Chapter IX

ENERGY CONVERSION WITH HEAT ENGINES

Chapter IX.— ENERGY CONVERSION WITH HEAT ENGINES

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Chapter IX

Energy Conversion With Heat Engines

BACKGROUND

The basic resource of solar energy is a constant temperature thermal source at approximately 10,000° F.* If this resource is to be used for anything other than lighting, the energy received must be converted into a more useful form. This paper examines three separate technologies for accomplishing this conversion:

1. Thermal devices which use sunlight to heat a fluid and direct this heated fluid either directly for applications requiring heat (such as space-heating or industrial processes) or to operate heat engines;
2. Photovoltaic devices which convert light directly into electricity; and
3. Photochemical devices which use light directly to drive chemical react ions.

This chapter compares the costs and performance of a number of specific heat-engine devices. Photovoltaic and photochemical processes are discussed in chapter X.

A large number of devices for converting thermal energy into mechanical energy and electricity have been developed over the years, and many of these could be converted for use with solar power. The only energy conversion cycles with which direct solar power would not be easily compatible are those requiring internal combustion—diesel engines, for example, would be cliff i cult to convert to a direct-solar application.

The following cycles are considered in some detail:

Rankine-cycle systems using organic working fluids such as Freon show the greatest promise for producing useful mechanical work from solar-heated fluids with temperatures in the range of 650 to 3700 C (1490 to 6980 F). The technology is reasonably well-developed and prototype devices are currently available in sizes ranging from kilowatts to many megawatts. An Israeli manufacturer has been selling small units for nearly a decade, and devices are now available from U.S. manufacturers. Small organic Rankine devices are similar to air-conditioners working in reverse and should be able to exhibit the reliability, simplicity, and low cost enjoyed by refrigeration equipment. Organic Rankine devices are able to make efficient use of the temperatures available, but the overall cycle efficiency is relatively low (5 to 20 percent) because of the low theoretical maximum efficiency of low-temperature heat engines, Low-temperature engines can, however, be operated from fluids produced by simple nontracking collectors and tracking collectors with low-concentration ratios and can use relatively inexpensive storage.

Steam Rankine devices are probably the most attractive contemporary heat-engine designs for temperatures in the range of 3700 to 550“C (6980 to 1,0220 F). (Reciprocating steam engines and saturated steam devices can also operate at lower temperatures.) A variety of devices are available and the technology is mature, although the market for small steam turbines has, until recently, been quite small and designs are somewhat outdated. Rankine-cycle devices operating with steam or other working fluids at temperatures higher than **600“C (1,1100 F) are possible, but the equipment must be made from special materials.**

***This is the effective “blackbody” radiation temperature of the Sun, not its actual surface temperature**

One difficulty with Rankine devices operating in conventional temperature regimes is that their generating efficiency falls sharply if waste heat is recovered.

Brayton-cycle (gas-turbine) engines operate at temperatures of 900"C (1 ,6520 F). Commercial devices are available in a variety of sizes, although efficient devices are typically only available in units producing more than 1 MW. The technology is well understood, although work is needed to develop reliable heat exchangers for solar receivers and regenerators needed to improve efficiency. The efficiency of Brayton-cycle devices is lower than steam Rankine efficiencies, even though the former operates with much higher initial temperatures. The high temperature of the exhaust, however, permits recovery of waste heat without excessive loss of generating efficiency.

Stirling-cycle piston devices are available on a prototype basis and can operate at temperatures in the range of 6500 to 800°C (1 ,2000 to 1,4700 F). Development work is needed to design a reliable commercial device. The engines will probably initially be best suited for applications where individual devices generate less than about 300 kilowatts. They may be able to achieve very high efficiences (40 to 50 percent).

Advanced Ericsson free-piston engines and highly regenerated Brayton devices with multiple stages of reheat are being investigated, and some units are in the development stage, Those cycles would operate in a temperature range of 7500 to 1,000"C (1,382 °to 1,8320 F) and also show promise of achieving high efficiency. The free-piston device may be able to achieve high efficiency with a small, relatively simple engine.

Research is also underway on several other advanced concepts including: Rankine-cycle devices operating with liquid metals, therm ionic devices (prototypes of these devices are available which operate in temperatures of 1,0000 to 1,500 "C; efficiency is poor, but they reject heat at temperatures high enough to drive other engines in a bottoming cycle), and thermoelectric sol **id-electrolyte** devices (systems have been tested which operate in the temperature range of 7500 to 1,5000 F, **but research is in a very early stage).**

The overall system efficiency of these cycles is illustrated in figure IX-l. The temperature ranges which can be produced by different types of collectors are also shown to indicate which collectors would be used to provide heat for the cycles.

THERMODYNAMICS

The cost of most solar systems depends critically on the cost of the collector field and the area of collectors required will depend directly on the efficiency of the energy conversion system employed. The efficiency of an ideal heat engine increases with the temperature available. If heat is available at a constant temperature T_h and is rejected at a constant temperature T_c, the maximum engine efficiency is given by the Carnot efficiency (η_c) where

$$\eta_c = 1 - (T_c/T_h) \qquad (1)$$

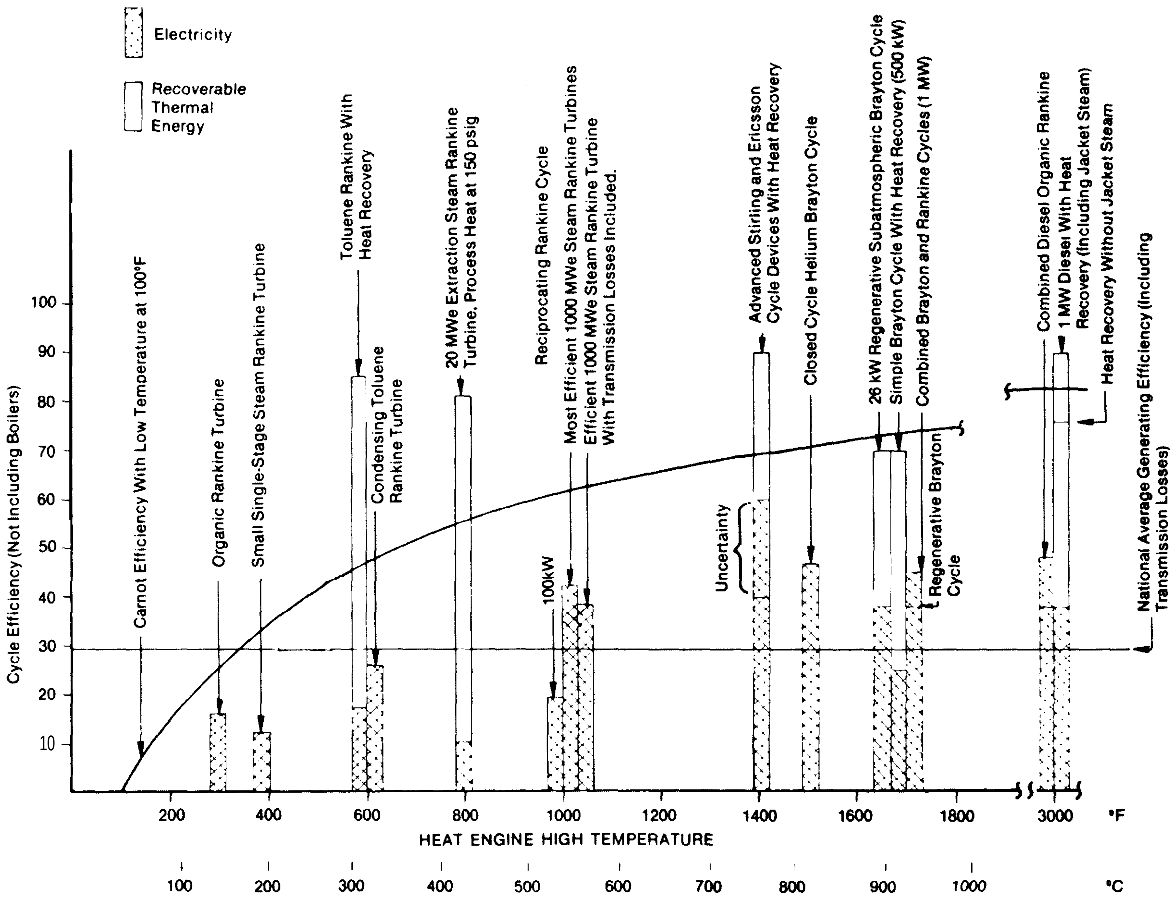
(Both temperatures must be expressed as absolute temperatures.) I n many cases, however, heat will be available only in the form of a heated fluid which cools as energy is extracted. If energy is extracted from a fluid which cools from T_h to T'_h, while giving up heat to the engine, in this case, the maximum efficiency is given by the "ideal" efficiency (η_i) where

$$\eta_i = 1 - \frac{T_c}{T_h - T'_h} \ln(T_h/T'_h) \qquad (2)$$

This is equal to the Carnot efficiency in the limit where $T_h = T'_h$.

In practical externally heated systems, it is not possible to make use of the maximum temperatures available from the combustion of fossil fuels, and the systems are certainly not capable of operating at the temperatures possible from high-performance solar concentrators. The major limitation is the materials available for the receiver in

Figure IX-1 .—Cycle Efficiencies of Heat Engines



* Local temperatures In the combustion chamber only Exhaust gas IS 9000 to 1,4000 F
Note References for Indlvidual estimates can be found In relevant sections of this chapter
SOURCE Prepared by OTA using manufacturer's data

the collector **system and** for engine components. Materials have been developed which can be used with gas turbines at temperatures in the range of 1,8000 F, and it may be possible to develop material (such as silicon nitride or silicon carbide) which can be used at temperatures as high as **2,0000 to 2,5000 F in the next decade. '** The cost of systems using such materials has not yet **been established,** however, and could be quite high.

In spite of the theoretical increase of efficiency with temperature, there are a number of reasons to believe that the use of the highest available temperature may not result in either the most inexpensive solar energy or even the highest efficiency. If both the cost and the efficiency of collectors or of storage devices increases rapidly with temperature, for example, there would be an optimum temperature which would

'Arthur L Robinson, "Making Gas Turbines From Brittle Materials, " Science, Vol. 188 (1975), p 40

minimize overall system costs. (The preceding chapter has presented evidence that collector costs may be nearly independent of the temperatures produced, but this result can only be tested with more experience.) Even if collector and storage costs are independent of temperature, however it may not be desirable to operate at the highest available temperature because the efficiency of real devices does not necessarily increase with increasing temperature. It can be seen from figure IX-I, for example, that the efficiency of steam turbines operating at 8000 to 1,0000 F can be higher than the efficiency of gas turbines operating at 1,4000 to 1,8000 F. A final choice of designs will require a net assessment of the economic attractiveness of the integrated system.

COGENERATION

The analysis of efficiency becomes significantly more complex when there is a need both for electricity and thermal energy. There are several alternatives to choose f rem:

- Generate electricity at the maximum possible efficiency and produce the thermal energy with a separate collector or with a fossil boiler;
- Generate electricity at the maximum possible efficiency and use a heat pump to produce the needed thermal energy (i. e., the heat engine would reject heat at the lowest temperature); or
- Use a heat engine which rejects heat at a temperature high enough to be useful for the thermal processes (cogeneration).

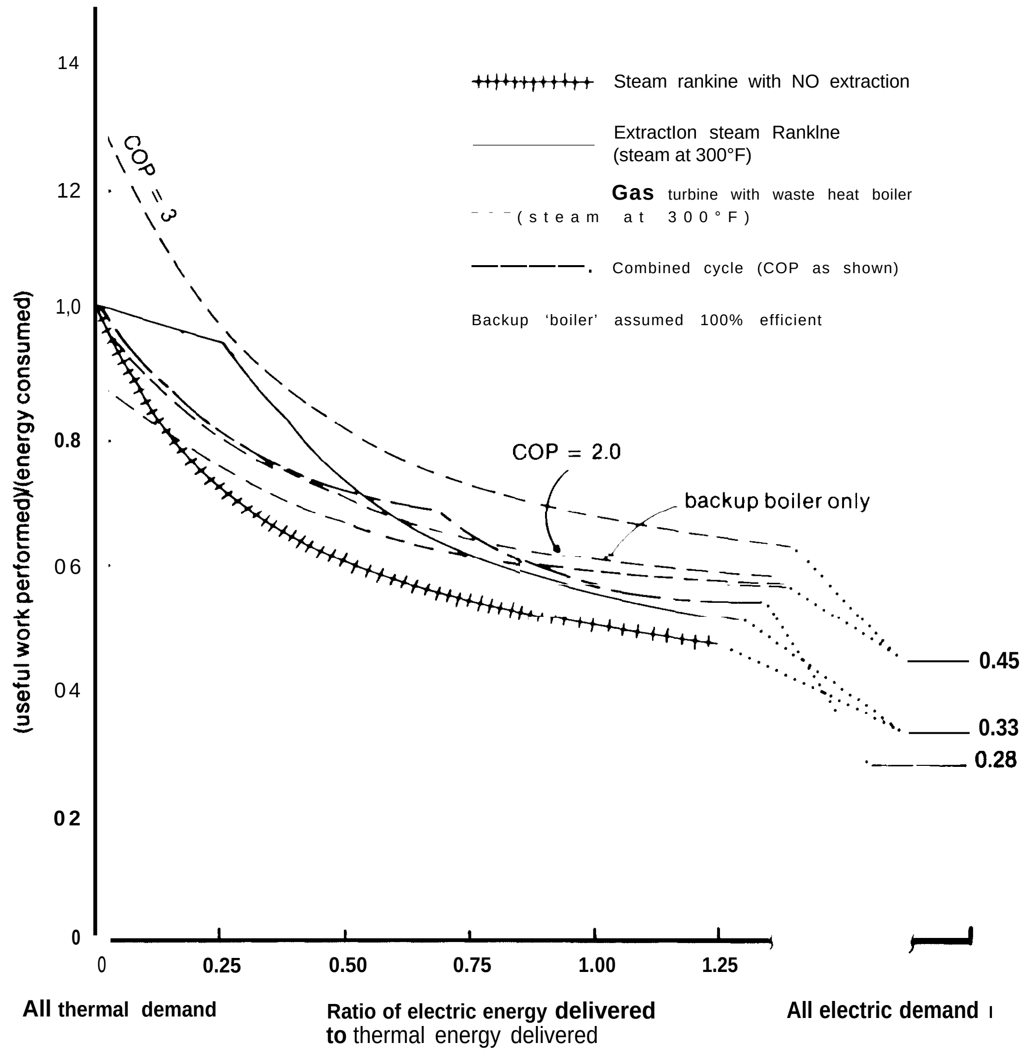
The optimum selection will depend critically on the nature of the thermal and electric loads and on the details of the operational performance of available heat engines.

If ideal systems were available, the second alternative would always define the maximum efficiency; the cogeneration system could equal the maximum efficiency only if the load had a unique ratio between thermal and electrical requirements defined by the waste-heat temperature. With other ratios, some part of the load would have to be met either with a backup "boiler" or with a heat engine using the highest possible electric-generating efficiency.

The complexity of the situation can be een in figure IX-2. This figure shows how the energy required by several types of systems varies as a function of the ratio between electric and thermal demands. The most efficient system is the device employing an efficient heat pump and an efficient heat engine. Commercial heat pumps are not able to produce temperatures above 100 "C, but most space-conditioning applications and many industrial processes can use heat at temperatures below 100°C. The seasonal coefficient of performance of space-conditioning heat pumps is typically below 2, however, and figure IX-2 shows that with this efficiency, cogeneration systems using engines with lower electric-generating efficiency could have better overall performance than high-efficiency engines driving heat pumps as long as the ratio of electric to thermal demand is below about 0.8. The least-efficient system shown, however, is the relatively low-efficiency engine with a backup boiler for providing thermal energy.

All that can be concluded from this analysis is that great care must be taken in designing systems to maximize efficiency. The decision depends heavily on the ratio between electric and thermal loads and the way in which this ratio varies over time. If electricity which exceeds local requirements can be sold to a utility, the perspective of a designer could change. Since the ratio between thermal and electric loads could be changed, in this way the overall efficiency of the system would always be reduced by increasing the electric to thermal ratio. In some circumstances, the greater value of the electricity generated would compensate for the extra cost. The addition of storage equipment could also permit some adjustment of the ratio between the thermal and electric demands placed on the energy conversion system.

Figure IX-2.—System Performance (Ratio of Electric and Thermal Energy Produced to Energy Entering the System)



Note. It is possible for a heat pump to perform several units of useful work for each unit of energy consumed since the "energy consumed" by the engine does not count the energy in the ambient air used as a source of heat "pumped" by the device
SOURCE. Prepared by OTA using manufacturer's data

The following review of each cycle includes a brief description of the way the cycle works, an analysis of the prospects for using the cycle for cogeneration, an estimate of the cost and performance of different design options, and a summary of the current status of research, development, and manufacturing.

THE RANKINE CYCLE

The Rankine cycle has been used since the early 19th century for everything from steamboats to nuclear powerplants. It continues to be the most commonly used for generating stationary power. Designs have, of course, improved over the years and a variety of devices are currently available.

Typical Rankine cycles operate as follows: a liquid is pumped under pressure into a boiler (which could be a receiver in a solar collector) where heat is added, boiling the liquid into a vapor (in some applications the vapor is also superheated); the vapor is then expanded over turbine blades or in a piston to produce mechanical energy; the low-pressure vapor which emerges from this expansion process is condensed to a liquid and pumped under pressure to the boiler where the cycle begins again. In sophisticated systems, efficiency can be increased 4 to 5 percent by preheating the water returning to the boiler with hot vapor extracted from high-temperature stages of the expansion process. Water is the fluid most commonly used in the cycle, but other liquids can offer advantages at lower temperatures.

There is no fundamental limit to the temperatures which can be used in the Rankine cycle, but practical limits are imposed b} the steel alloys used in boilers and other components. The highest practical temperature with current technology is about 1,1000 F. Higher temperatures may be possible in the future using advanced materials, but a recent study by the Federal Power Commission concluded, "It would probably require *10* to *15* years to develop materials for use at temperatures above 1,2000°F."[2] It may be possible to achieve much higher operating temperatures if liquid metals are used as a working fluid.

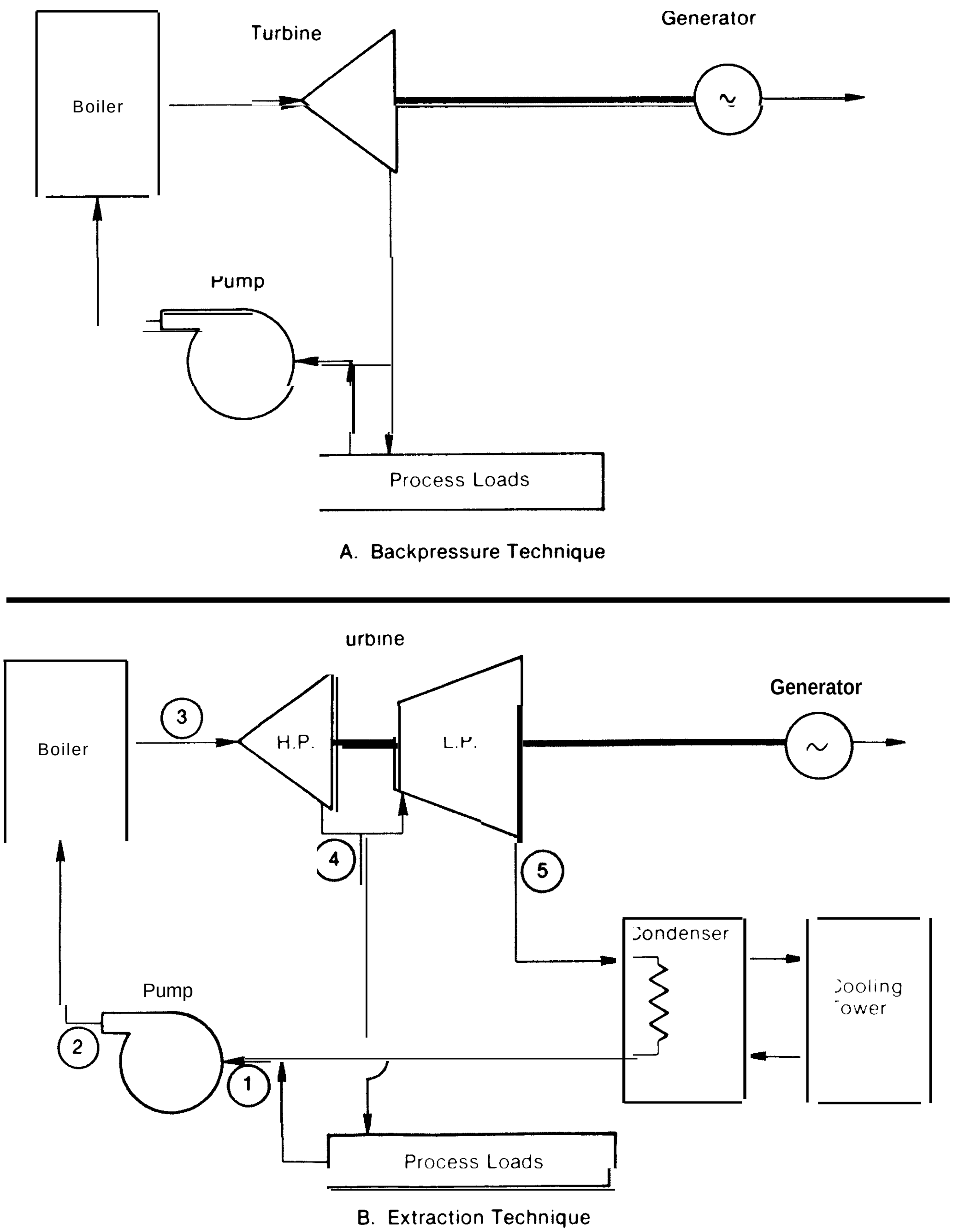
Two techniques are used to extract heat from Rankine-cycle devices for direct thermal applications. Figure IX-3A shows a simple "backpressure" device in which low-pressure vapor is simply sent directly to the process loads. If organic fluids are employed, or if the process requiring thermal energy could contaminate the water used in the turbine, a heat exchanger is used which condenses the turbine fluid and transfers energy to a separate piping system used in spaceheating or industrial processes. The temperature of the steam produced is controlled by the pressure maintained at the end of the final turbine-expansion stage. This temperature can be changed somewhat to adjust to different loads, but a large amount of control is not possible. The system is most useful in situations where there is a relatively constant demand for process heat during the year; it does not require costly condensing equipment or cooling towers since this operation is being performed by the industrial process or building heaters. If there are periods when the heat is not required, however, condensing stages must be purchased to reject the unwanted heat. The backpressure devices producing steam at high pressure can significantly reduce the amount of electricity generated by a given rate of steam flow. A very large fraction of the total energy sent to the system can be recovered as steam heat or electricity, however, since the only losses in the system result from mechanical losses in the turbine, losses in the generator, and oil-cooler losses. These losses are quite small.

