borrowed capital, $\$10^3$ (c)	Interest rate, percent	Case 1 - Rate of return, percent				Case 6 - Rate of return, percent			
			No inflation		5 percent inflation (a)		No inflation		5 percent inflation (a)	
			Before taxes	After taxes (b)	Before taxes	After taxes (b)	Before taxes	After taxes (b)	Before taxes	After taxes (b)
910	0	----	44.2	24.0	49.2	28.6	7.6	3.7	12.3	7.1
728	182	7.5	52.8	28.7	58.0	33.4	7.6	3.7	13.2	7.9
728	182	10.0	52.3	28.5	57.6	33.3	6.9	3.3	12.7	7.6
546	364	7.5	67.2	36.3	72.6	41.4	7.6	3.7	14.5	9.0
546	364	10.0	65.9	35.8	71.4	40.9	5.8	2.7	13.4	8.4
364	546	7.5	95.9	51.5	101.6	56.9	7.7	3.7	16.9	11.1
364	546	10.0	93.0	50.5	98.8	55.9	3.5	0.9	14.5	9.8
182	728	7.5	181.9	97.2	188.0	102.9	7.8	(d)	22.1	16.2
182	728	10.0	174.2	94.4	180.5	100.3	-6.5	(d)	16.9	13.3

[a]Costs and revenues are assumed to grow 5 percent annually.

[b]50 percent tax rate assumed. Straight line depreciation over 20 years with 10 percent salvage value.

[c]Load repayment assumes 20 uniform (equity + interest) payments.

[d]Cash flow vector was negative near end of 20-year period, making rate of return calculation of little value.

TABLE VI. - YEARLY FUEL SUMMARY

	Natural gas, million ft^3	No. 2 fuel oil, gal	Solvent refined coal, ton
Conventional system	184	1 310 000	5750
Integrated utility system	114	815 000	3560
Fuel savings	70	495 000	2190