An alternative approach is illustrated in figure IX-3B. This system, called "extraction" turbine (or "pass out" turbine by the English and Europeans) is simply an ordinary condensing Rankine device with provision for extracting steam at some intermediate stage in the turbine-expansion process. The device has the advantage of permitting great flexibility in the temperature and quantity of steam produced but, of course, it requires the purchase of condensers, cooling towers, and relatively expensive low-pressure expansion stages. (Low-pressure stages are physically large since the volume of the steam has increased at the lower pressure, and thus these stages are more costly per unit output.)

Steam turbines are used in many industrial cogeneration installations, but are used by less than 1 percent of the "total energy" space-conditioning installations in the

'John H. Nassikas, Chairman, Advisory Committee Report: *Energy Conservation,* Federal Power Commission, The National Power Survey, December 1974, p 86.

Figure IX-3.— Rankine-Cycle Devices With Heat Extraction



SOURCE Prepared by OTA using manufacturer's data

United States.[3] This is due to the fact that their efficiency is low when there is a small demand for space heat, and that local ordinances frequently require experienced operators to be on duty whenever pressurized steam is used. Extraction turbines are, however, frequently used in district heating systems in Europe where a variety of designs are employed. Stal-Laval apparently has a system which saves the expense of a condenser by using low-temperature steam to provide "heating of swimming pools, snow melting in winter, pavement heating, etc."[4]

One difficulty with all large steam turbines is that all of these devices require complex procedures when they are started and when they are turned off. Usually an hour or more is needed and skilled personnel must be present. The process is expensive and wastes energy. It could be a serious barrier to the use of these devices in solar applications where systems must be turned on and off each day. The problem could be alleviated if fossil fuel were used to fire the system when storage was exhausted.

Cycle Performance

The Rankine cycle permits a great range of design options and the system efficiencies vary widely. Efficiency depends principally on the following design features:

- The maximum temperature and the condensing temperature of the cycle.
- The working fluid used.
- The efficiency of the turbine (or piston) expansion process and the mechanical efficiency of the system.
- A number of features, such as the number of stages of expansion used, the use of feedwater heating, etc.

The overall system efficiencies of a variety of simple and regenerated Rankine-cycle devices (i.e., systems in which the working fluid is preheated by hot sections of the turbine before being sent to the boiler) are illustrated in figure IX-4. The extremely high efficiencies of large contemporary steam plants result from the use of many reheat cycles (i.e., adding heat to the working fluid at some stage during expansion) and extremely high pressures. Such sophistication cannot be afforded in small systems. The attractiveness of organic working fluids depends on the power levels required and the characteristics of available heat sources. Organics may prove to be more attractive than steam in small systems working at relatively low temperatures, although ideal steam cycles can produce competitive efficiencies. There are several reasons for this:

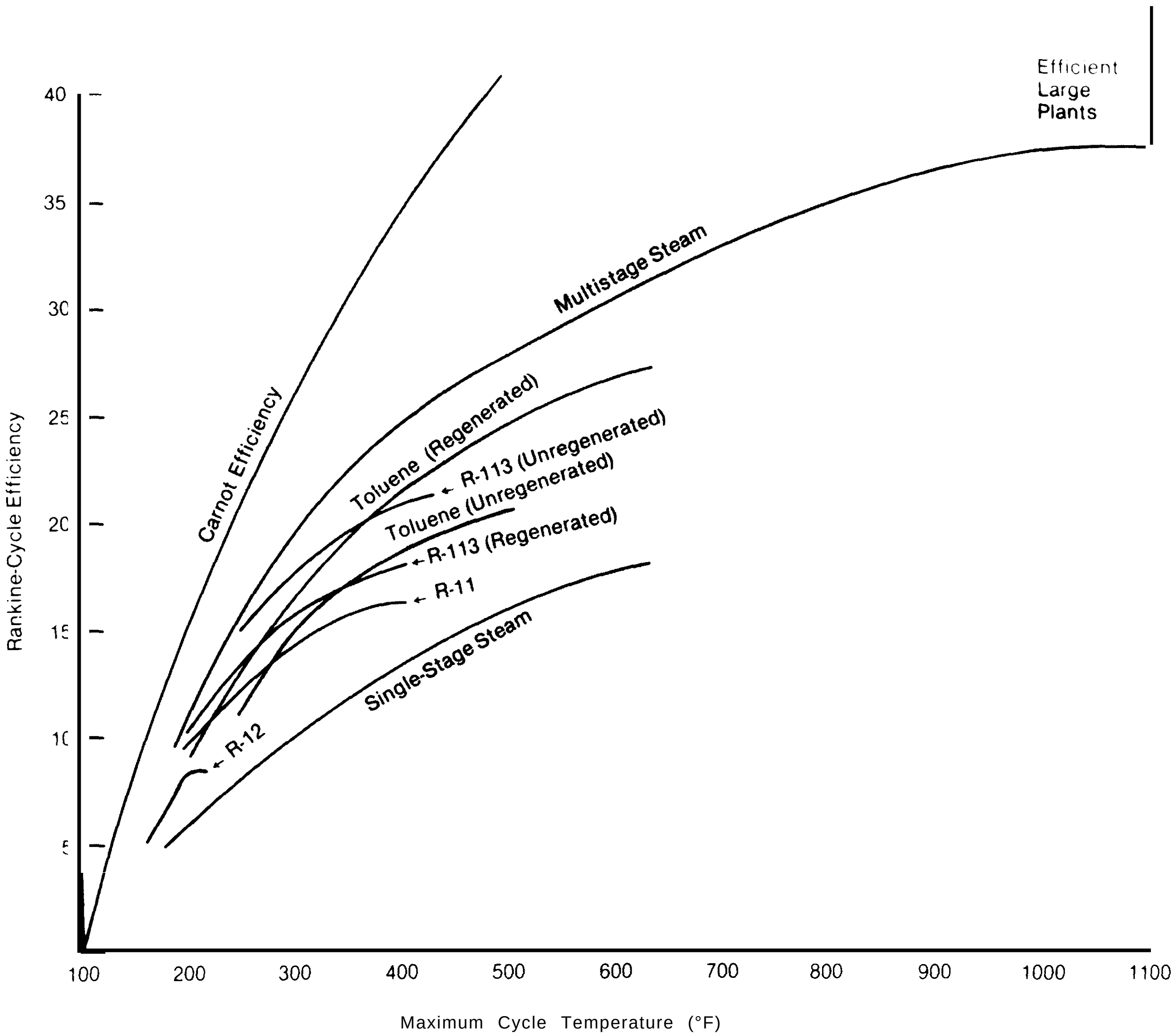
- The organic working fluids remain vaporized under temperature and pressure conditions where steam would be gin to condense. In steam systems, the turbine blades can be eroded severely by the impact of droplets on the rapidly moving blades. These droplets reduce system reliability and system life, as well as efficiency. This problem can be reduced if the turbine is divided into several stages with liquid removed between stages, but this adds to the system's costs
- The efficiency of the organic turbines proves to be greater than steam turbine efficiencies in many systems now operating at low-power levels (figure IX-5).
- The optimum turbine speed of organic systems is lower than equivalent steam systems (potentially saving costs).
- Organic systems are relatively simple compared to multiple-stage steam de-

[3] 1971 *Total Energy Directory and Data Book,* Volume 1, Total Energy Publishing Company, January 1971, pp. 40-66,

[4] I. G. C. Dryden, editor, *The* Efficient Use of *Energy,* IPC Science and Technology Press, Surrey, 1975, p. 355.

'Dean T. Morgan and Jerry P. Davis (Thermo Electron Corporation), *High Efficiency Decentralized Electrical Power Generation Utilizing Diesel Engines Coupled With Organic Working Fluid Rankine-Cycle Engines Operating on Diesel-Reject Steam,* NSF Grant No. G 1-40774, November 1974, pp. 8-28.

Figure IX-4.—Temperature Dependence of Rankine-Cycle Devices



SOURCES Low-Temperature organic and steam efficiencies computed by R E Barber "Solar powered Rankine Cycle Engine Cycles —Characteristics and Costs, " June 1976, with the following assumptions" Expander efficiency 80 Percent, Pump efficiency 50 Percent, Mechanical efficiency 95 Percent, Condensing temperature 95° •F, Regeneration efficiency 80 percent, High side pressure loss 5 percent, Low side pressure loss 8 percent

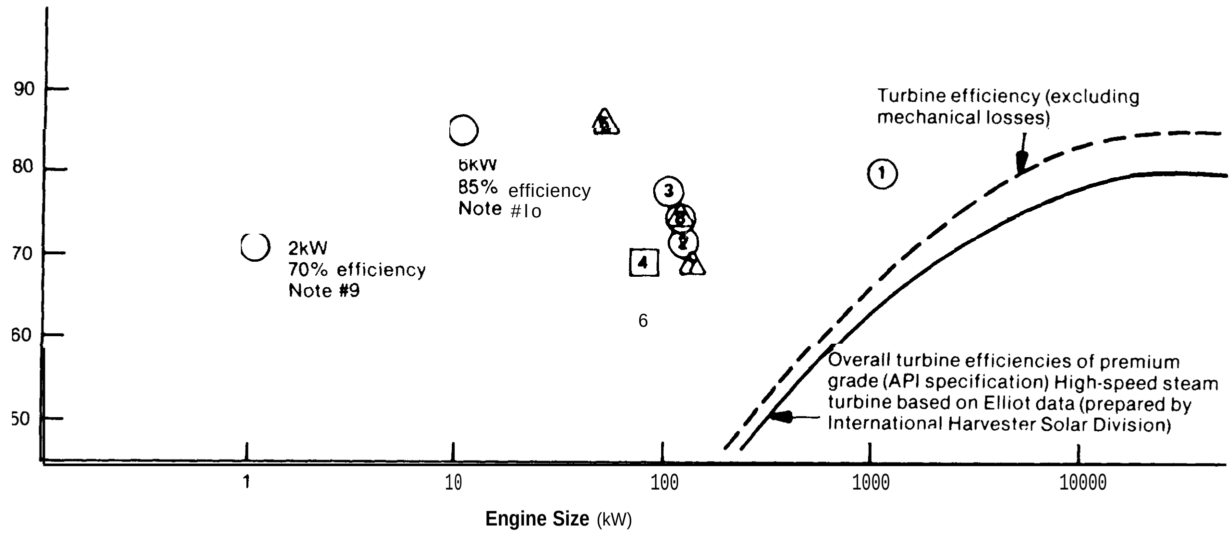
"High-temperature steam efficiencies from National Power Survey Advisory Panel Report On Energy Conservation, December 1974, page 102

vices **and can be constructed inexpensively from low-cost materials** if a noncorrosive working fluid **is used. The systems thus have the potential for** long life and high reliability at relatively low cost.

Thermodynamic properties can **be optimized by selection of an appropriate** organic working fluid for maximum efficiency and power; up to *35* percent greater power output can be achieved with organic relative to steam, depending on heat-source temperature characteristics.

The advantages of organics are counterbalanced to some extent by the fact that many of the fluids being studied are toxic or

Figure IX-5.—Rankine-Cycle Expander Efficiencies



NOTES
1. Thermo-Electron F-85 Organic turbine 1009 kWe, Thermo-Electron, Nov., 1974 op. cit., pages 3-26.
2. Thermo-Electron F-85 Organic turbine 117 kWe, ibid., pp. 3-26.
3. Sustained Aviation 100 kWe toluene cycle, Bud Capron, Sunstrand, private communication, May 1976.
4. ALRC preproto, Jet Propulsion Laboratory, August 1975, op. cit., page 7-7.
5. Carter prototype, JPL, ibid.
6. Lear prototype, JPL, ibid.
7. SES Prototype, JPL, ibid.
8. TECo. FL-50 reciprocating preprototype, JPL, ibid.
9. Barber, op. cit.
10. Eckard, op. cit.

Expander Efficiencies

- △ Reciprocating steam
- □ Steam turbine
- ○ organic turbine
- Reciprocating organic turbine

SOURCE. Prepared by OTA using manufacturer's data

flammable. The systems are sealed, however, and only small amounts of the fluid should leak from the cycle in a properly maintained system. Another potential drawback is the cost of the fluids, although fluid costs tend to be only a small fraction of overall system costs even if expensive fluids are used. (Water clearly has the advantage of being cheap, plentiful, and nontoxic.) The characteristics of a variety of materials which have been considered for turbine applications are shown in table IX-I.

Refrigerants are attractive for applications up to about 4000 F. They are nontoxic and the technology of Rankine systems using these materials is very well known since refrigerators are simply Rankine cycles operating in reverse. A number of other materials have been examined for application at temperatures up to about 8000 F, and the search for the desirable materials is continuing. In the temperature range of 7000 to 1,1000 F, there is no advantage in using fluids other than water.

Many early organic systems have had reliability problems resulting from failures of bearings and seals. These problems have apparently been overcome by several manufacturers, and high reliability is one of the selling points of organic Rankine engines designed for use in isolated regions. Reliable systems are presently quite expensive, however.

Turbine Efficiency

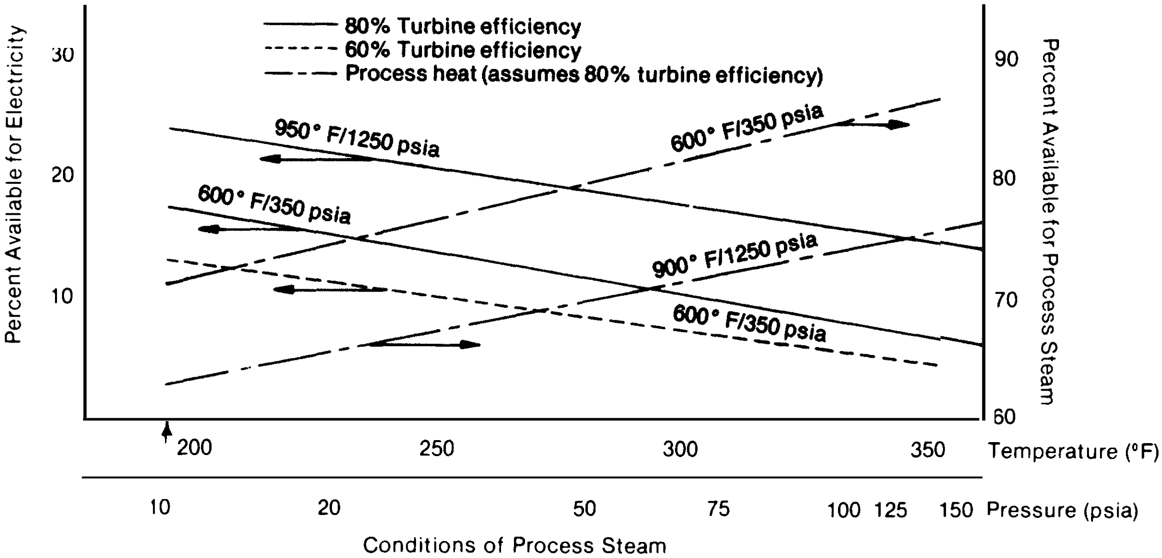
Turbine performance is limited by the size of the equipment as well as by the temperatures available. Figure IX-6 illustrates the efficiency with which turbines of varying

Table IX-1. —Organic Power-Cycle Working Fluids Used in System Testing or in Development

Fluid	Developers	Maximum boiler out let temperature ‘F	Freezing point ‘F	System test experience	Flammabillty	Current development underway	Comments
Freon 11	IHI (Japan) Sofretes (France) Barber-Nichols (US) United Technologies (US)	-250	-168	Yes	Non-flammable	Yes (primarily IHI and Sofretes)	Favorite low temperature working fluid; power and combined power/air-conditioning
Freon 114	TECUS)	-400	-137	Limited	Non-flammable	No	Combined power/air-conditioning
Freon 22	TECO (US)	425	-256	Yes	Non-flammable	No	Combined power/air-conditioning
Isobutane	Rogers Engineering (US)	-500	-217	Yes	Highly flammable	Yes	Other aliphatic hydrocarbons and as propane, butane are under consideration, primarily for geothermal, although Sofretes (France) has operated a propane system
Thiophene	TECO (US)	550	-37	Yes	Highly flammable	No	Vertical saturated vapor line on T-S Diagram (Isentropic fluid)
FC-75 (3 M Co)	Fairchild-Hiller (US)	-600	-76	Yes	Non-flammable	No	Requires very high regeneration generally lower efficiency than other fluids at given boiler outlet temperature
Chloro-benzenes	Dupont (US) Ormat (Israel)	-600	-49 (Monochloro-benzene)	Yes	Fire resistant	No Yes	The Ormat unit is the only Rankine-cycle system used commercially
Monoisopropyl Biphenyl	Ford Aero-neutronic (US)	-600	-68	Yes	Highly flammable	No	Requires high regeneration, very low condenser pressure
Fluorinol	TECO (US)	625-650	-82	Yes	Fire resistant	Yes	Extensive experience 7 years of system testing
Pyridine/ water mixture	Union Carbide (US) Monsanto (US)	-700	75	No	Flammable	No	—
Dowtherm A	Aerojet-General (US)	-700-750	+ 54	Yes	Flammable	No	Requires high regeneration, very low condenser pressure
Toluene (CP-25)	Sunstrand (US)	-750	-140	Yes	Highly flammable	Yes	Extensive experience
Hexafluoro-benzene Octofluoro-benzene mixture	Aerojet-General (US)	-800-850	-40	Yes	Non-flammable	No	Very expensive fluid at present
Hexafluoro-benzene Pentafluoro-benzene mixture	Monsanto (US) TECO (US)	-800-850	-40	No	Non-flammable	Yes	Very expensive fluid at present

SOURCE Thermoelectron Corp

Figure IX-6.— Efficiency of Backpressure Steam Rankine Devices



Assumptions

Working fluid: water
Turbine expansion efficiency 80% and 60% (as shown)
Pump efficiency 70%
Generator efficiency 95%
5% loss in blowdown
Inlet conditions 1250 psia/900 °F and 350 psia/600 °F (as shown)

SOURCE: Prepared by OTA.

sizes can **extract** the energy available in the fluids sent to them. It can be seen that with current designs the efficiencies of small systems are quite low. This is in part the necessary result of the fact that a clearance must be maintained between the turbine blades (or pistons) and their containment cylinders. (This is not a limiting factor for single-stage impulse turbines.) The fluid which can leak through this aperture does not perform work and thus limits efficiency. In smaller systems, the clearance area is a larger fraction of the total useful turbine blade area and thus smaller systems are more seriously affected by these effects. The figure illustrates, however, that several advanced turbine and reciprocating engine designs have been able to achieve relatively high efficiencies even at small sizes.

High turbine efficiencies have been demonstrated even in very small devices. Barber-Nichols Engineering Company, for example, has constructed a 2.5 hp turbine, operating on a refrigerant, which demonstrated a turbine efficiency of 72 percent.[6] A small multivane expander developed by the General Electric Co. has demonstrated efficiencies as high as 85 percent.[7] It is clear, therefore, that high-turbine performance is not necessarily restricted to large devices.

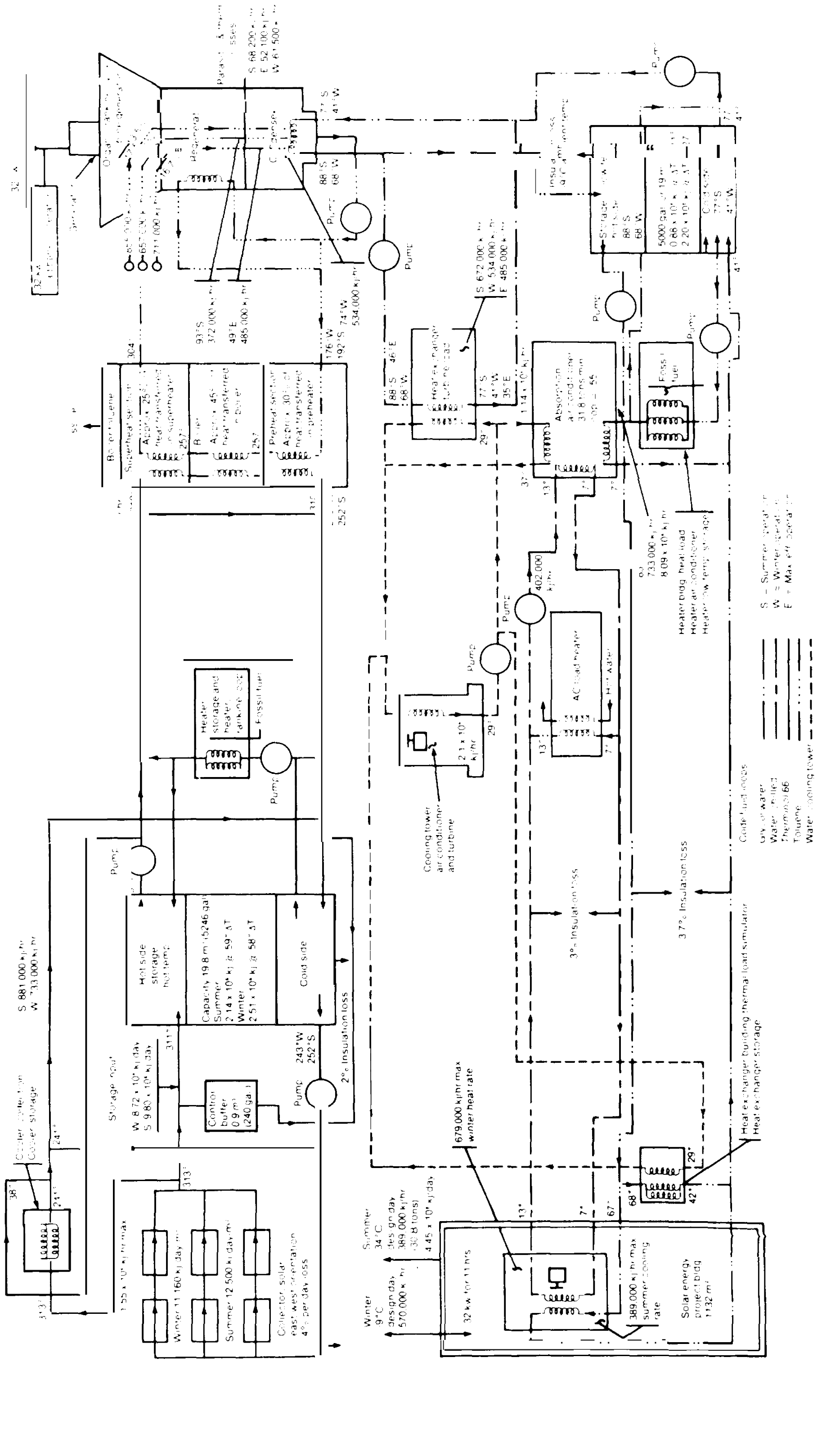
Performance With Heat Recovery

The decline in generating efficiency which is experienced by steam Rankine devices operating with backpressure and ex-

[6]Robert E. Barber, "Solar Air-Conditioning Systems Using Rankine Power CycleDesign and Test Results of Prototype Three-Ton Units, " *Proceedings,* the Second Workshop on the Use of Solar Energy for the Cooling of Buildings, Los Angeles, Calif , Aug. 4-6, 1976, p. 91.

[7]S. E. Eckard and J. A. Bond, "Performance Characteristics of a Three-Ton Rankine Powered Vapor Compression Air-Conditioner, " Proceedings, the Second Workshop on the Use of Solar Energy for the Cooling of Buildings, op. cit., p. 110.

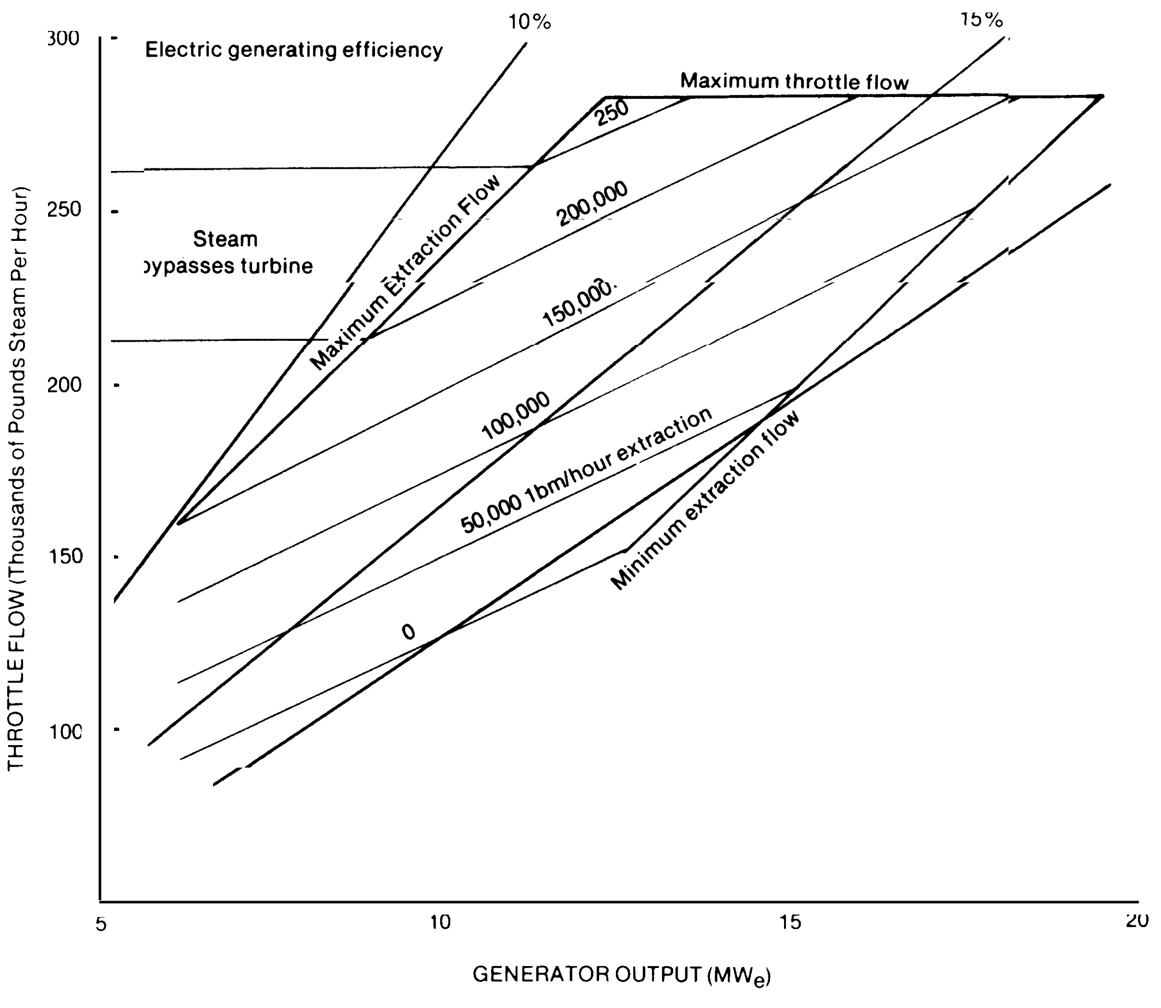
Figure IX-7.—Schematic Diagram of the Solar Total Energy System Installed at Sandia Laboratories in Albuquerque, N. Mex.



SOURCE: Sandia Laboratories, Solar Energy Projects Division "Solar Total Energy program Semiannual Report October 1975-March 1976 (June 1976) page 19 (SAND76-0205) traction systems is shown in figures IX-7 and IX-8. The efficiencies shown in these figures represent a highly simplified analysis of the cycle and are intended only to illustrate the sensitivity of generating efficiency to changes in several important variables.

Figure IX-6, for example, illustrates the difficulty of using backpressure turbines with relatively low-inlet temperature systems to produce process steam at high pressures and temperatures. Generating efficiency falls off rapidly with increasing backpressure and

Figure IX-8.— Electric and Therma Performance of a 12.5 MW_e General Electric Extraction Turbine



INLET CONDITIONS	400 psig, 750° F	maximum throttle flow: 280,000 lb/hour
OUTLET CONDITIONS	5 psia,	
EXTRACTION:	40 psig,	maximum extraction flow: 150,000 lb/hour
		minimum extraction flow: 5,500 lb/hour

SOURCE: GE Corp

the problem is exaggerated unless high-turbine efficiencies can be achieved.

Figure IX-7 illustrates the operation of a backpressure device using toluene as a working flu id which has been installed in Albuquerque to test the concept of solar-powered "total energy" systems. The system is equipped with a cooling tower since the heat extracted from the turbine is used for a heating and cooling application where loads are likely to vary greatly from day to day.

The performance of an extraction device is illustrated in figure IX-8, using a format which has become standard for presenting data about such systems.

Steam Rankine devices have been selected by all three contractors working on a design for DOE'S 10 MWe **solar central-receiver demonstration plants,**[8 9 10] **The** total energy test design developed by Sandia uses the toluene-based Rankine cycle shown in figure IX-7.

Performance With Backup Power Sources

It is possible to design Rankine-cycle systems which are capable of operating both from fossil fuels and from solar power. The temperatures used are low enough to permit piping energy from boilers operated from different sources to a single Rankine turbine device. *In* addition, the boilers can be externally fired so coal or other solid fuels can be easily used for backup fuel.

Two approaches are shown in figure IX-9A. The most efficient type of backup systems provide energy from a fossil-fired boiler or a storage unit at temperatures and pressures which are as close as possible to those of fluids supplied directly from the solar collectors. With this approach, the performance of the cycle is not changed by a shift from solar to backup power.

If a storage device capable of supplying temperatures close to those supplied directly from the solar collectors is not available at an acceptable price, it would be possible to use a turbine with two different inlets: one for high-temperature fluids received directly from the collectors, and one for lower temperature fluids received from storage. (This is shown by the dotted line in figure IX-9 A.) Steam turbines with multiple inlets have been available for many years, although most are relatively large.

Another approach which may be attractive under some circumstances would use the "hybrid" system illustrated in figure IX-9B. In this design, solar energy at relatively low temperatures is used to boil the working fluid and a fossil boiler is used to superheat the liquid to the turbine inlet conditions, This system takes advantage of the fact that the majority of the energy absorbed by conventional Rankine cycles is absorbed at a constant temperature while the liquid is converted into vapor. This system would take advantage of the relative simplicity of solar collectors operating at moderate temperatures, while permitting more efficient utilization of the high-flame temperatures available from burning fossil fuels.

The performance of these different approaches can be summarized in the following simplified analysis. If the fraction of the thermal energy applied to the system which leaves as mechanical energy through the high-pressure and low-pressure stages of the turbines is called η_{hp} and η_{lp}, respectively, and a fixed fraction f of the liquid vapor mixture emerging from the high-pressure stage is available to be sent to the low-pressure stage (the remainder being used to preheat the feedwater going to the boiler), the total electric output of the engine E is written as follows:

$$E = Q_b(\eta_{hp} \bullet \alpha\gamma\eta_{lp}). \qquad (3)$$

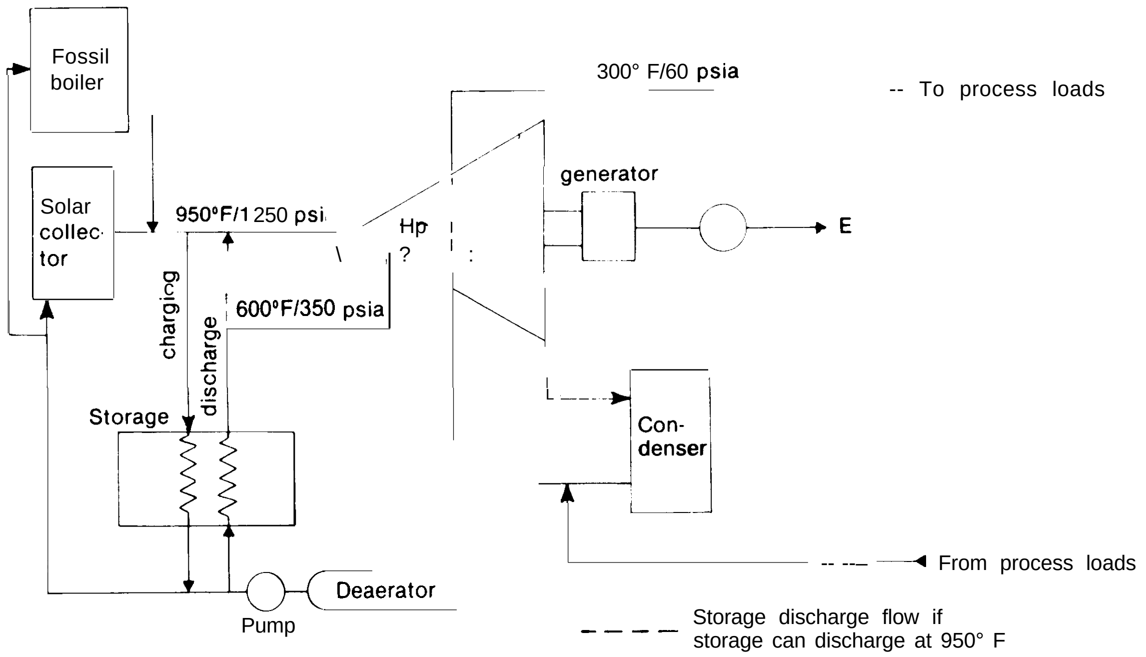
Here Q_b is the energy available from the

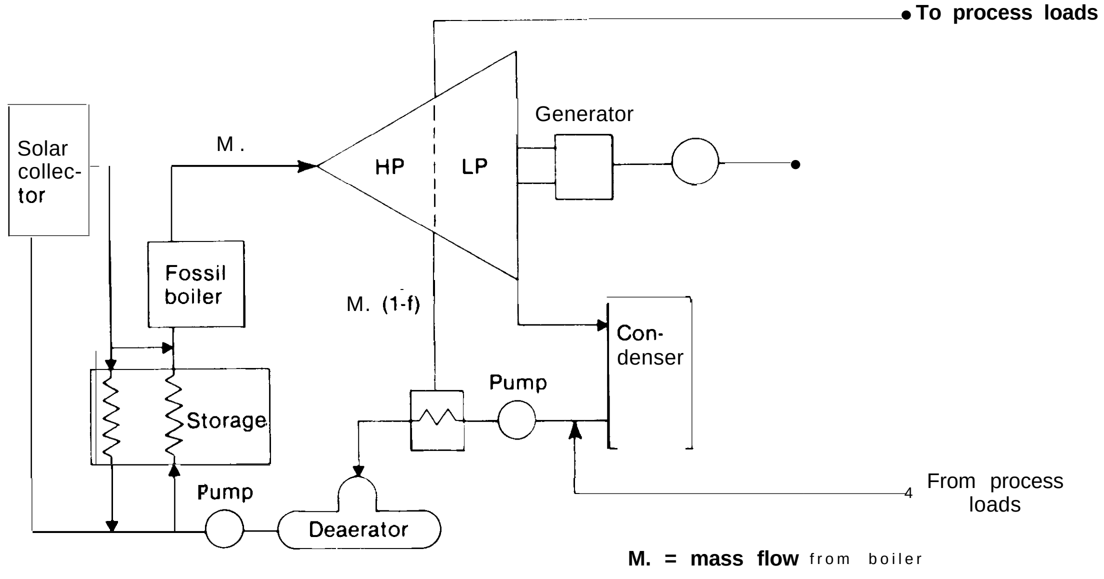
[8] Quarterly Report No 1, Central Receiver Solar Thermal Power System, Phase 1, January 1976, Martin Marietta (ERDA Contract E(04-3)-1 110)

[9] Central Receiver Solar Thermal Power System, Phase 1, Final Report, January 1976, McDonnell-Douglas Astronautics Company (ERDA Contract E(04-3-1 108)

[10] "Solar Pilot Plant, Phase 1, Conceptual Design Report, Dec. 18, 1975, Honeywell, Inc. (ERDA Contract E(04-3)-1 109)

Figure IX-9.— Designs for Providing Backup Power for Solar Rankine-Cycle Systems





SOURCE. Prepared by OTA using manufacturer's data boiler or from other sources and γ is the fraction of the energy available from the first turbine stage which is sent to the second stage. The remaining fraction $(1-\gamma)$ is available for process loads. Using the same notation, the energy available in the process heat Q_p can be written as follows:

$$Q_p = (1-\gamma)\, \alpha\, Q_b \qquad (4)$$

where α is a constant which is dependent on the temperature of the process heat stream. These parameters are illustrated in figure IX-9B. A sample set of these parameters is illustrated in table IX-2 for a turbine operating with 9500° F, 1,250 psia steam. The decrease in system performance resulting from the lower storage temperatures can be clearly seen. The performance can be improved considerably if the fossil boiler is used to raise the temperature to the original inlet conditions.

Table IX-2. —Efficiency of Steam Rankine Devices operated From Storage at Reduced Temperature

	Single-feed water regenerator	No feed water regenerator
Turbine inlet conditons		
η_{hp}	0.26	0.23
η_{lp}	0.11	0.11
$\eta_{hp} + \alpha\eta_{lp}$	0.34	0.30
α	2.68	2.94
f	0.82	1.00

Assumptions: generator efficiency = 95%
turbine efficiency = 800/0
pump efficiencies = 700/o
steam extracted for reheat at 300° F
inlet conditions 950° F/l 250 psia

η_{hp} = fraction of energy entering system which leaves as mechanical power in the first turbine stage

η_{lp} = fraction of energy entering system which leaves as mechanical power in the second turbine stage

α = 300° F energy available for process heat or low pressure turbines per unit of energy available from the high-pressure turbine

SOURCE Prepared by OTA using manufacturer's data.

The performance of designs using a fossil system to superheat the steam can be estimated from the efficiencies shown in table IX-2 and the ratios shown in table IX-3. This last table indicates the percentage of the energy entering the turbine which results from the boiling process. Boiling can represent a large fraction of the total energy requirements. The boiling temperature for this system shown is 5720 F. Using fossil fuels only to provide superheat would effectively increase the efficiency of converting fossil energy into electric output.

Table IX-3.—Ratio of Energy Required for Boiling to Total Energy Sent to Turbine

	Boiling temper-ature	Ratio
extraction turbine 950° F/l 250 psia (feedwater regeneration)	572° F	0.76
950° F/1250 psia(no feedwaterheat)	572° F	0.79
600° F/350 psia backpressure50 psia	486° F	0.91
400° F/150 psia backpressure50 psia	247° F	0.99

SOURCE: Prepared by OTA using manufacturer's data.

State of the Art

While Rankine-cycle engines are available in a variety of sizes, most of the development work in the United States in recent **years** has been directed to perfecting very large devices optimized for centralized **utility applications.** Because of the limited demand for small steam turbines, designs tend to be somewhat antique, although interest in smaller devices has been greatly increased in recent years.

A number of companies are working on devices capable of improving the performance and reducing the costs of small Rankine-cycle systems. Table IX-4 indicates some of the steam turbines which were identified by Sandia Laboratories in their review of devices for use in their total energy system. Extraction turbines and backpressure

Table IX-4.—Small Steam Rankine Turbines (1973 Dollars)

Capacity (kW)	cost ($ in thousands)	Source
2	2.0	5
	4.5	2
3	3.7	1
5	3.0	1
10	4.1	1
	3.8	5
	2.5	5
20	6.0	1
100	18.0	1
	11.3	1
	10.0	5
	9.6	6
	9.0	2
250	50.0	3
400	17.5	1
500	30.0	4
1000	100.0	2
	70.0	3
	45.0	4

SOURCE: Solar Total Energy Program Semiannual Report, April 1975- September 1975, Sandia Laboratories, Solar Energy Projects Division, April 1976, p. 96.

Source Legend:
1 - Coppus Engineering Corporation
2- The Terry Steam Turbine Company
3- The Trane Company, Murray Division
4- Turbodyne Corporation, Worthington Turbine Division
5- The O'Brien Machinery Company
6- Carling Turbine Blower Company

turbines are also available in the sizes of interest to intermediate total energy applications. Most interest in this research comes from several directions including:

1. A desire to develop devices to improve the fuel economy of diesel-generator sets and gas turbines through the use of a "combined-cycle" approach.
2. **Making use of waste heat from other industrial processes which is available at temperatures of 2500 to 1,0000 F.**
3. **Interest in exploiting geothermal energy** in the range of 2000 to 6000 F.
4. Interest in developing new engines for automobiles and other vehicles.

The Environmental Protection Agency and the State of California funded research on steam-powered automobiles, beginning in 1972, which led to the construction of two prototype steam vehicles–one built by Steam Power Systems and the other by Aerojet Liquid Rocket Company. There has also been a considerable amount of interest and investment in this area by private companies, including Lear, Carter Enterprises, and Saab-Scandia of Sweden. Table IX-5 summarizes the performance of some of the equipment which has been investigated.