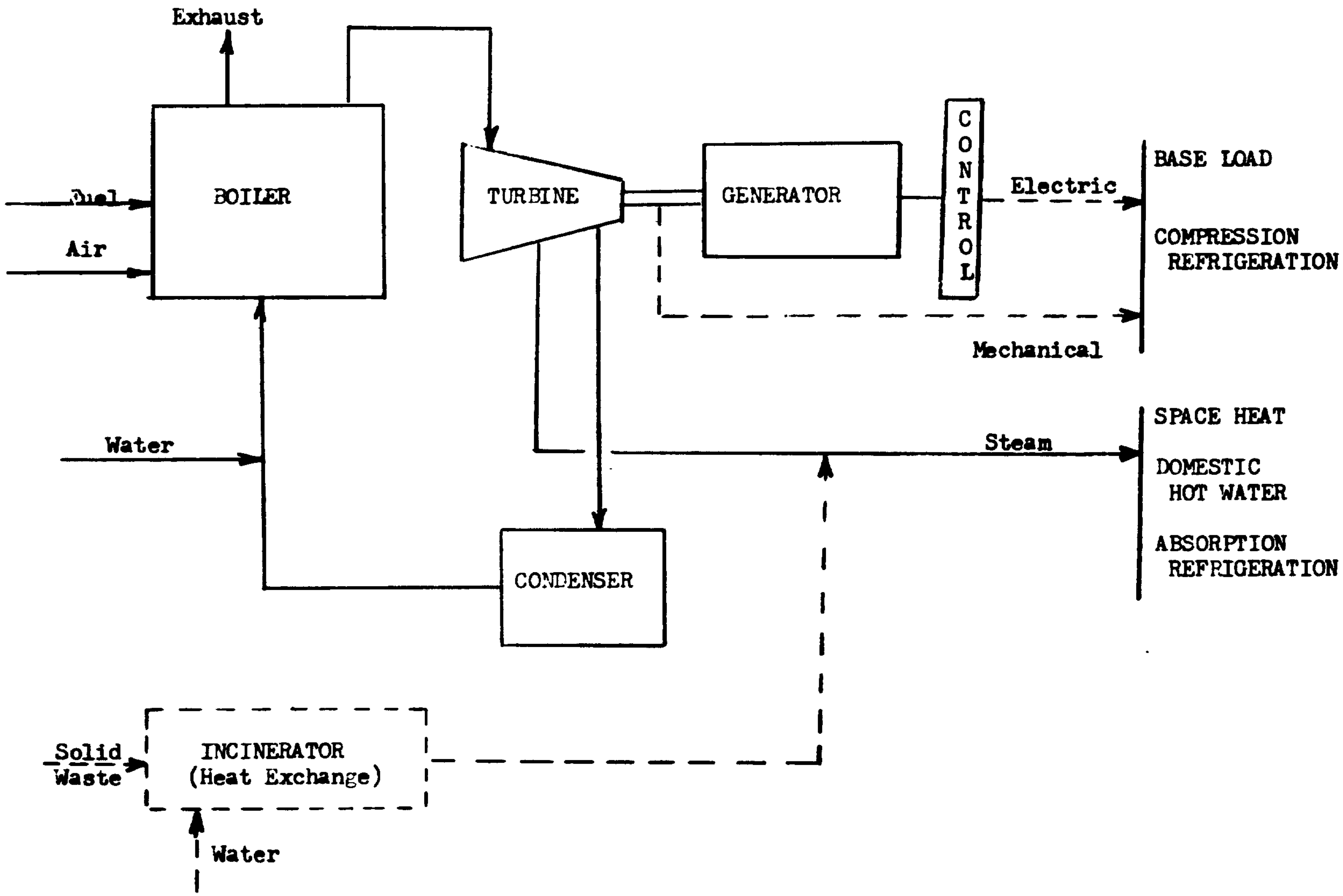

Figure 1. Boiler-Steam Turbine System