Interest in small, combined-cycle systems has come mostly from companies which construct onsite generating facilities for remote locations (pipeline **pumping stations, offshore drilling rigs, etc.). international Harvester, Solar Division,** for example, believes that a steam turbine which operates on the heat exhaust from their 2.6 MWe "Centaur" gas turbines could produce an additional 1.3 MWe, resulting in increasing generating efficiency from 26.6 percent to over 40 percent. Similarly, a steam turbine which operates on the heat exhaust from their 7 MWe "Mars" unit, could produce an additional 3.3 MWe, resulting in increasing generating efficiency from 31.5 to 43.5 percent. The Thermo Electron Corp. and several other companies are working on small steam turbines for similar applications.[12]

In addition to development work on improved steam cycles, a considerable amount of attention is being directed to the development of organic Rankine cycles. Work in this area has also been stimulated primarily by a desire to develop high-efficiency, combined-cycle, generating systems. Geothermal and even space applications have also motivated research in organic cycles. Several large organic Rankine units are now in use in various parts of the world. DOE is supporting work in organic Rankine devices of intermediate sizes by the Sunstrand Corporation, Thermo-Electron Corporation, and Mechanical Technologies, Inc. A summary of the

[11]Jet **Propulsion Laboratory,** *An Automobile Power Systems Evaluation,* **August 1975, p. 7-2.**

[12]**Donald L. Kearns, Regional Manager,** Government Relations, International Harvester, Solar Division, letter dated Mar. 10, 1977.

Table IX-5.—Design and Performance Parameters of Current and Projected Rankine Automotive Power Systems

Manufacturer version working fluid	ALRC Preproto AEF-78	ALRC Proto H_2O	Carter Proto H_2O	Lear Proto H_2O	SES Proto H_2O	SPS Proto H_2O	TECo Preproto FL-50	Carter Projected H_2O	SES Projected H_2O	TECo Projected H_2O
Vapor generator										
Rated temp, °F	650	1000	1000	1100	1000	800	625	1050	1000	650
Rated pressure, psia	1000	500	2000	1100	1000	1000	700	2500	1000	800
Expander										
Type	Turbine	Turbine	Recip-Uni	Turbine	Recip-Uni	Recip-DAC	Recip-Uni	Recip-Uni	Recip-Uni	Recip-Uni
Configuration	SS	SS	Radial-4	SS	IL-4	IL-4	v-4'	IL-2	IL-4	IL-4
Valve type	N/A	N/A	PAP	N/A	Series-P	spool	HAP	PAP	Series-P	HAP
Admission	N/A	N/A	Fixed	N/A	Variable	Variable	Variable	Fixed	Variable	Variable
Disp. vol. (in^3)	N/A	N/A	35	N/A	135	49	184	30	68	50
Exp. ratio	N/D	N/D	11.3:1	35:1	Variable	Variable	Variable	12:1	Variable	Variable
Max. rpm	42,000	60,000	5000	65,000	2500	2400	1800	6000	3200	2000
Condensor										
Inlet temp, °F	246	198	193	225	228	244	210	193	228	212
Inlet pressure, psia	33	11	10	19	20	27	35	10	20	32
Comp't efficiencies										
Feedwater pump, %	71	N/D	N/D	N/D	N/D	N/D	75	N/D	N/D	75
Vapor generator, %	85	90	90	N/D	N/D	N/D	87	N/D	N/D	87
Expander, %	68	N/D	86	62	68	N/D	75	N/D	N/D	75
System performance										
Max. bhp	106	60	70	107	150	65	145	90	90	60
Max. torque, ft-lb	N/D	N/D	N/D	620	755	N/D	N/D	N/D	600	N/D
Min. BSFC, lb/hp-hr	1.3	0.95	0.70	0.76	0.77	1.03	0.79	0.55	0.67	0.79
System weight (lbs)	N/D	665	425.5	765	857	835	1168	338	520	N ID

N/D = no data available
N/A = not applicable
Recip-Uni - reciprocating uniflow
Recip-DAC = double-acting compound
SS = single shaft
Series-P = series poppet

PAP = piston-actuated poppet
HAP = hydraulically-actuated popplet
Preproto type = test-stand version
Prototype = operational version
IL = in-line cylinder configuration
V - vee cylinder configuration

NOTE: Most of these programs are inactive.
SOURCE: Reproduced from "An Automobile Power Systems Evaluation: Volume II Technical Reports," Jet Propulsion Laboratory, August 1975, pages 7-7 and 7-8

characteristics of some of the devices which have been tested can be found in table IX-6.

The Sunstrand Corporation work started in 1961, and a number of units rated from 1.5 kilowatts up to 600 kilowatts have been operated successfully. One of the Sunstrand 100-kilowatt units has been modified to operate on **5500** F solar heat and has been tested at the Sandia Albuquerque Labs.

Development work at Thermo-Electron has been proceeding in several different areas. Among the organic Rankine cycle systems (ORCS) applications are a 10 MW combined steam/ORCS unit, a 4.3 MW diesel/ORCS unit, a 1.25 MW ORCS bottoming unit, a 400-kilowatt ORCS as a prime mover, and a 40-kilowatt ORCS bottoming unit for a truck diesel engine.[3] The turbines used by Thermo-Electron are typically axial impulse turbines and may have up to six stages. These designs all utilize either Fluorinol 50 or Fluorinol 85.

No large organic system is now being manufactured on a large scale, although a number of prototype units have been successfully operated. Engines ranging in size from a few kilowatts to a few megawatts are commercially available from Sunstrand, Sun Power, Kinetics Corporation, and other firms, although none is produced in large

[3] *Organ/c Rankine Cycle System for Power Generation from Low-Temperature Heat* **Sources,** Thermo-electron Corporation, Sept. 10,1973.

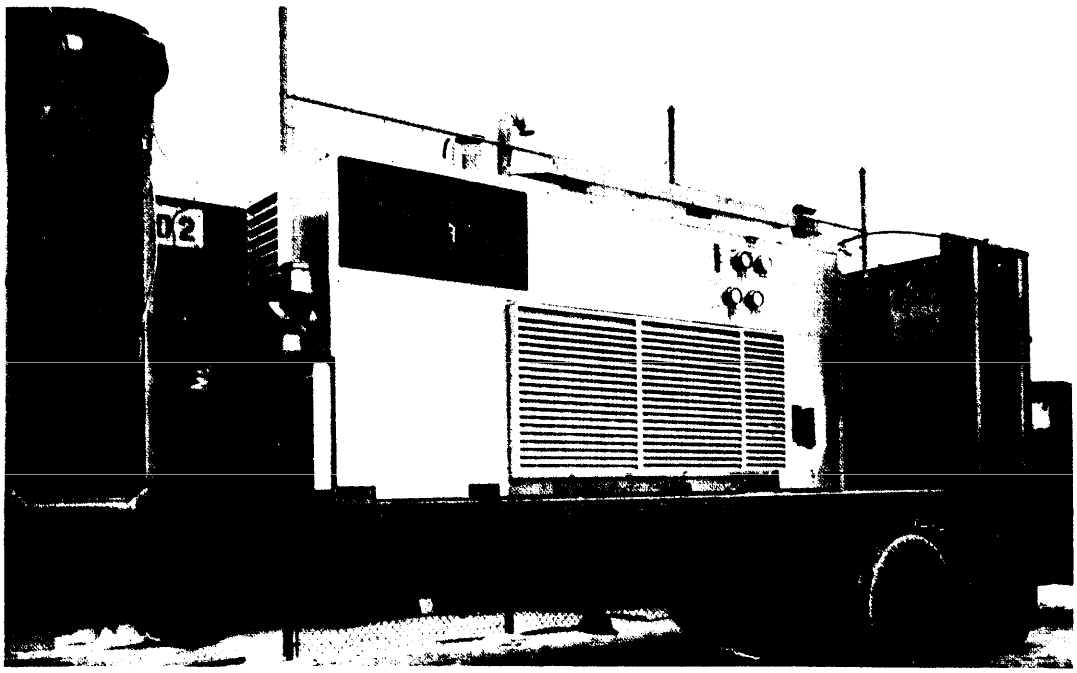
quantities. (A 100 kW Sundstrand unit is shown in figure **IX-10.**) The Ormat Corporation of Israel has sold a number of small organic Rankine-cycle devices for use where extremely high reliability is required (e. g., remote pipeline pumping stations). The high reliability guarantee results in a high initial cost. Several hundred of these units have been sold over the last 10 years and millions of hours of operating experience have been obtained.

Table IX-6.– Experimental Organic Rankine Turbines in the United States

	Sunstrand Aviation	Elliot • Turbo-machinery	Thermo-Electron	Thermo-Electron	Thermo-Electron
Working fluid	Toluene	Isobutane	Fluorinol-85	Fluorinol-50	Fluorinol-85
Turbine Inlet	550° F	350° F	550° F	600° F	550° F
Turbine type	Single-stage partial admission impulse turbine	3-stage double flow axial turbine	Single-stage axial flow impulse turbine	3-stage axial turbine	1-stage axial turbine
Unit-rated capacity	36 kWe	65 MWe	104 kWe	33 kW shaft	3 kWe

● Developed for geothermal application.
SOURCE: Prepared bv OTA using manufacturer's data,

Figure IX-10.—The Sunstrand 100 kW Organic Rankine Turbine

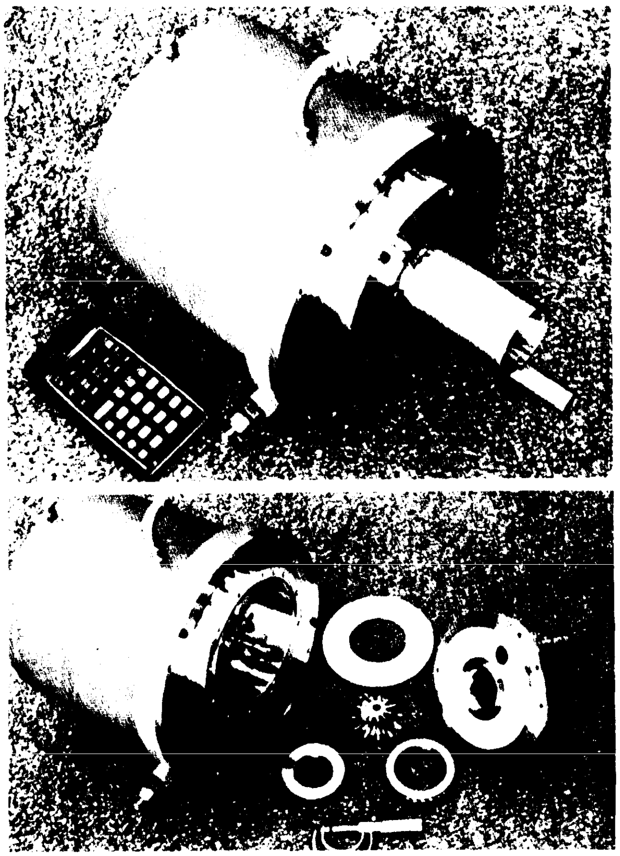


SOURCE: Sunstrand Aviation, Rockford, Ill., "100 kW Organic Rankine Cycle Total Energy System."

A number of firms are also developing organic Rankine devices which could be used for small residential or commercial installations. Several of the designs now under consideration are illustrated in figures IX-II through IX-I 5. Hundreds of hours of operating experience have been achieved with many of these devices, even when the units are unattended; the expanders have run very quietly and without vibration. (The sound is similar to the hum of an air-conditioner.)

The major development problem for these engines is demonstrating acceptable lifetimes and reliabilities. **A** critical element in this design work is finding an inexpensive safe working fluid with an acceptably long life. **A** variety of other design details (blade shapes, etc.) will undoubtedly also be improved for optimum performance. The technology of steam turbines has been developed over nearly a century. While organic systems can profit from this development work, much remains to be done to realize their full potential.

Figure IX-1 1 .—Components of the Solar Heated, Rankine-Cycle Electric Power/3-Ton Air-Conditioning System

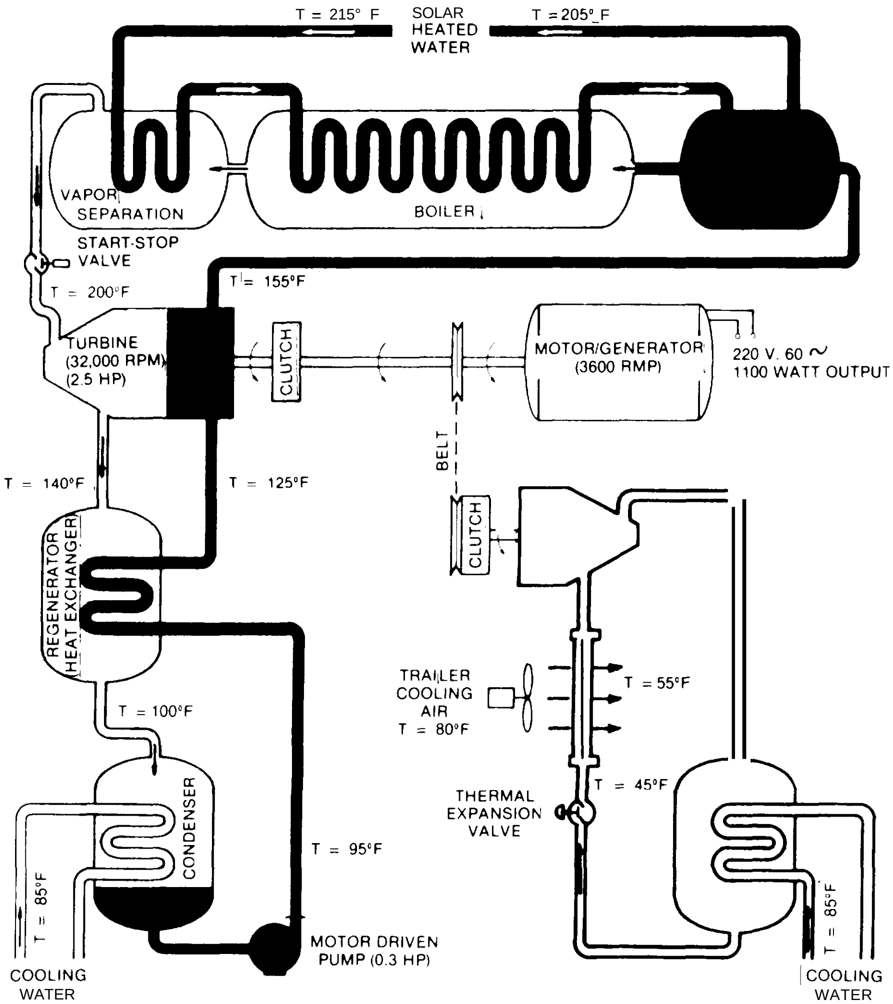


The Organic Turbine

Prototype Integrated System

SOURCE Robert E Barber, "Solar Air Conditioning Systems Using Rankine Power Cycles —Design and Test Results of a Prototype Three Ton Unit, " *Proceedings 01 the Second Workshop on the Use of Solar Energy for the Cooling of Buildings,* LOS Angeles, Calif., Aug 461975, PP 101 and 102

Figure IX-12.— Flow Diagram of the Solar Heated, Rankine-Cycle Electric power/3-Ton Air-Conditioning System

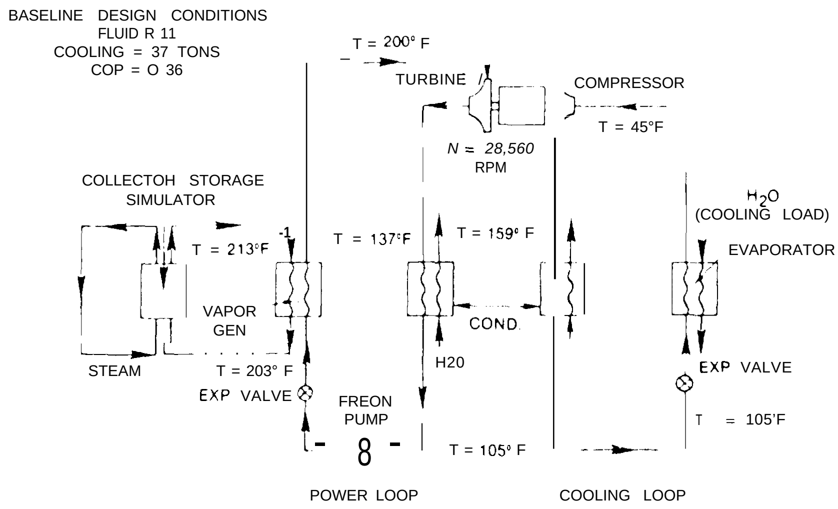


RANKINE CYCLE REFRIGERANT 113
AIR CONDITIONER REFRIGERANT 12
SOLAR COLLECTOR WATER
COOLING WATER

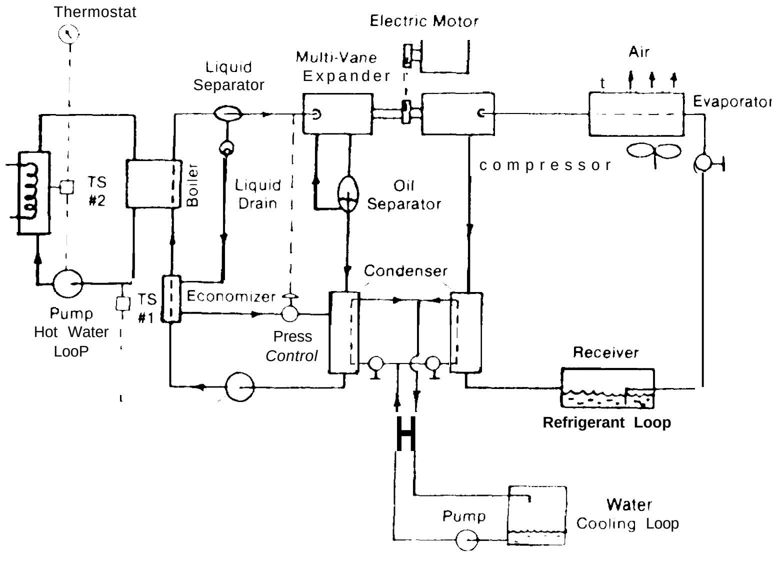
DESIGNED AND FABRICATED BY
BARBER-NICHOLS ENG CO
DENVER, COLORADO

SOURCE: See figure IX-1 1.

Figure IX-13.— United Technologies Design for Rankine Cycle Air-Conditioner

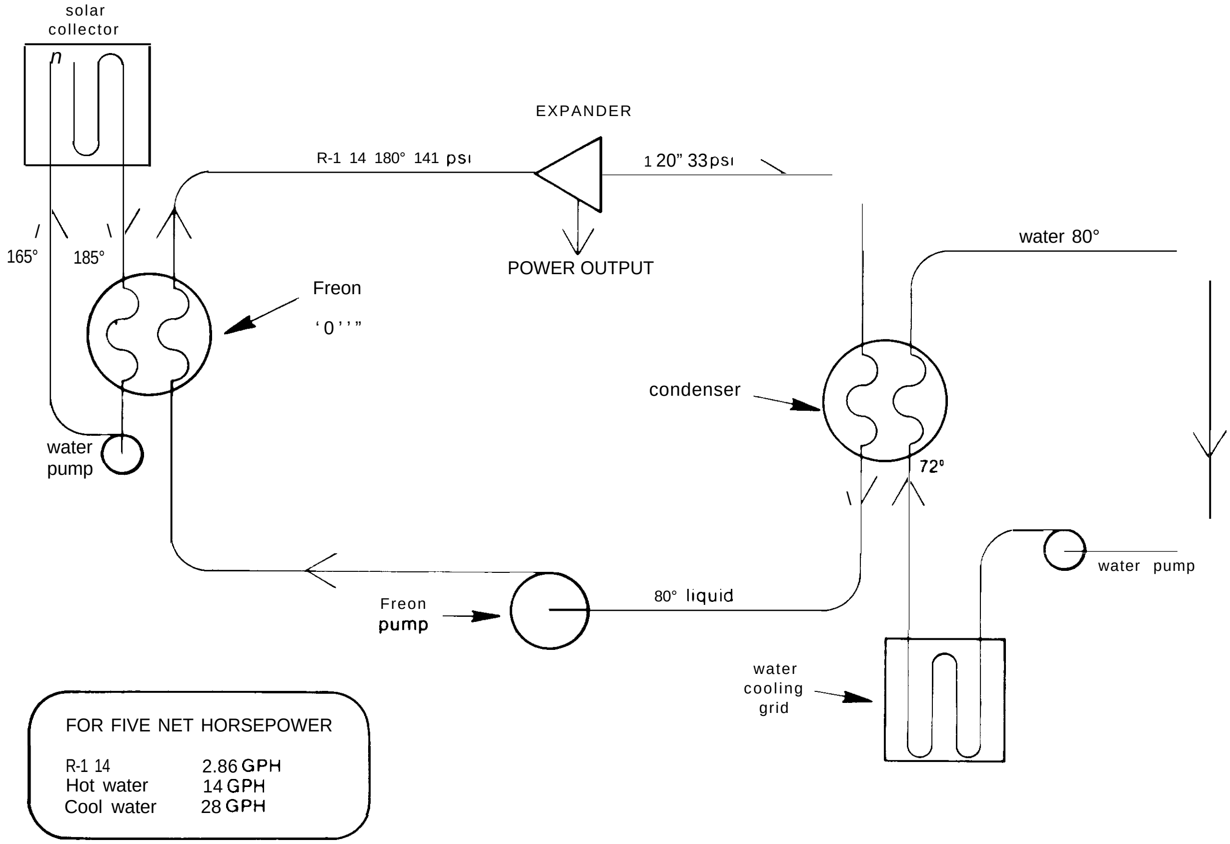


SOURCE" Fran Biancardi and Maurice Meader (United Aircraft Research Laboratories), "Demonstration of a 3-Ton Rankine Cycle-Powered Air-Conditioner," *Proceedings of the Second Workshop on the Use of Solar energy for the Cooling of Buildings,* Los Angeles, Cal If., Aug. 4-6, 1975, p. 142.



SOURCE S E Eckard and J A Bond (General Electric Company), "Performance Characteristics of a 3-Ton Rankine Powered Vapor.Compression Air. Conditioner," *Proceedings of the Second Workshop on the Use of Solar energy for the Cooling of Buildings,* Los Angeles, Calif , Aug. 4-6, 1975 p 129

Figure IX-14.—Sun Power Systems Flow Diagram for 5 HP, Rankine Cycle Air-Conditioner



SOURCE: Sun Power Systems, Inc , Sarasota, Fla.

While improvements in design will certainly be forthcoming, there is no apparent technical barrier to developing a commercial device. The General Electric device, based on a multivane expander, is an adaptation of a system called **"ELEC-PAC" which was designed to be a simple, portable, total energy system** used to provide electricity and heat for mobile homes, boats, or recreational vehicles. The device is shown in figure IX-I **5,** together with some of the advantages of the device claimed by G. E.

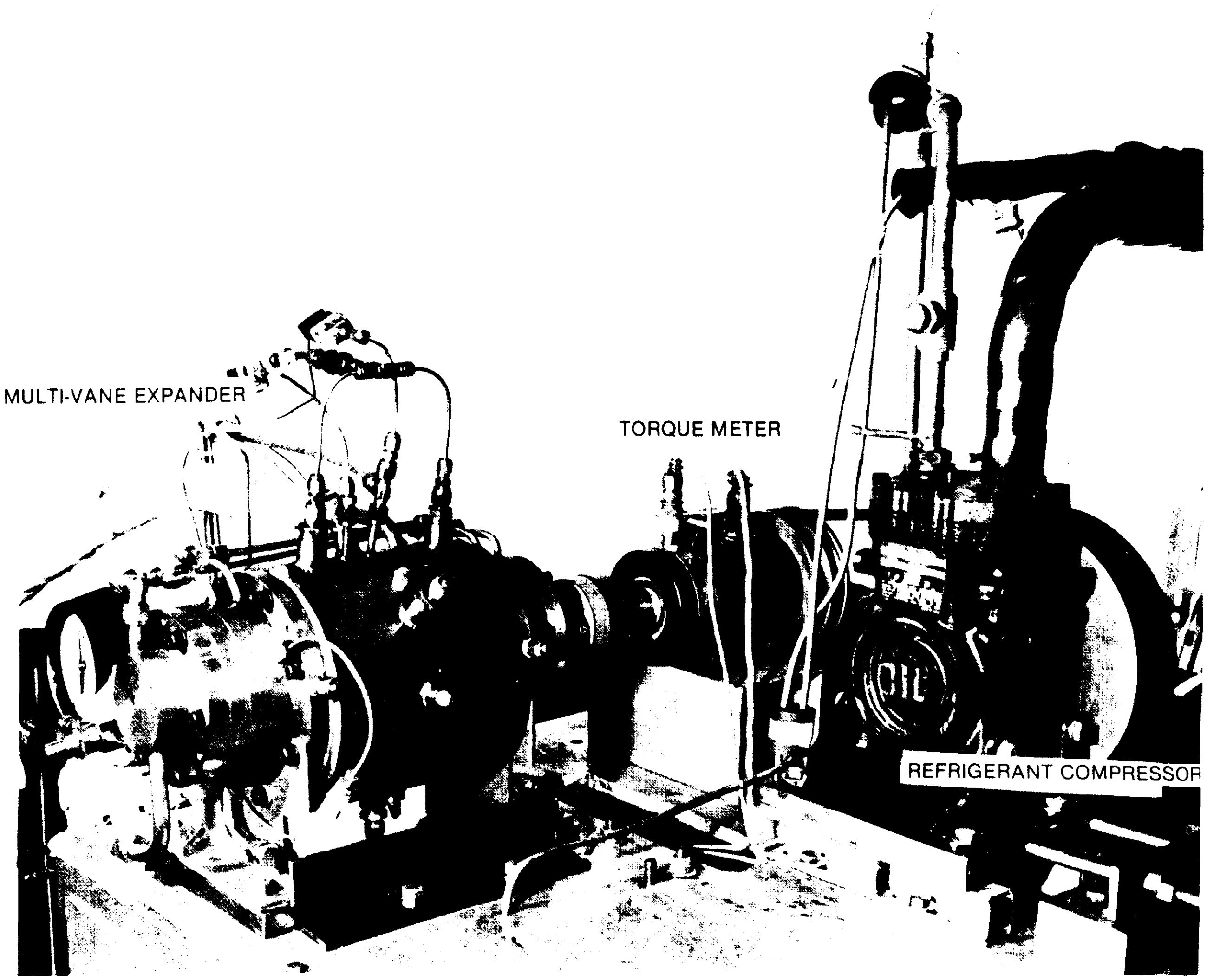
It can be seen from the pictures in figure IX-11, that devices large enough to provide adequate power to a single-family home can be quite small. The entire device shown is not much larger than the air-conditioner which it would be designed to replace.

System Costs

The costs of Rankine-cycle devices in small sizes is difficult to estimate, as relatively few installations are presently being constructed; however, the cost of installing contemporary steam devices in the megawatt range can be estimated with fair accuracy. The costs can be divided into four general categories:

1. The cost of heat exchangers which may be required to transfer heat from the collector circuit or storage device to the working flu id in the turbine;
2. The cost of the turbine itself;
3. The cost of any condensing systems and cooling towers which are employed; and

Figure IX-15.– Experimental Expander at General Electric



FEATURES AND CHARACTERISTICS OF
MULTI VANE EXPANDER

High Brake Efficiency Over a Wide Range of
- — Loading
- — Speed
- — Vapor Pressure

Tolerates Wide Range of Vapor Quality
- – No Erosion Problems
- — No Liquid Compression Problems

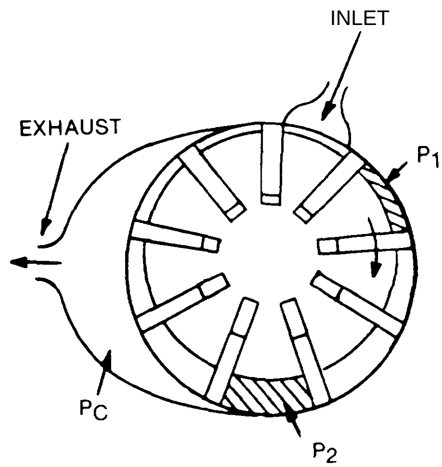
High Torque at Zero Speed
- — Self Starting Under Load

Low Speed Compared to Turbine
- — Matches May Load Requirements

Simple Construction
- — No Valves or Gears
- — Simple Seals and Conventional Bearings

Permits Simple Control System
- — Low Noise and Vibration
- – Good Life Potential

SOURCE Eckard and Bond, op cit , page 123



4. The cost of a backup boiler to provide energy when solar energy is not available.

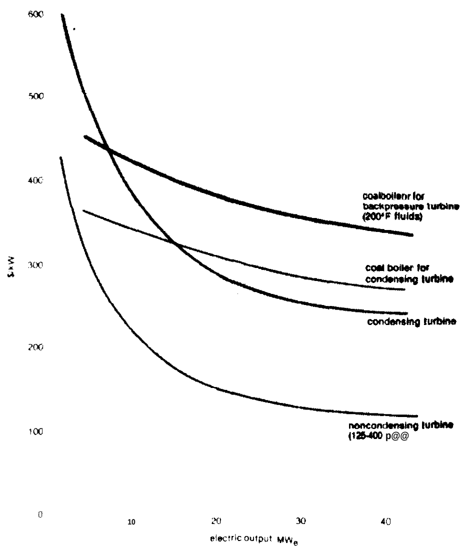
It would be possible to reduce the cost of the smaller turbine units if large numbers are manufactured. The Jet Propulsion Laboratory estimated the costs of producing units in the 150-kilowatt size range if manufacturing were performed on the scale with which automotive engines are now produced. There estimates show a wholesale price of $13/kW and a retail price of $17/kW.[14] This is more than an order of magnitude lower than the cost of the units manufactured with conventional turbine manufacturing techniques.

The cost of condensing units and cooling towers required by condensing systems (in addition to the turbine costs shown in figure IX-16) are illustrated in figure IX-17. Costs range from about $90/kWe to about $30/kWe.

The cost of providing backup power to an onsite solar system is shown in figure IX-18. The costs assume the construction of field-erected boilers and include the cost of maintaining all of the ancillary equipment (pumps, feedwater treatment, etc.) required for the operation of the system. Approximately 10 percent of the cost shown is due to devices designed to remove sulphur and particulate from the boiler exhaust, and about 10 percent is traceable to systems for fuel-handling and storage.

[14] *An Automobile Power Systems Evaluation,* Jet Propulsion Laboratory, Volume 11, pp. 11-12.

Figure IX-16.– Installed Costs of Steam Rankine Turbines



Turbine costs include installation .. ntrols and generator boiler costs include sulphur rem. val wale< treatmentfuel storageash removal build ngs piping instru mentsduct work and stack auxiliary equipment

Rl , Based The Electron c Plan ! Electri Power . 1975

Costs of Organic Rankine Systems

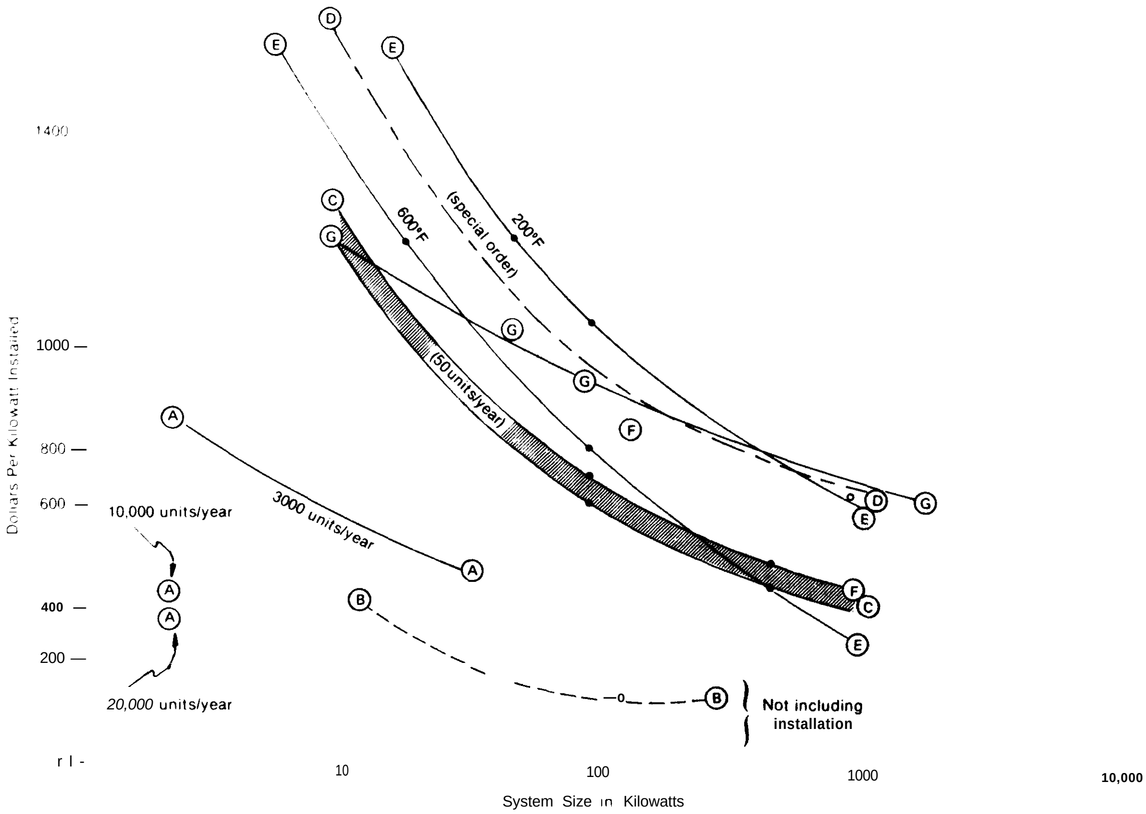
Estimating the potential cost of organic Rankine devices requires a considerable amount of speculation, since the few units now on the market are essentially handmade. I n spite of this, there is a fair degree of agreement about the price of devices manufactured in relatively small numbers. This pattern could change, however, if mass-production techniques were employed for the smaller units. The figure shows estimates indicating that production of 10,000 to 20,000 units per year could reduce the costs of units in the 5 to 10 kWe range to $200 to $300/kW, a price which compares favorably with the costs of even the larger steam- turbine systems. These costs are in general agreement with the costs of commercially available reciprocating and centrifugal air-conditioning systems. The comparison is a reasonable one for determining the potential future price of mass-produced organic Rankine turbines since the mass-produced air-conditioners employ a nearly identical technology.

THE BRAYTON CYCLE

The Brayton cycle (which uses gas at all phases in the thermodynamic cycle) has been used extensively for jet aircraft and is commonly used by utilities to provide power during peak demands. **Its** usefulness for peaking applications results from the low initial cost of the devices. Since they are relatively inefficient, however, they are typically used only to help meet peak loads and are typically used by utilities less than 1,000 hours per year.

The rising cost of liquid and gaseous fuels compatible with conventional Brayton-

Figure IX-17.— Installed Costs of Organic Rankine Turbines



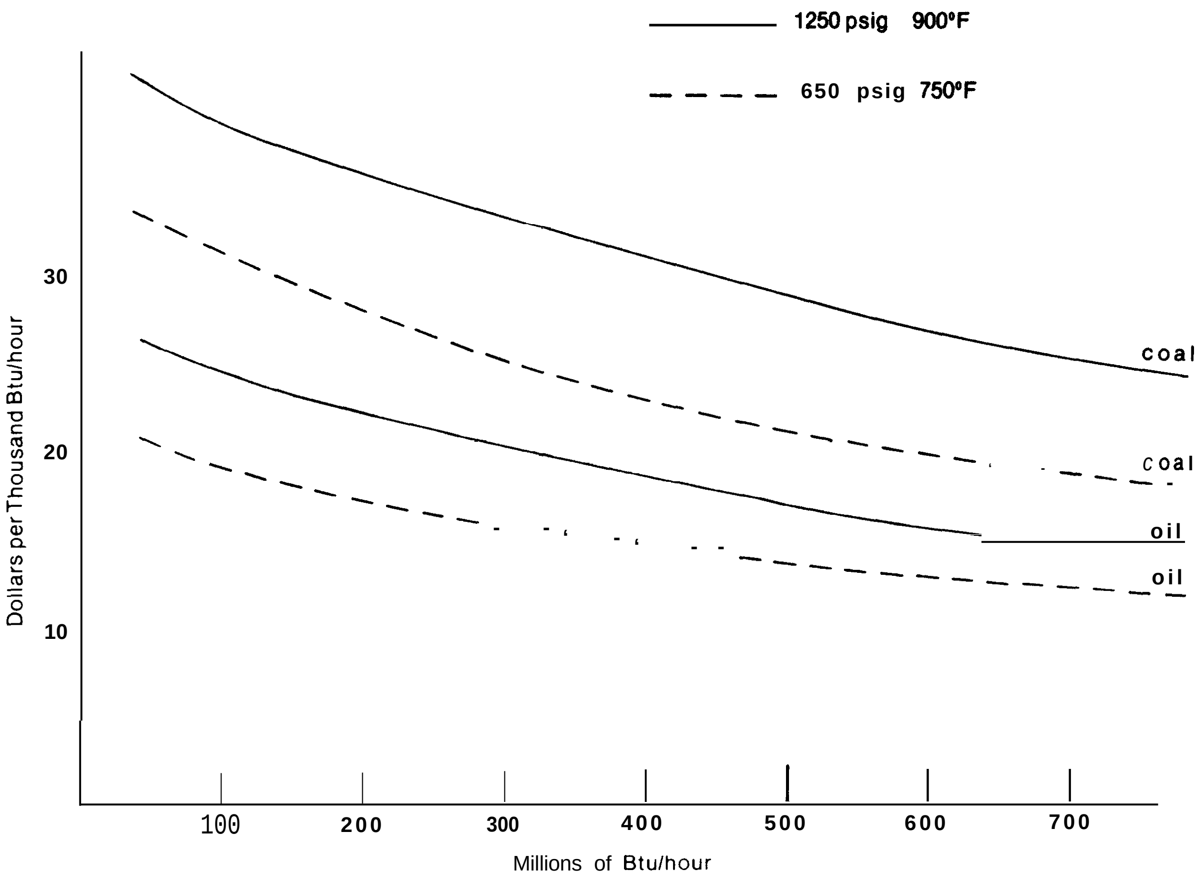
SOURCE
A Milton Van Horn (Market Manager General Electric Advanced energy group Private communication, June 1, 1976) (estimates in 1975 dollars)
B Price of electric chillers (assume 17% cycle efficiency when operated as turbine generators)
C Beno Sternlicht (Mechanical Technology Inc) Power, June 1975 p 71
D Sun Power Systems Inc (Dr Minto, President, private communication April 19, 1976)
E R E Barber "Solar Powered Organic Rankine Cycle Engines Characteristics and Costs " June 1976
F Thermo Electron " High Efficiency Electric Power Generation", November 1974, pages 59 and 510 (Increased by 9% for inflation since 1974)
G Sun Po-wer Systems price estimate 12/1/75 (200° F in let)

cycle gas turbines has dramatically increased operating expenses. There is, however, technology which shows promise of permitting Brayton-cycle devices to operate from external heat sources, such as coal (burned in a fluidized-bed boiler or a similar device) or from solar sources. The major barrier to the use of these devices has been the development of heat exchangers which are **capable of transmitting high temperatures into gaseous working fluids. Such materials now exist, but further** work is needed to develop commercial devices. The Boeing Corporation has recently completed a successful test which subjected the receiver to thermal-cycling equivalent to 30 years of operational performance. A heat exchanger, constructed from a material called Haynes 188, survived 10,560 cycles with a high temperature of 1,5000 F. Tests will also be done on a device using an Inconel 617 heat exchanger.[5] These materials will, however, be quite expensive.

As was the case with the Rankine-cycle devices, the maximum temperatures available for use with Brayton-cyc!e devices is limited by the performance of inexpensive

[15] John P Gintz, **Program Manager, Boeing Company Engineering and Construction Division,** *Closed-Cycle, High-Temperature Central Receiver Concept for Solar Electric Power,* **E PRI, February 1976.**

Figure IX-18.— Installed Costs of Field-Erected Boilers*



•Includes coal handling, ash removal, fuel storage, sulphur removal, and electrostatic precipitator for particulate removal, boiler erection, foundation, buildings, instruments, auxillary equipment, ductwork and stack, electric material in boiler building, feedwater sampling and treatment, fuel and ash handling, and indirect distribution costs.

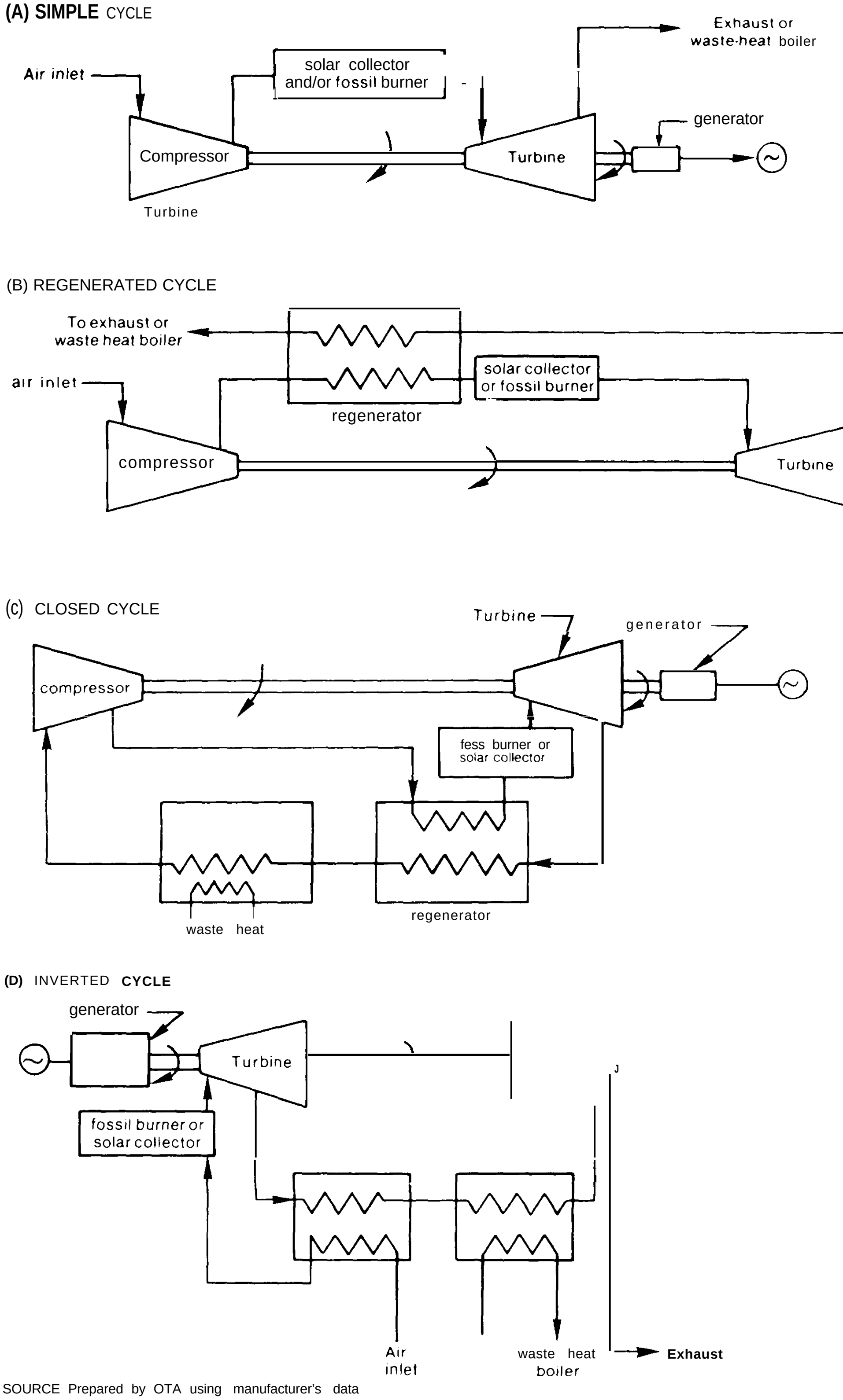
SOURCE Thermo-Electron Corp A study of Inplant Electric Power Generation of the Chemical, Petroleum Refining, and Paper and Pulp Industries, June 1976, pages 317 and 319

materials. Temperatures of 1,5000 F are typical for Brayton devices. Temperatures as high as 1,8000 F can be used, but this significantly shortens the expected operating life of the units.