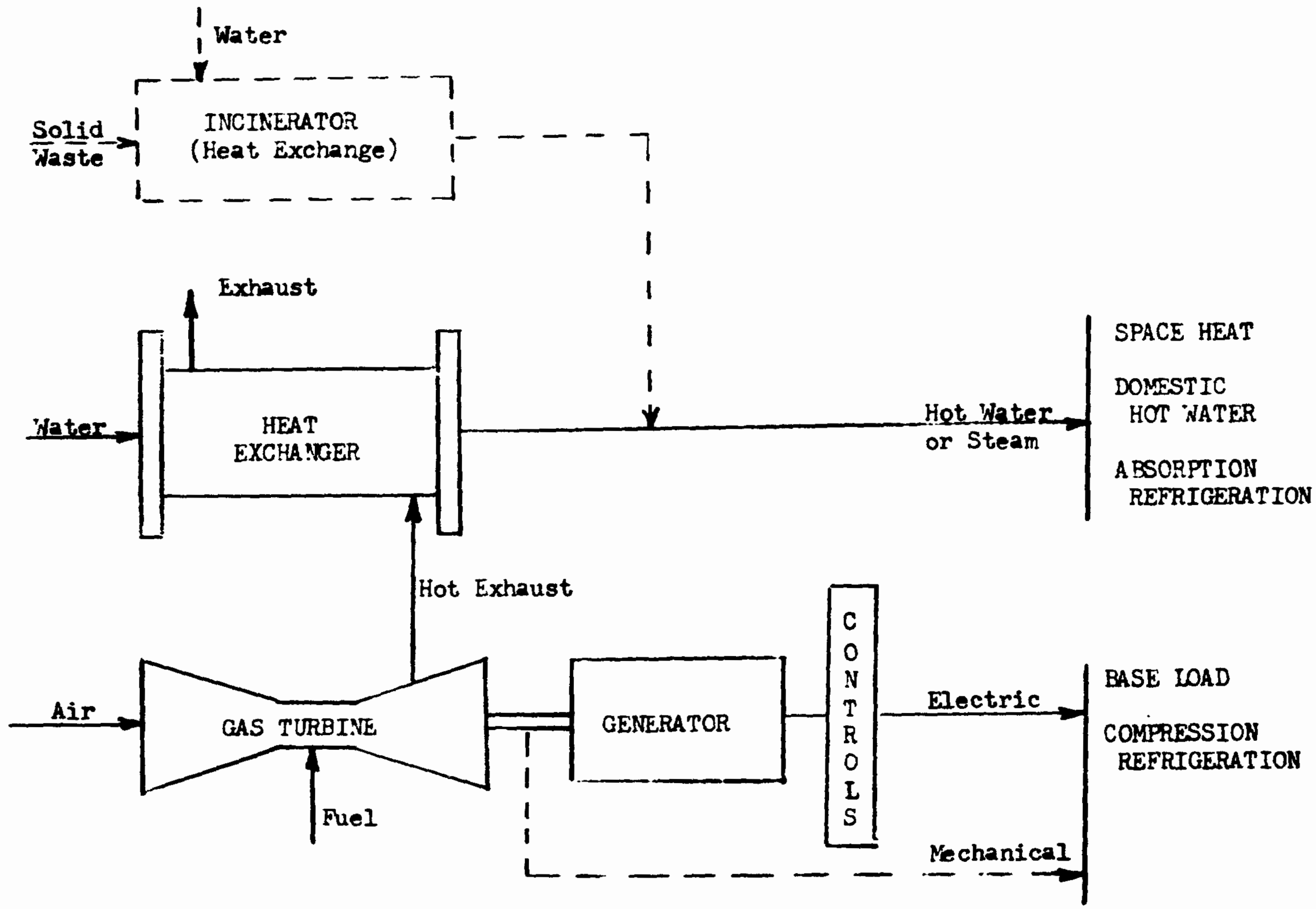

Figure 2. Gas Turbine System

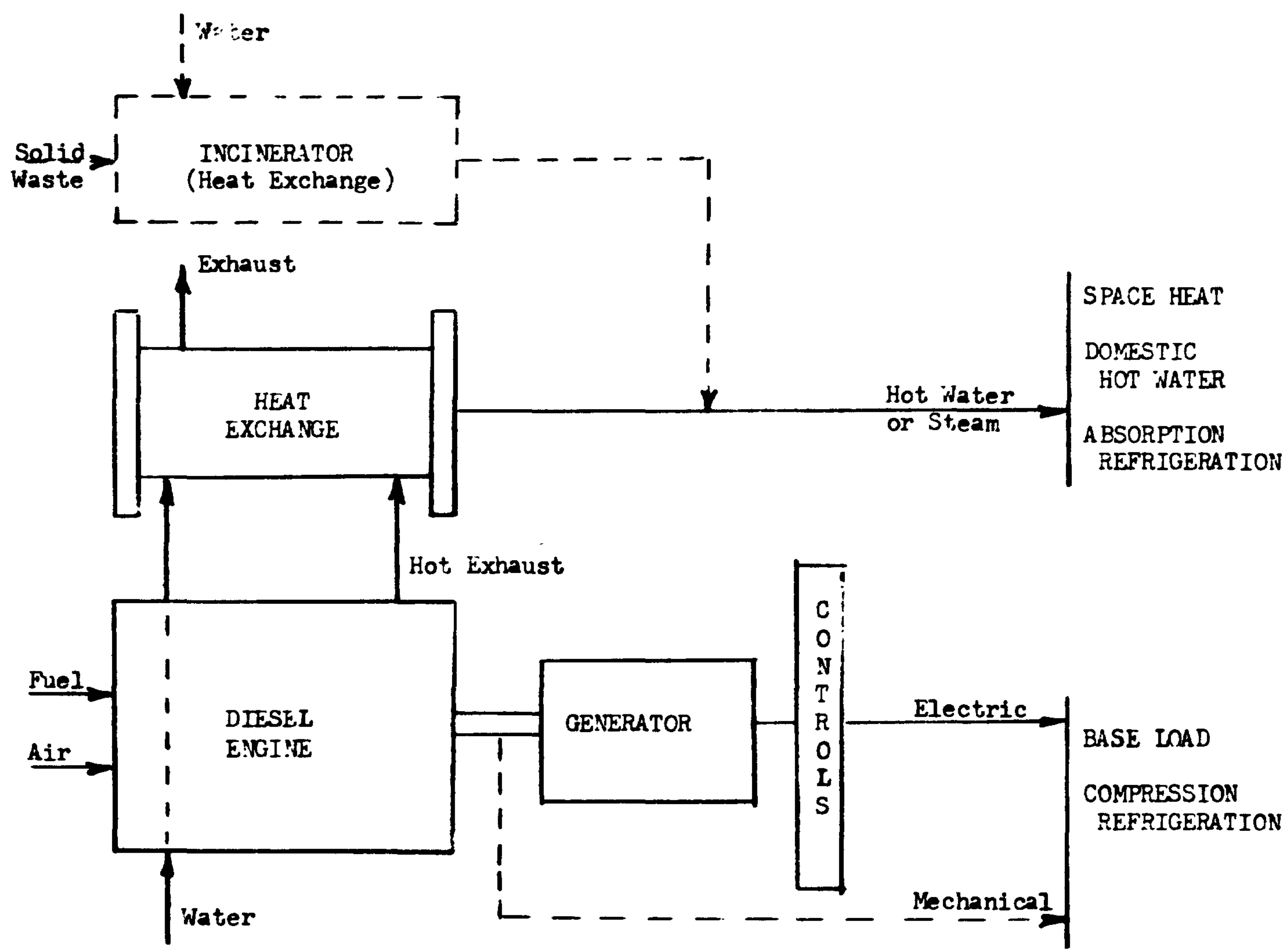