The Brayton cycle has an advantage over Rankine-cycle devices when used in connection with a total energy or cogeneration system because the Brayton devices operate at much higher initial temperatures. This means that heat can be recovered from the exhaust gases without reducing generating efficiency to the extent that Rankine-cycle efficiencies are reduced.

Four different Brayton-cycle systems which may be of interest for solar energy applications are shown in figure IX-I 9. The simple cycle is the basis for most of the gas-turbine power generated in the United States. Commercial devices are available

Figure IX-19.— Four Brayton-Cycle Systems Compatible With Solar Applications



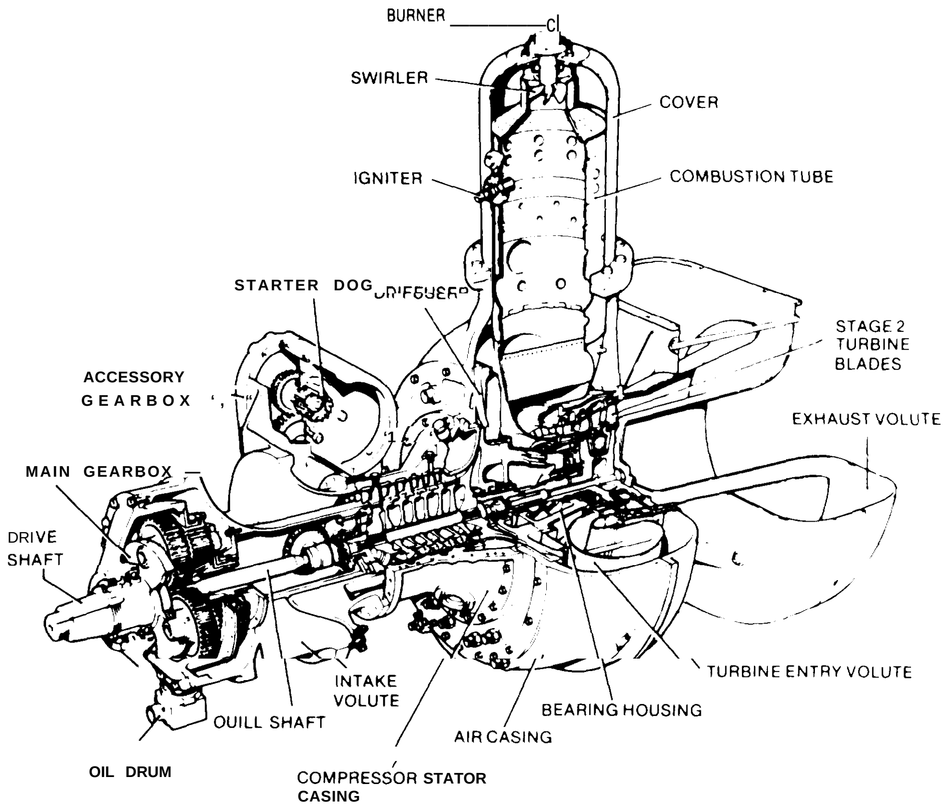
SOURCE Prepared by OTA using manufacturer's data which range in size from a few kWe to over 50 MWe.[16]

Ambient air is compressed, heated, and expanded through a turbine. About two-thirds of the turbine's power is required to provide the compressor with power, with the remaining power being available for operating a generator. The gas is heated in a conventional device by igniting oil or natural gas in a combustion chamber. In a solar or an externally fired device this combustion chamber would be replaced with a high-temperature heat exchanger. A commercial single-cycle gas turbine is shown in figure IX-20.

A variety of techniques can be used to improve the efficiency of the cycle. The air can be cooled during the compression stage, for example, and the gas can be reheated during expansion in the turbine. The most effective technique for increasing efficiency, however, is to use the techniques in connection with a regenerator as shown in figure IX-19(B). In this design, the compressed air is preheated by the turbine exhaust before being heated in the combustion chamber or heat exchanger. Cycle efficiencies can be increased from *28* percent to nearly *38* percent in this way. The major barrier to the use of such devices, however, is the cost and reliability of the regenerative heat exchangers.

[16] G. Samuels and J. T. Meador, *MIUS Technology Evaluation:* Prime Movers, Oak Ridge National Laboratory (ORNL-HUD/MIUS-11), April 1974, p. 22.

Figure IX-20.—Components of a 500kW Gas Turbine



SOURCE. Electrical Research Association, Limited "Electric Power Plant International 1975-1976 edition" Surrey, England, 1975 (Acknowledgements to Centrax LTD)

Commercial regenerative heaters can be guaranteed only if they are not turned on-and-off frequently, since the materials used fail if they are repeatedly heated and cooled. This I imitation is, of course, inconsistent with using the devices for meeting intermittent loads in utility peaking applications, and it is inconsistent with the demands of a solar installation where the available energy is intermittent. Progress in developing reliable regenerators is being made, however, and the Garrett Corporation claims to have a device which is capable of withstanding large numbers of on-and-off cycles without damage.[17]

A third approach to the Brayton cycle is to close the cycle as shown in figure IX-19(C). In this device, the gas emerging from the turbine is sent back to the compressor instead of being exhausted. The device must be fired externally since the circuit must be closed. The closed cycle has a number of advantages, the most important of which is that it permits the use of gases other than air. Helium and other light gases can be used to improve heat-exchange characteristics. The closed cycle can also be used at higher pressures with the advantage that smaller turbines can be used. No penalty need be paid in efficiency for using gases other than air.[18,19]

While a few closed-cycle, gas-turbine devices have been built in the United States (a closed-cycle device developed for NASA by the Garrett Corporation has been operating or under test for about 15 years), several German and Swiss firms have had devices operating from coal for a number of years. The cycle is being investigated for use with gas-cooled nuclear reactors. A picture of a large, closed-cycle plant now being checked out in Oberhausen, Germany, is shown in figure IX-21. A closed-cycle gas-turbine system is being investigated by EPRI for a central receiver solar application.[20]

The "inverted" Brayton cycle illustrated in figure IX-19(D) may offer some advantages when used as a bottoming cycle for

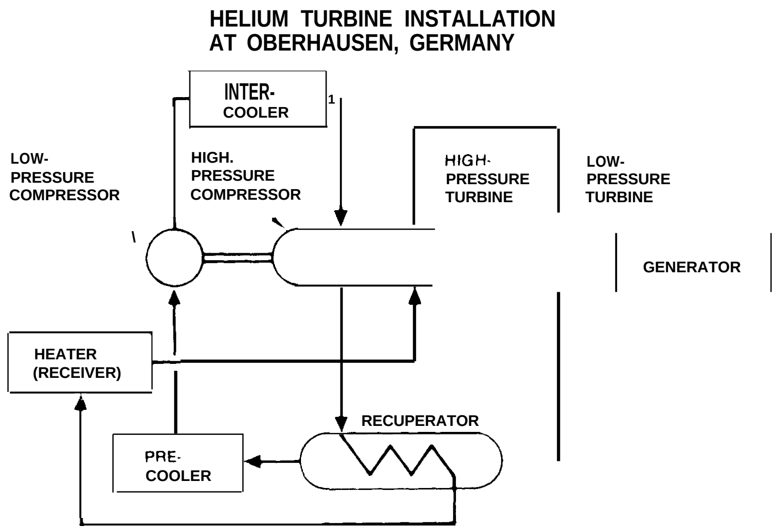
[17] Patrick G Stone, Garrett Corporation, private communication, December 1975

[18] Samuels, op. cit , p. 42

[19] R. M. E, Diamant, *Total Energy,* pergamon Press, pp. 229-232

[20] Gintz, op. cit.

Figure IX-21.—50 MW_e Closed-Cycle Gas Turbine



HELIUM CYCLE SCHEMATIC

SOURCE Gintz, John R (Boeing Company, Engineering and Construction Division), "Closed Cycle High Temperature Central Receiver Concept for Solar Electric Power," February 1976, EPRI any process generating hot air at ambient pressures.[21] It may also have some advantages in small solar applications. The device operates by heating ambient air in a heat exchanger before the gas is sent to the turbine. The hot air expands through the turbine into a vacuum produced by a compressor (which acts like a pump in this application), which exhausts the gas at ambient pressure in an open-cycle system or returns it to the heat source in a closed-cycle system. The efficiency of the inverted cycles can be as high as similar devices operating at higher pressures. The advantage of such a device for solar applications is that the heat exchanger can operate at atmospheric pressure. This greatly reduces the demands placed on the materials which transfer high temperatures to the engine. The major disadvantage of this approach is that the density of the gas is much lower than in a pressurized system and thus the turbine units must be relatively large. This is less of a restriction in small sizes, however, since small turbines must be relatively larger per-unit-energy output to minimize the effect of gas escaping around the ends of the turbine blades. Another disadvantage of the inverted cycle is that a heat-rejection heat exchanger is required in addition to the heat exchanger where external heat is applied. This is not a problem in applications where a second heat exchanger is required for a heat-recovery system. Heat exchangers will need to be relatively large, however, because of the low density of the gases used in the cycle.

Few inverted-cycle devices have been constructed, but a prototype, developed by the Garrett Corporation for a gas-fired heat pump, has operated successfully since November 1976. The designers claim that an efficiency of over 38 percent has been measured on this device in initial tests.[22]

Another approach which can be used to increase the generating efficiency of Brayton-cycle devices is to recover the energy in the turbine exhaust in a boiler and use the heated fluids generated in this way to drive a steam or gas turbine. Overall efficiencies as high as 48 percent in large units can be achieved in this way.[23]

Waste heat can be recovered from gas turbines in two ways. The most commonly used technique is simply to install a large boiler in the path of the turbine exhaust. Heat can also be extracted between compression stages if more than one compressor is used. One system for removing thermal energy from a Brayton-cycle device is shown in figure IX-22.

Two approaches have been proposed for using Brayton-cycle turbines in solar applications. Small units could be mounted at the focus of individual tracking-collectors, or they could be located at the counterweight position of these collectors with heat transferred to the units through a heat pipe. Heat pipes using sodium vapor have been developed which operate successfully in the temperature regimes necessary.

In a central receiver used for larger systems, it would be possible to pipe the hot gases to a heat exchanger on top of a receiver tower. This is the approach being examined by EPRI (figure IX-23).

System Efficiency

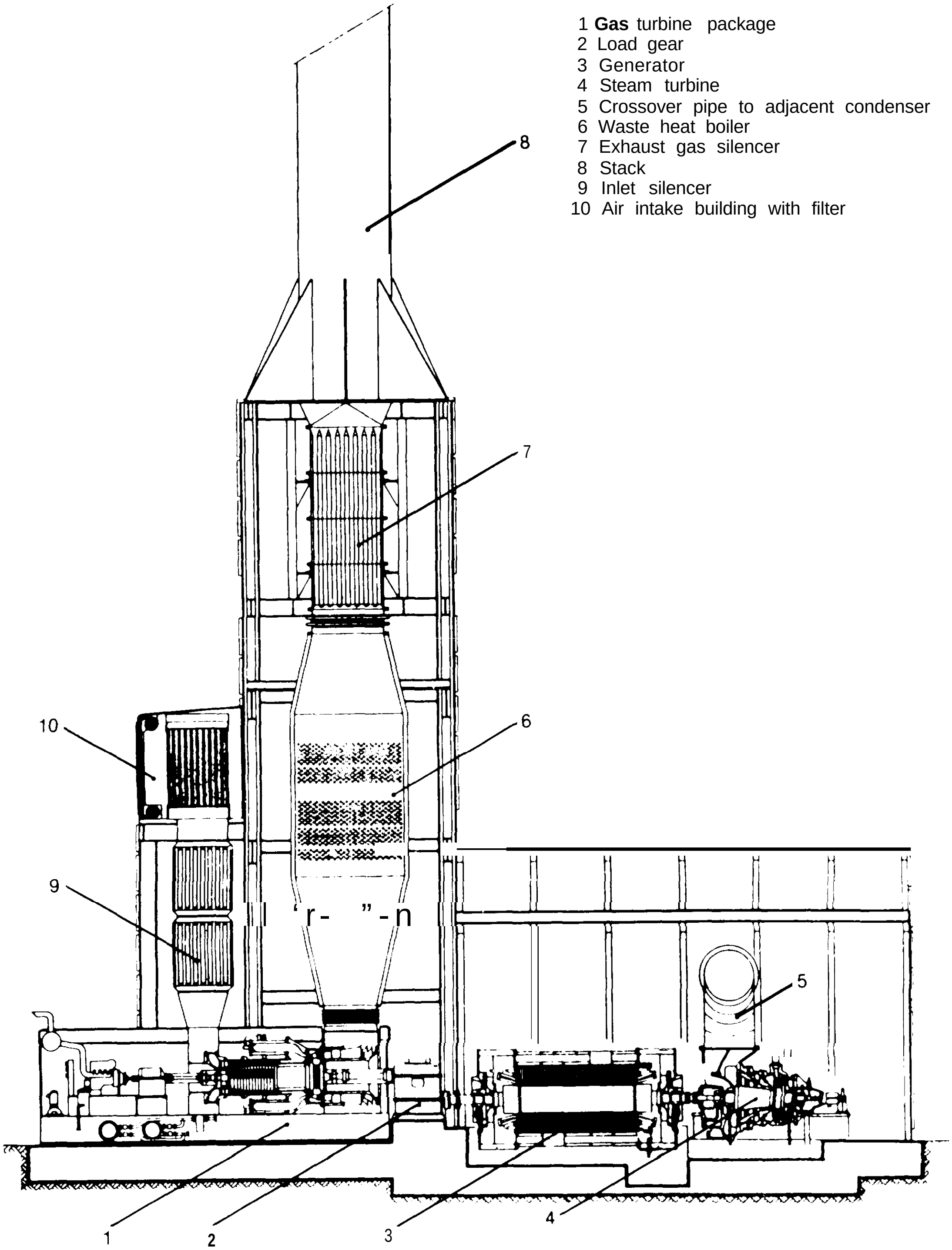
The optimum cycle efficiencies of simple and regenerative Brayton cycles are shown in figure IX-24 as a function of the temperature available. (It is important to recognize, however, that the comparison is made only for turbines operating at full load; operating efficiencies at part load may compare quite differently.) The great advantage of developing materials capable of operating at high temperatures can clearly be seen. The performance of actual units is summarized in table IX-7. It can be seen that the efficiency

[21] D. C. Wilson, and N. R. Dunteman, *The Inverted Brayton Cycle for WasteHeat Utilization*, ASME publication, 73 CT-90, April 1973,

[22] Patrick G. Stone, Garrett Corporation, Private communication, December 1976.

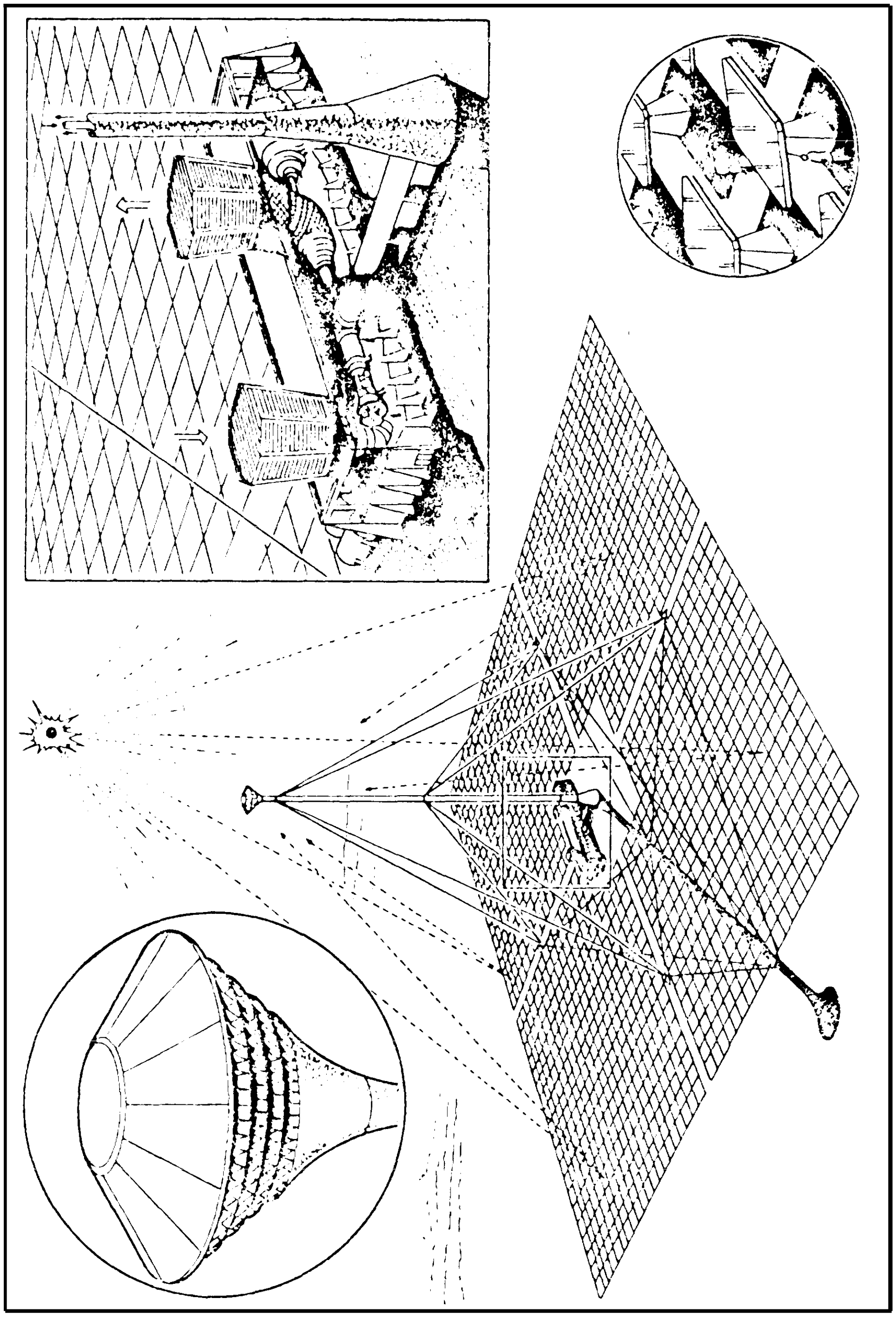
[23] Morgan, op. cit., pp.4-9.

Figure IX-22.—Section Through a Combined Gas and Steam Turbine Powerplant



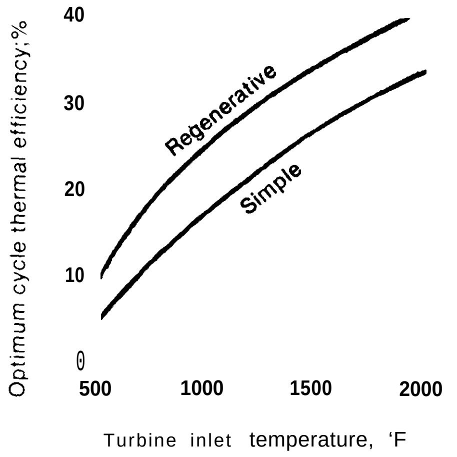
SOURCE Electrical Research Association Limited, *Electric Power Plant International*, 1975-1976 edition, Surrey, England, 1975 (With acknowledgements to A E G Kanis)

Figure IX-23.—Artist's Rendering of Proposed Solar-Heated Air Turbine Generating Facility



SOURCE: Philip O. Jarvinen, "Solar Heated Air Turbine Generating System."

Figure IX-24.—Temperature Dependence of Optimum Cycle Efficiencies



SOURCE. Beno Stemlicht, "The Equipment Stale of LowLevel Heat Recovery," *Power,* June 1975, page 73

of simple-cycle devices decreases dramatically in small sizes. The 2.7 MW **"Centaur"** gas turbine manufactured by International Harvester, for example, can achieve 26.6-percent efficiency, while the small **20** k W Gemini unit achieves only 13.7 percent efficiency. The inefficiency of smaller engines is decreased somewhat if regenerators are used. A small turbine developed for **automobile applications, for example, can develop 26.8-percent efficiency and, as noted earlier, the small inverted-cycle turbine developed by the Carrett Corporation has** shown 38-percent efficiencies in preliminary tests. All of these efficiencies are, however, substantially less than the 47-percent efficiency which apparently can be" achieved by the 50 MWe closed-cycle device.

The generating efficiency of a gas turbine is reduced if waste heat is recovered in a

Table IX-7.—Brayton Cycle Efficiencies

Cycle	Cycle Efficiency’			
	Nominal Size (kW)	Present (1976)	Future 1980-85	**Reference**
Simple cycle	20	**13.7**		(1)
	100	**13.7**	**22-28**	**(1) (2)**
	800	**22.8**		**(1)**
	2700	**26.6**		**(1)**
	7200		31.5	**(1)**
Regenerated cycle	**20**	**26.8**	38	**(5)**
	100		32-35	**(2)**
	central station	35		**(3)**
	2800	32.2		**(8)**
Closed cycle		25-32		**(4)**
(Regenerated)		35-39		**(9)**
Combined cycle	4200		36.8	**(8)**
(Simple cycle)	4550		40.2	**(8)**
	57400		44.4	**(8)**
Combined cycle	3606		**40.7**	**(8)**
(Regenerated gas turbine)	3860		**43.6**	**(8)**
	73700		**48.0**	**(8)**
	235000		**47.0**	**(lo)**

*Losses in the mechanical equipment Will reduce the cycle efficiency by 3-8%

SOURCE (1) *International Harvester* Solar Division estimates based on cost and performance of the 30 hp Gemini, 150 hp Titan, 1146 hp Saturn, and 3860 hp *Centaur* turbines.
(2) JPL "An automobile power systems evaluation," pp. 5-6.
(3) Beno Sternlicht "The equipment side at low-level heat recover," Power, June 1975, p. 71.
(4) G. Samuels and J. T. Meador, MIUS Technology Evaluation: Prime Movers, ORNL-HUD-MIUS-11, April 1974, p. 29.
(5) Patrick Stone (Garrett Corp.), private communication, December 1976.
(6) John R. Gintz (program manager, Boeing Engineering and Construction Division of the Boeing Company), "Closed Cycle High Temperature Central Receiver Concept for Solar Electric Power."
(7) R. M. E. Diamant (editor), *Total Energy*, Pergamon Press, p. 225.
(8) Dean T. Morgan and Jerry P. Davis (Thermo-Electron Corporation), "High Efficiency Decentralized Electric Power Generation Utilizing Diesel Engines Coupled with Organic Working Fluid Rankine-Cycle Engines Operating as Diesel Reject Heat," November 1974, pp. 4-12.
(9) Based on analysis made by GE for the ECMS study.
(lo) Stal-Laval GASTEAM Technical Information, March 1975, p. 6.

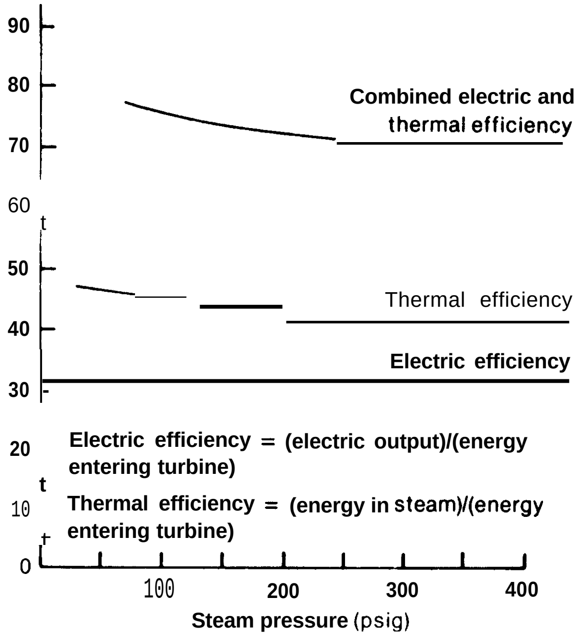
boiler placed at the turbine outlet. Overall performance of the simple-cycle gas turbines producing both thermal and electric energy is shown in figure IX-25. It can be seen that, in contrast with the Rankine cycle, the efficiency changes very slightly as a function of the temperature of the waste heat recovered.

The regenerative cycles apparently exhibit a combined electrical and thermal efficiency similar to that of the simple-cycle efficiencies shown in figure **IX-25,** but the ratio between electric and thermal output increases as a result of the regeneration.

The performance of a closed-cycle Brayton-cycle system, which provides thermal energy to a district heating system requiring pressurized water at temperatures between 2000 and 3000 F and returns the water at 1220 F, is illustrated in figure IX-26. In this case, it can be seen that the combined efficiency can exceed 80 percent.

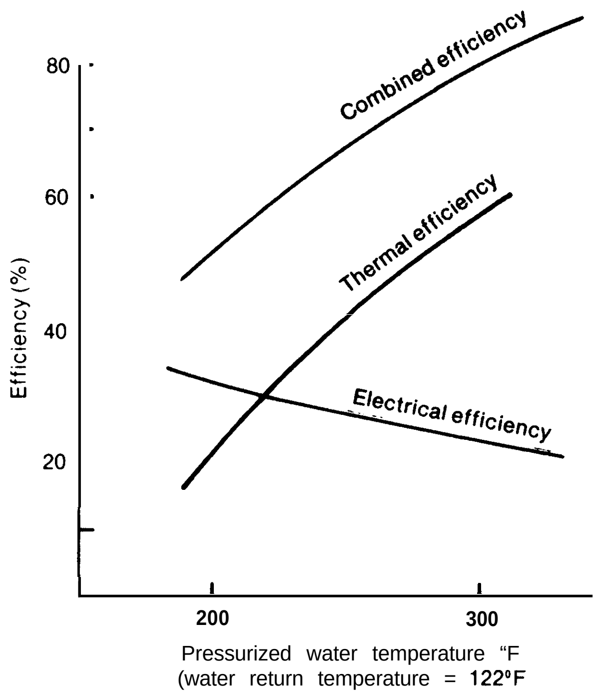
in a solar application where alternating current is required, all of the efficiencies

Figure IX-25.—The Effect of Waste-Heat Extraction on the Performance of Gas Turbines



SOURCE Calculations based on performance of Rolls Royce RB.211 Gas Turbine (28,960 BHP), 2% electric efficiency loss due to backpressure

Figure IX-26.—Closed Regenerated-Cycle Gas Turbine



SOURCE. Diamant, et al , op cit , page 244

discussed above must be reduced by the efficiency of some type of power-conditioning equipment. This is because the speed of Brayton-cycle devices changes rapidly as a function of the incident power; thus, frequency control cannot be maintained in an alternator, although the Brayton-cycle device can be locked into a utility grid frequency if it is attached to utility power. In such cases, electric output power will be proportional to the energy available from the solar collector.

This frequency control problem can be solved for a stand-alone system by rectifying the output of the alternator and then using an inverter to produce a constant 60-cycle output. The efficiency of this process will be typically in the range of 85 to 90 percent. Constant-speed mechanical devices are also available which can produce a constant speed in an output shaft, given variable speed inputs. It is, for example, possible to operate a drive-flywheel combination and controller in reverse. There have also been ingenious proposals for providing frequency stability by continuously changing the number of fixed magnets **in the alternator. All of these** schemes result in some loss of efficiency.

Operation With Fossil Backup

It should be possible to design a Brayton cycle system **which is capable of operating from either fossil or solar energy** sources. In a closed cycle, all that would be required would be to insert an additional heat-exchanger and fossil burner into the piping circuit. In an open-cycle turbine, a fuel injector could be included in the circuit for use when backup was needed. There might be some difficulty in operating a fossil-burning device which was attached to the focus of a tracking collector because the exhaust might accelerate the aging of optical components; however, this problem should not be insurmountable.

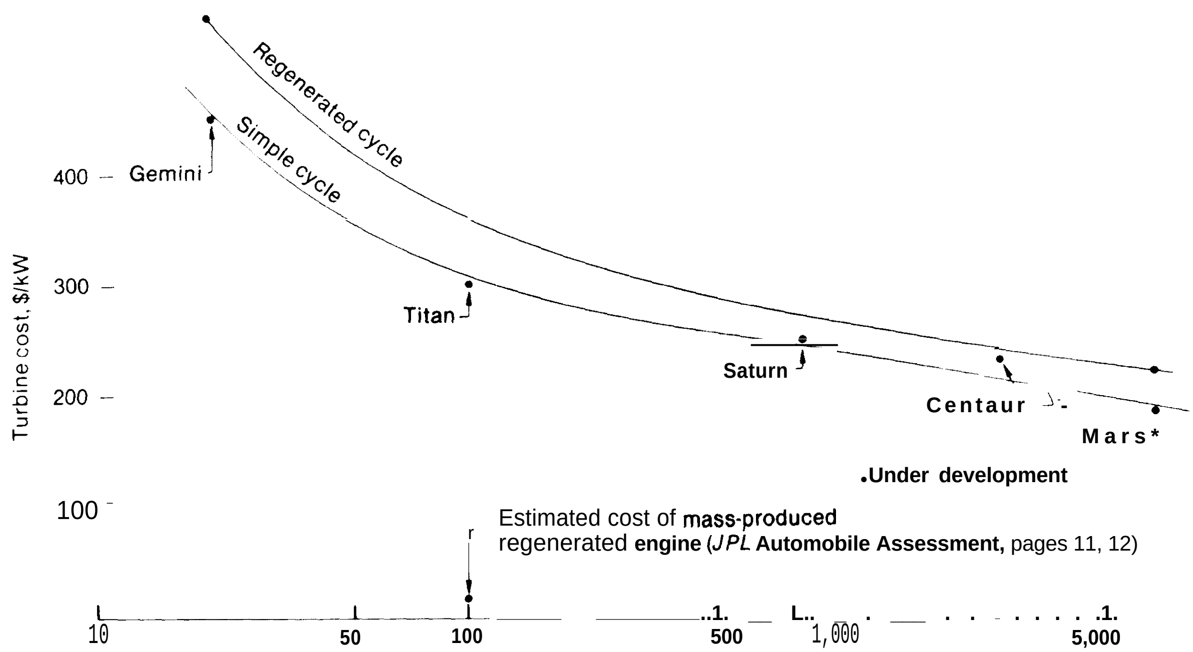
System Costs

The installed costs of gas turbines of various sizes are illustrated in figure IX-27. There is a clear economy of scale in these devices, given current manufacturing techniques, although the effect is not as pronounced as it was in the case of Rankine-cycle engines. The enormous advantage of using mass-production techniques for the production of small equipment is also apparent from this figure.

The total cost of an installed Brayton device must include the cost of several components in addition to the turbine. Waste heat boilers (if used) would add $15 to $75 per kilowatt to the costs shown in figure IX-27 (depending on the temperature and pressure of the process steam required).[24] Miscellaneous equipment for controls and

[24] Sternlicht, op. cit

Figure IX-27.— Installed Costs of Open-Cycle Brayton Turbines



SOURCE Prices based on estimates made by International Harvester for units shown Regenerator Prices are assumed to be 20°. of the turbine price (see Sternlicht, op cit p 72) other equipment will add about 20 percent to the cost.[25] The cost of the equipment required to maintain a constant output frequency will vary with the size of the installation. The cost of power-conditioning equipment is discussed in detail in the section on electric storage. If a backup fossil capability is required for the equipment, fuel storage would add approximately $30 per kilowatt.[26]

THE STIRLING AND ERICSSON CYCLES

Even if devices employing Rankine or Brayton cycles were constructed from perfect components (i.e., if there were no friction or fluid losses around turbine blades), these devices would not achieve the efficiencies of ideal heat engines operating between the same temperature limits. This is because neither cycle accepts heat only at the highest cycle temperature nor rejects heat only at the lowest temperature; an ideal engine would maintain a constant temperature during these heat-exchange processes.

Both the Stirling and the Ericsson cycles maintain a constant temperature during the heat-exchange processes associated with expansion and compression and thus are, in principle at least, capable of achieving the maximum permitted Carnot efficiency. Existing engines which approximate Stirling and Ericsson cycles are externally fired, piston engines. (No real device actually maintains a constant temperature during heat addition or heat rejection and thus the devices fail to operate on a true Stirling or Ericsson cycle.) In addition to the potential for high efficiency, they should also be capable of long lifetimes, and quiet, reliable operation.

Also, since heat is applied externally, the engines are easily compatible with solar energy applications, and backup energy can be provided from any type of fuel. In total energy applications, they have the additional advantage of rejecting nearly all of their waste heat in the form of heated liquids, and thus a heat-recovery boiler is not required. The cycles are capable of operating at a variety of different temperatures, with the upper-temperature range limited only by the capabilities of the heat-exchange materials. They also have an inherently low RPM and thus need not use expensive gear-reduction systems. Devices based on the Ericsson cycle also can be designed to operate at relatively low inlet temperatures and can span the entire spectrum of temperatures available from solar collectors. The systems are particularly interesting for onsite-power applications since efficiency is not sacrificed by building units as small as a few kilowatts.

There have been proposals for using Stirling engines for vehicle propulsion, electric-power generation (including residential, total-energy systems), artificial hearts, and water-pumping applications.[27 28 29 30 31 32] A major study conducted recently by the jet Propulsion Laboratory concluded that the Stirling engine was one of the two most promising systems for future automobile engines because of its potential for high efficiency, low emissions, and quiet operation.[33]

Principles of Operation

The operation of ideal Stirling- and Ericsson-cycle devices is explained in some detail in figure IX-28. Both cycles described here

[25] Estimate made for OTA by the Ralph Parsons Company,
[26] Sukuja, et al., Op. cit., pp. 3-26

[27] W. R. Martini, *Developments in Stirling Engines*, presented to the American Society of Mechanical Engineers, New York, N. Y., Nov. 26-30, 1972

[28] *Stirling Total Energy System* (a Philips Corporation paper).

[29] W. R. Martini, *Unconventional Stirling Engines for the Artificial Heart Application, Proceedings*, 9th Intersociety Energy Conversion Engineering Conference, San Francisco, Calif., Aug 26-30, 1974.

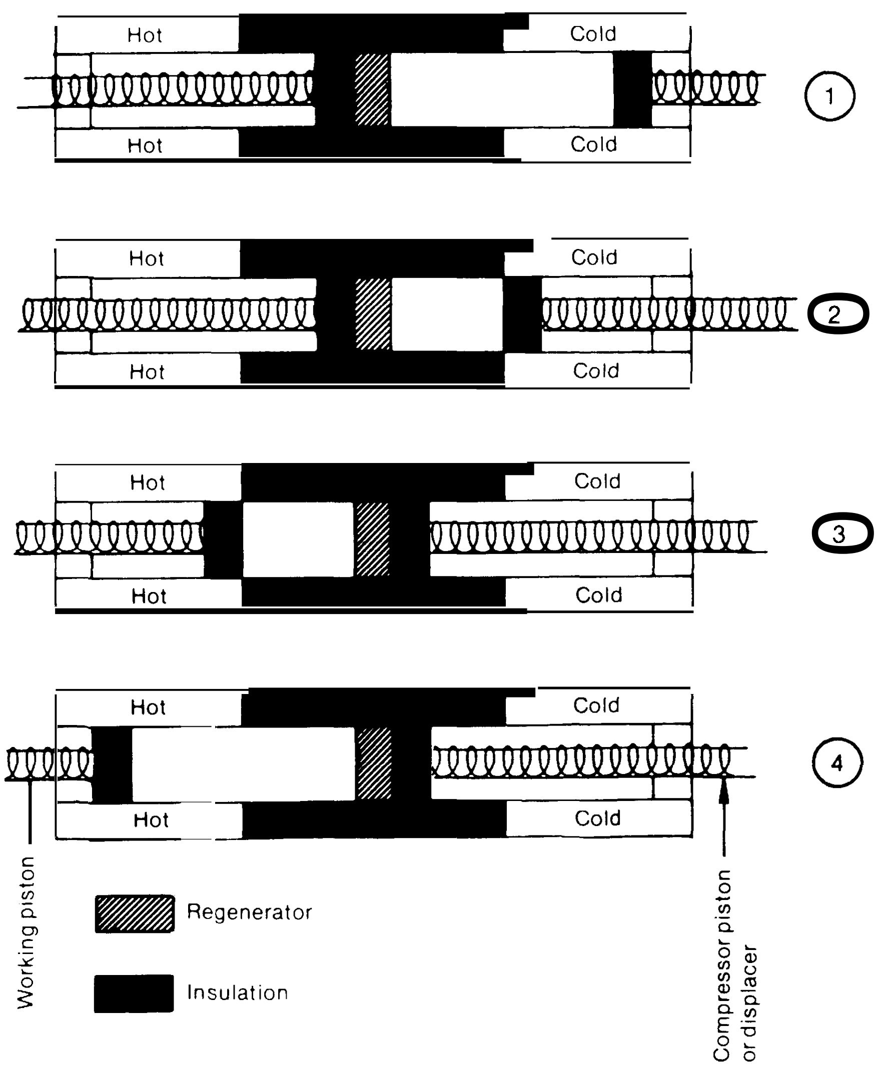
[30] G. M Benson, "Thermal Oscillators," *Proceedings*, Eighth Intersociety Energy Conversion Engineering Conference, Philadelphia, Pa., August 1973.

[31] *3-5k W Stirling Engine Alternator*, ERG, Inc., report to U.S Army, MERDC (1969).

[32] *Stirling Engine Driven Total Energy System*, ERG, Inc, report to Am Gas Association (1969).

[33] *An Automobile Power Systems Evaluation*, jet Propulsion Laboratory.

Figure IX-28.—Ideal Stirling and Ericsson Cycles



SOURCE: Prepared by OTA using manufacturer's data.

STAGES OF THE IDEAL STIRLING AND ERICSSON CYCLES

MOVING FROM STAGE 1 TO STAGE 2
- compression at constant low temperature raises the pressure
- energy is rejected into the cold heat exchange surfaces
- work is done on the system through the compressor piston

MOVING FROM STAGE 2 TO STAGE 3
- working fluid is forced through the regenerator and is heated as it absorbs heat from the regenerator
- no work is done on the system and no heat enters or leaves the working fluid except through the regenerator
- the process takes place at constant volume with increasing pressure in the Stirling cycle (as shown in the figure) and at constant pressure with increasing volume in the Ericsson cycle

MOVING FROM STAGE 3 TO STAGE 4
- the working fluid is allowed to expand at a constant temperature and the pressure decreases
- energy is absorbed from the hot heat exchange surfaces
- work is performed on the working piston

MOVING FROM STAGE 4 TO STAGE 1
- working fluid is forced back through the regenerator and is cooled as it gives up heat to the regenerator
- no work is done on the system and no heat enters or leaves the working fluid except through the regenerator
- the process takes place in constant volume with decreasing pressure in the Stirling cycle (as shown in the figure) and at constant pressure with decreasing volume in the Ericsson cycle

In actual engines, these stages will not be distinct.

would be capable of ideal efficiency. Both cycles absorb and reject heat at a constant temperature and employ a permeable thermal mass, called a regenerator, to heat and cool the working fluid without exchanging energy with systems external to the engine.

This regenerator is the key to the system's efficiency. In principle, it cools heated working fluids passing through it, absorbing energy from the fluid in the process, and restores all of this energy to the fluid when cool fluid passes through it in the opposite direction. The only difference between the two cycles is that in the Stirling cycle the regenerative heating and cooling of the working fluid occurs in a constant volume while the Ericsson cycle performs this function at a constant pressure.

It was noted earlier that the efficiency of Brayton-cycle devices could be improved with regenerators and by heating and cooling the gas during expansion and compression. It can be seen that the Ericsson cycle represents the ideal limit of the Brayton cycle.

In actual cycles, of course, performance is limited by failure to follow the ideal cycle, by "heat leaks" between the hot and cold ends of the cylinder, by pressure losses through heat exchangers and regenerators, by miscellaneous mechanical losses, and by imperfect heat exchange and regeneration processes. Major development problems include the design of high-temperature heat exchangers and regenerators which are easy to manufacture and have displayed acceptable lifetimes.

A problem unique to the Stirling and Ericsson cycles is the requirement for systems capable of ensuring that the working-fluid temperature remains constant during the heat absorption and rejection processes. A variety of schemes for accomplishing this function have been proposed. One technique involves constructing pistons with a series of fins which slide between mating fins attached to cylinder ends maintained at constant temperatures. These fins ensure a large heat-exchange surface between the constant-temperature source and sink and the working fluid, even though the fluid volume is changing.