Figure 3. Diesel System

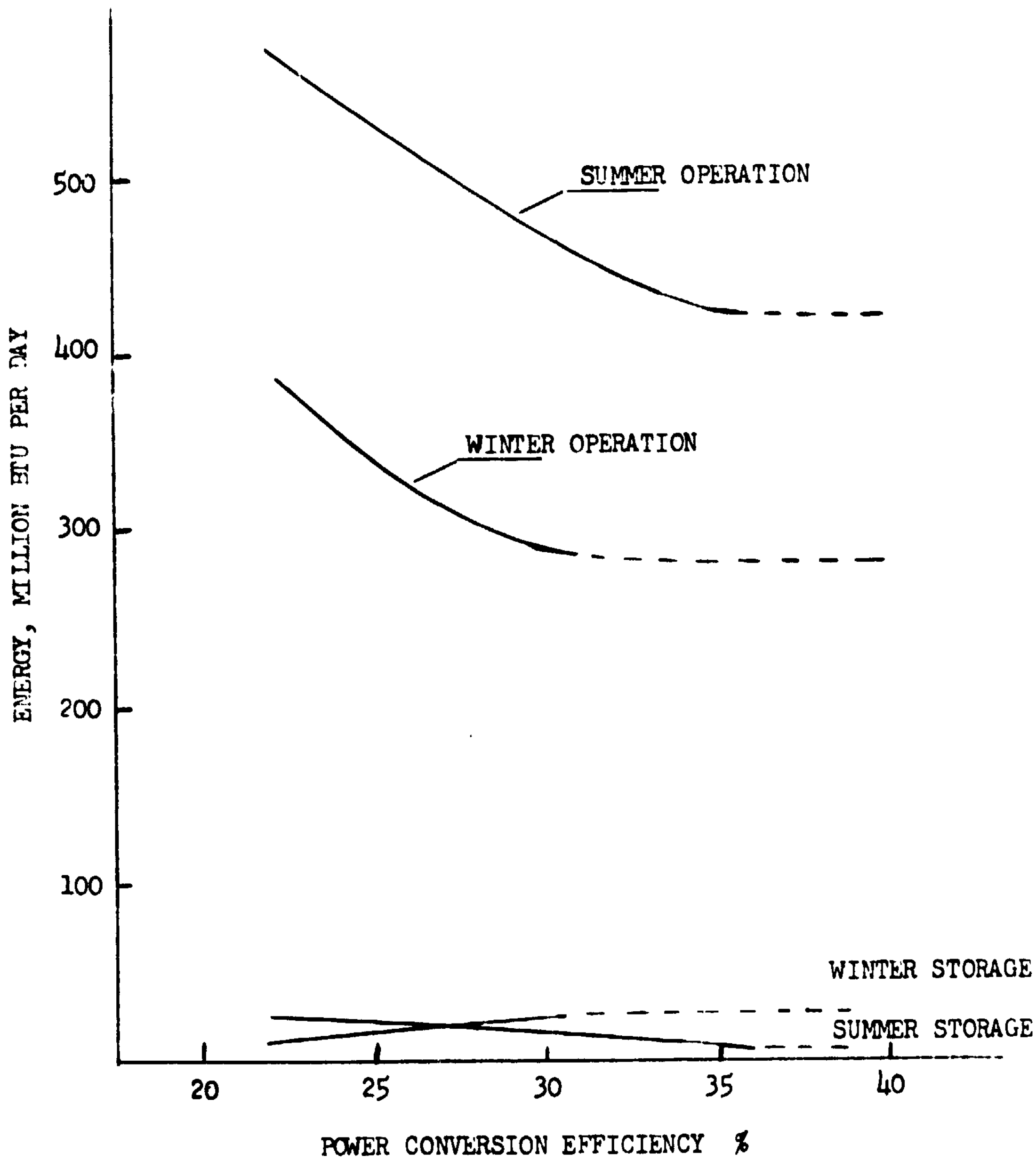

Figure 4. Powerplant Baily Operation

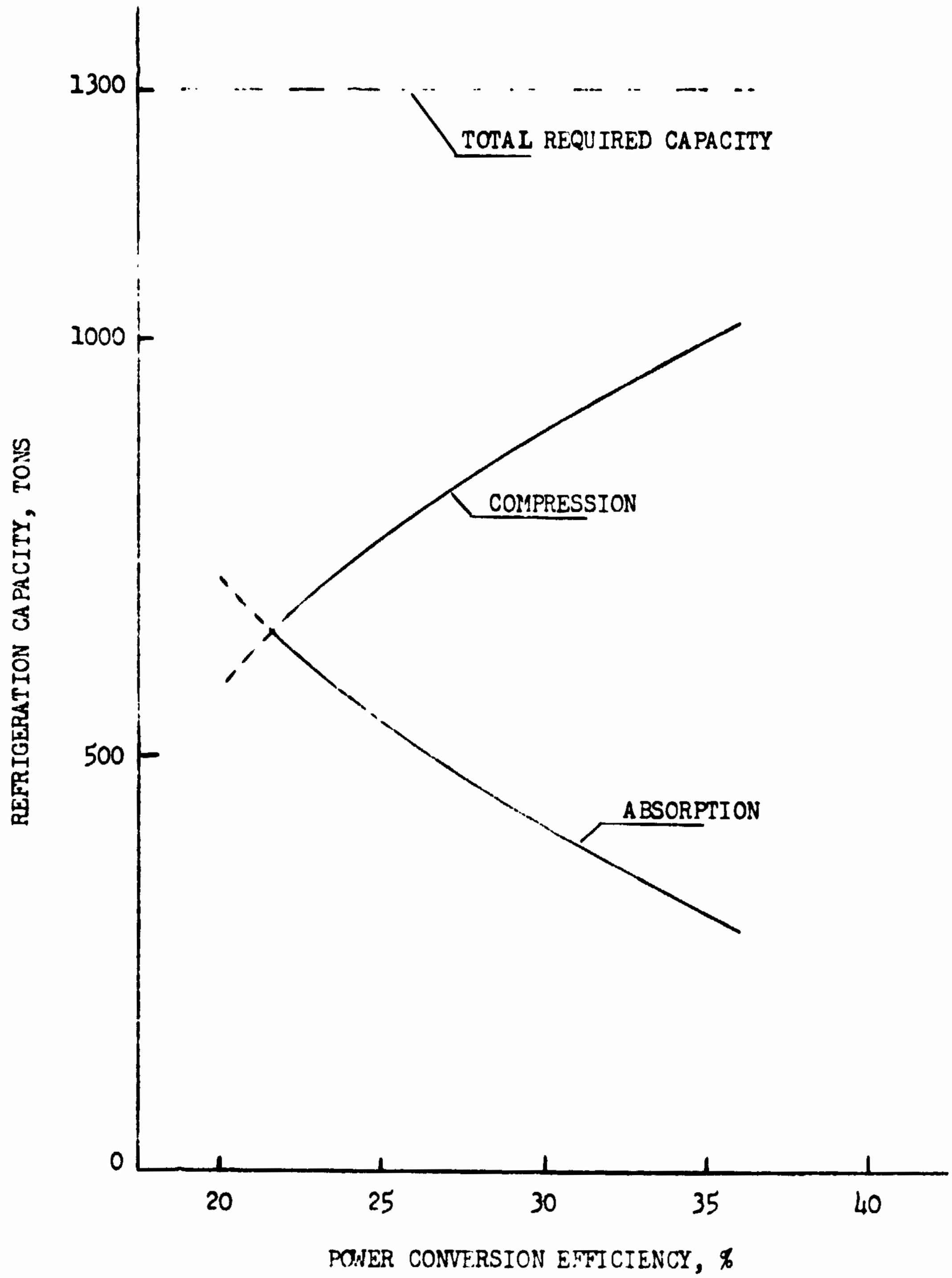

Figure 5. Refrigeration Split