Another design decision is the choice of a working gas. The cycles operate most efficiently with a gas with high thermal conductivity, low density, low viscosity, and a large change in volume when heated.[34] It can be seen from figure IX-29 that hydrogen achieves the best theoretical performance. It was selected by Philips and Ford Motor Company for their prototype automobile engine.

Hydrogen is highly flammable and could create a fire hazard if it escapes, although the quantities used in small engines are extremely small. It may also be incompatible with certain heater designs and some types of heat pipes. (Heat pipes may be needed to transfer thermal energy from a separate heater.) A recent study by Philips and Ford concluded that helium is a "requirement when operating with the heat pipe since hydrogen permeates the joints and 'poisons' the heat pipe."[35] Theoretical work has also been done on a variety of other working fluids, including dissociating fluids and boiling and condensing fluids.

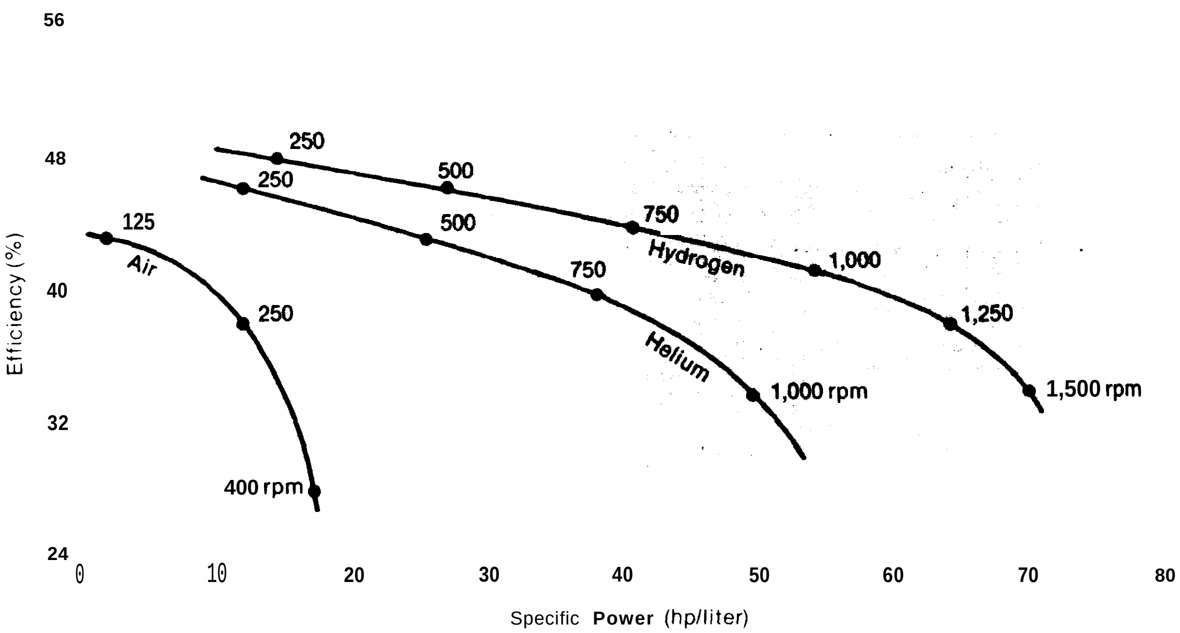
Design Alternatives

Prototype designs capable of approaching the ideal cycles are illustrated in figures IX-30 and IX-31. The rhombic-drive device, shown in figure IX-30, has been used by the Philips Corporation since the 1930's. It uses a pair of pistons in the same cylinder and an ingenious mechanical linkage to maintain the proper phase between them. The newer Philips design is shown in figure IX-31. This system uses the working piston in one cylinder as the displacer for the adjacent cylinder, with four cylinders forming a closed

[34] W. R. Martini, *Developments in Stirling Engines,* presented to the Annual Winter Meeting of the American Society of Mechanical Engineers, New York, N. Y., Nov. 26-30,1972, p.1

[35] R. J. Pens and R. D. Fox, A Solar/Stirling Total Energy *System,* published by Aeronutronic Ford Corporation.

Figure IX-29. —Calculated Performance of a 225-hp Stirling Engine as a Function of the Specific Power and Working Gas



SOURCE Samuels et al op cit, page 54

loop. The phase is maintained with a "swashplate" as shown in the figure.

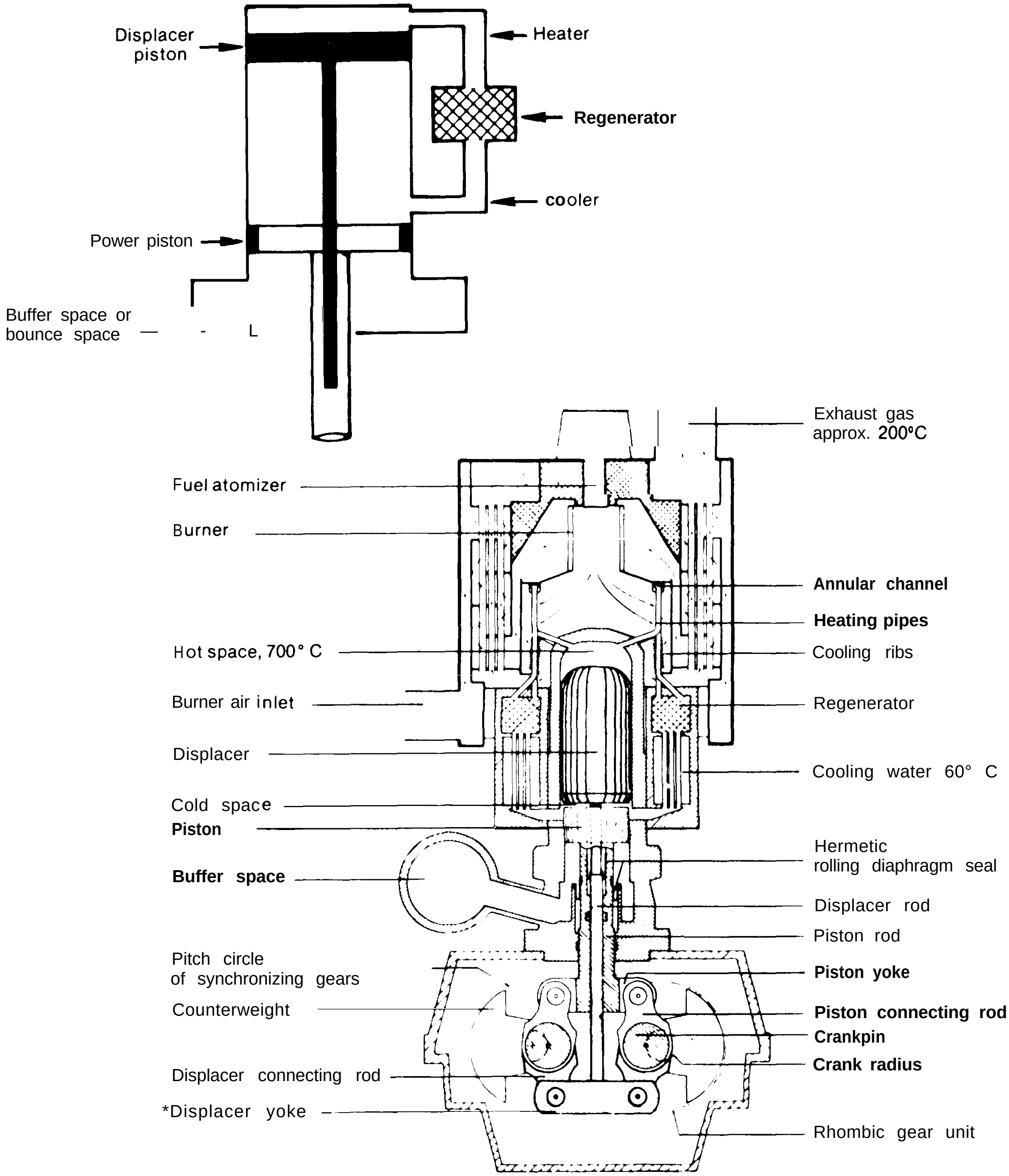
A major problem for both of these devices is the seal which must be made between the working fluid (usually helium or hydrogen), and the reciprocating shaft emerging from the engine. The Philips design employs a flexible membrane called a "roll-sock seal" for this function, which links the piston shaft to the cylinder wall with a flexible membrane (see figure IX-30).

The United Stirling Company of Sweden uses a Sliding seal in most of their designs. progress is being made, but these seals apparently still remain the major limit on engine life and reliability. The seals could present difficulties for total energy applications where they must be maintained at the temperature of the hot water used for space-conditioning; the life of the seals decreases sharply at high temperatures.

The problem of these seals could probably be overcome for continuous power applications if the seals were separately cooled or if the engine were designed to be sealed hermetically with an alternator. Such systems, however, have not yet been designed. It can be seen from figure IX-32, that if the energy available to these mechanical drive systems changes, the engine speed will change. A constant a.c. output from the system can be achieved in one of two ways: 1) the engine speed can be permitted to change and the variable frequency output rectified and inverted (as was necessary in the case of the Brayton-cycle devices), or 2) frequency control can be achieved by varying the pressure of the system using techniques developed for controlling Stirling-cycle automobile engines.

Some of the difficulties encountered by the mechanical drive systems could be overcome if the free-piston systems shown in

Figure IX-30.— Philips Rhombic-Drive Stirling Engine



SOURCE: "Towards Cleaner Air: A Passenger Coach Powered by a Philips Stirling Engine," N. V. Philips, Netherlands, January 1971.

Figure IX-31 .—Swashplate Stirling Engine

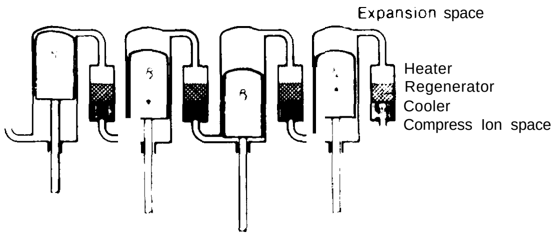
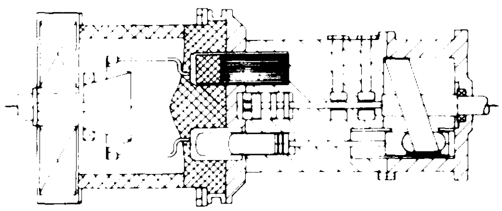


Diagram of the double-acting type Stirling engine principle of the double. acting engine There is a hot space—expansion space—at the top and a cold one—compression space—at the bottom of each of the cour cylinders shown The hot space of a cylinder is connected to the cold through a heater, a regenerator, and a cooler The pistons Pn of the cylinders move with a suitable phase shift between them In the case of four cylinders, as shown here, this shift is 90°



Schematic diagram of a four cylinder, double acting type Stirling engine with swash plate drive One of the four cylinders and one of the four cooler regenerator units *are* shown in cross-section In these engines, the movement of the pistons is transmitted to the main shaft by a swashplate

SOURCE Pictures and captions taken from R J Meijer and C L Spigl, "The Potential of the Philips Stirling Engine for Pollution Reduction and Energy Conservation " presented at the Second Symposium on Low Pollution Power Systems Development, Dusseldorf, Germany, November 48, 1974

figure IX-33 are successfully **developed.** [36 37 38] These systems are thermal/mechanical oscillators **in which the working piston and the displacer piston simply bounce** in the working fluid at a frequency determined by the properties of the gas and the mass of the pistons.

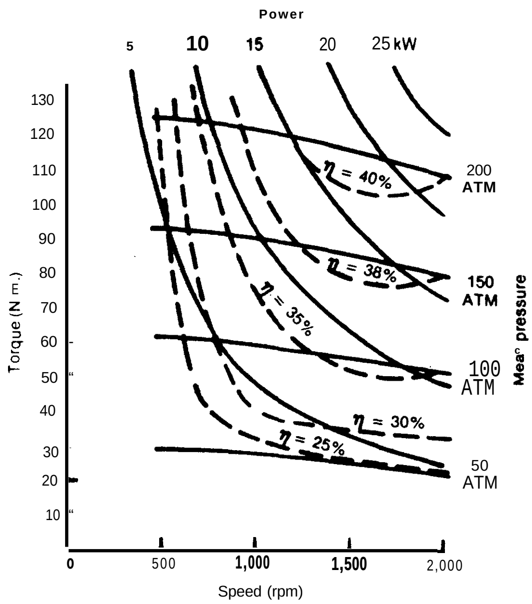
The designers of the ERG "thermal oscillator" system claim to have developed

Figure IX-32.—Calculated Performance of a Philips Rhombic-Drive Stirling Engine

General Design Data

Item	*Value*
Shaft power	*22.4* kW
Effective efficiency	40%
Engine shaft speed	**2000** rpm
Working fluid	helium
Mean pressure	200 atm
Max. cycle pressure	276 atm
Min. cycle pressure	141 atm
Expansion gas temperature	9650 K
Compression gas temperature	335 'K
Number of cylinders	4
Piston swept volume	55 cm^3
Piston phase	**900**
Pressure phase	**630**
Piston diameter	**4.4** cm
Piston stroke	3.5 cm
piston rod diameter	1.7 cm
Water temperature in	303 'K
Water flow	**0.9 *l*/s**
Heat pipe temperature	1,070° K
Engine length	75 cm
Engine diameter	45 cm
Engine weight	100 kg

System Efficiency at Various Power Levels and Speeds



SOURCE H A Jaspers and F K du Pre, "Stirling Engine Design Studies of an Underwater and **a Total** Energy System,' North American Philips Corporation publication #739035, 1973 *IECEC Record,* pp 588.593

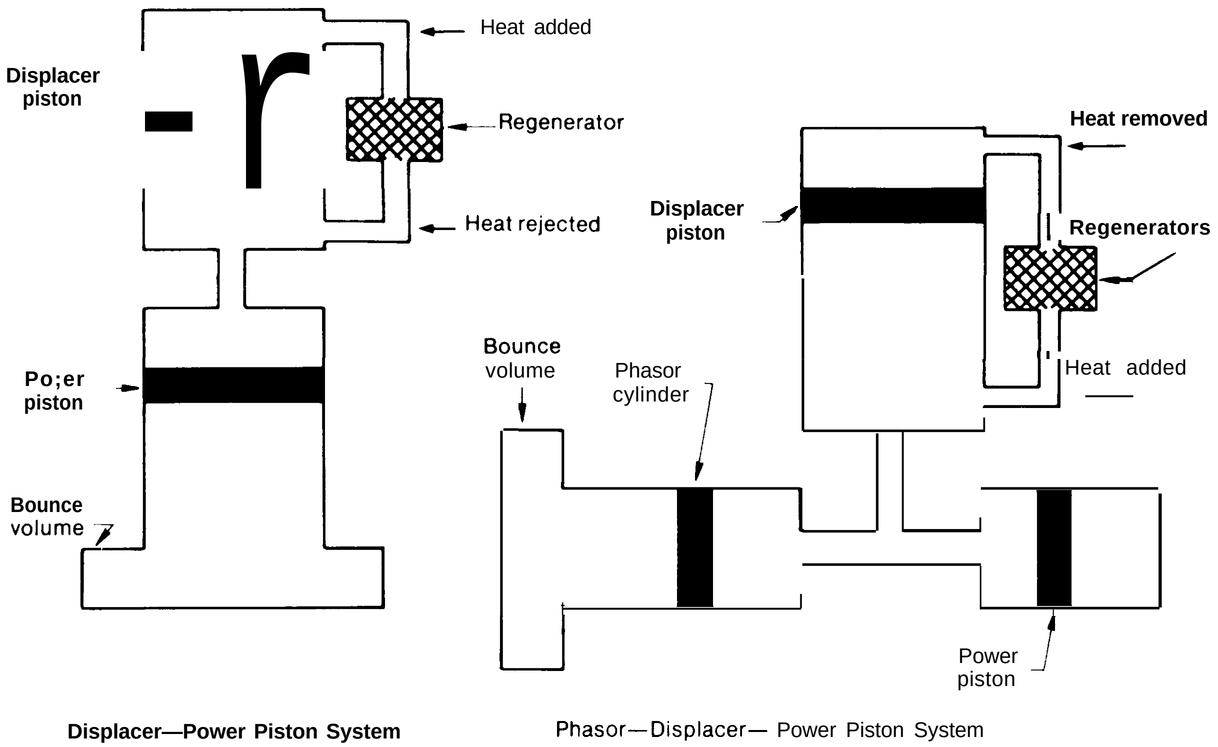
a free-piston system in which the frequency of oscillation is independent of the load applied as long as the average working pres-

[36] W Beale, et al , Free *Piston Stirling Engines, Some Model Tests and Simulations,* SAE Paper 690230, January 1969

[37] W Beale, et al , *Free Piston Engines, A Progress Report,* **SAE** Paper 730647, June 1969.

[38] *G. M.* Benson, *Thermal Oscillators, Proceedings,* Eighth IECES Conference, Aug 14, 1973, Philadelphia, Pa

Figure IX-33.– Free-Piston Stirling and Ericsson Cycle Designs



SOURCE: Diagrams of free-piston devices shown above based on similar diagrams in G M Benson, "Thermal Oscillators," presented to 8th IECEC meeting, August 14, 1973, Philadelphia, Pa.

sure is maintained in a sealed unit. The energy applied to the load is automatically adjusted as the pistons change stroke and relative phase angle.[39] **The use of the free-piston designs avoids the problem of mechanical linkages (having** only two or three moving parts), the need for starters (the machines start themselves when heat is applied), and the problem **of sealing a reciprocating shaft. As a result, it may be possible to** develop a system which is inexpensive to manufacture and has a long life and low annual maintenance. With pressures on the order of 1,000 to 2,000 psi, and the use of gas bearings where the working fluid provides the necessary lubrication, efficiencies as high as 70 to 80 percent of ideal should be obtainable. (Some designers contend that 90 percent of ideal efficiencies may be achieved, but this clearly will be extremely difficult.)

[39]G. M **Benson, op. cit., p. 10**

One unique problem with the free-piston design is that no rotating shaft emerges from the system. The power is in the form of linear oscillations of the working piston. The piston may not move very far; a *1* kW unit can move as little as 1 inch. '" "Linear alternators" suitable for this application have been successfully constructed, however, and exhibited efficiencies comparable with conventional alternator designs. " 4243

[40]G. **M. Benson, op. cit., p. 1.**

41 Ibid,

[42]**William** Beale **(Sunpower, Inc.), private communication, July 1976,**

[43]William Beale, *A 100-Watt Stirling* **Electric** *Generator for Solar* **or** *Solid Fuel* **Heat Sources, I ECEC 75,** Record, p. 1,020.

Power is produced either by moving a conductor (in a design similar to a loudspeaker voice coil) or by moving a magnet or flux gate. One design approach is **shown** in figure **IX-34.**

While these devices have great promise, relatively little work has been done on their design **in comparison with** the more conventional designs. Their performance in operational configurations has not been extensively tested, and disagreements about their practical achievable efficiencies and their stability to varying loads and input conditions cannot be resolved until more work is done. Working devices have been built, however, and high efficiencies measured in the laboratory. " 45

The development of a heat-transfer surface which can transport energy at high rates into a small cylinder head has proved to be a difficult undertaking. The materials required for this purpose must withstand high pressure, as well as exposure to oxidizing hot gases on one side of the heat-exchange surface and hydrogen on the other side. Devices capable of accomplishing this function can be made, but they must use alloys which are relatively expensive **in comparison with the mild steel used in** conventional engines— and in many cases, the designs appear to be difficult to manufacture. Heat pipes may be able to solve some of the problems faced in this area by providing **rapid heat transfer** in a system which does not produce a large pressure drop in the working fluid.[46] **The development of ceramic heat-exchange materials would be a great asset to the technology,** since ceramic devices would be able to operate at very high temperatures (i. e., 2,0000 F) and it may be possible to manufacture them with low-cost, mass-production techniques. The high **operating temperature permitted would also increase the potential efficiency of the system.** DOE is **sponsoring research** to develop a ceramic heat exchanger for Stirling applications beginning in FY 1978.[47]

An interesting sidelight to the Stirling- and Ericsson-cycle devices just described is their ability to integrate engines and heat pumps into a single device. Two approaches to this design, using the free-piston concept, are **shown in figures IX-35 and IX-36. This design can** be **modified to include electric generation by using the "phaser" pistons as linear alternators, thereby making** the device an attractive total energy system. The system is also attractive in that the performance of the heat pump does not drop rapidly as outdoor temperatures decrease (as is the case with conventional electric heat pumps). 'n 49

An Ericsson-cycle heat pump would probably have a higher efficiency than commercial heat pumps, but the impact of the new cycle on overall system performance would not be dramatic since most of the losses in current heat-pump systems result from the need to heat (or cool) the refrigerants to temperatures far above (or below) room temperature so that the room air-flow will be kept to comfortable levels. Heat exchangers and the requirements of fans are the second greatest source of inefficiency. 50 These effects reduce the performance of contemporary heat pumps by more than a factor of five. The efficiency of the compressors used in contemporary heat pumps is typically 75 percent of the ideal Carnot ef - ficiency.

It **is also** possible to operate a Stirling engine as a standard total-energy system, as

[44]G M Benson, op cit , p 14

[45]Beale, private communication, July 1976

4'S G Carlquist, et al , "Stirling Engines Their Potential Use in Commercial **Vehicles and Their Impact on Fuel** Utilization, **"** *Instn Mech Engrs, 1975,* **p 35**

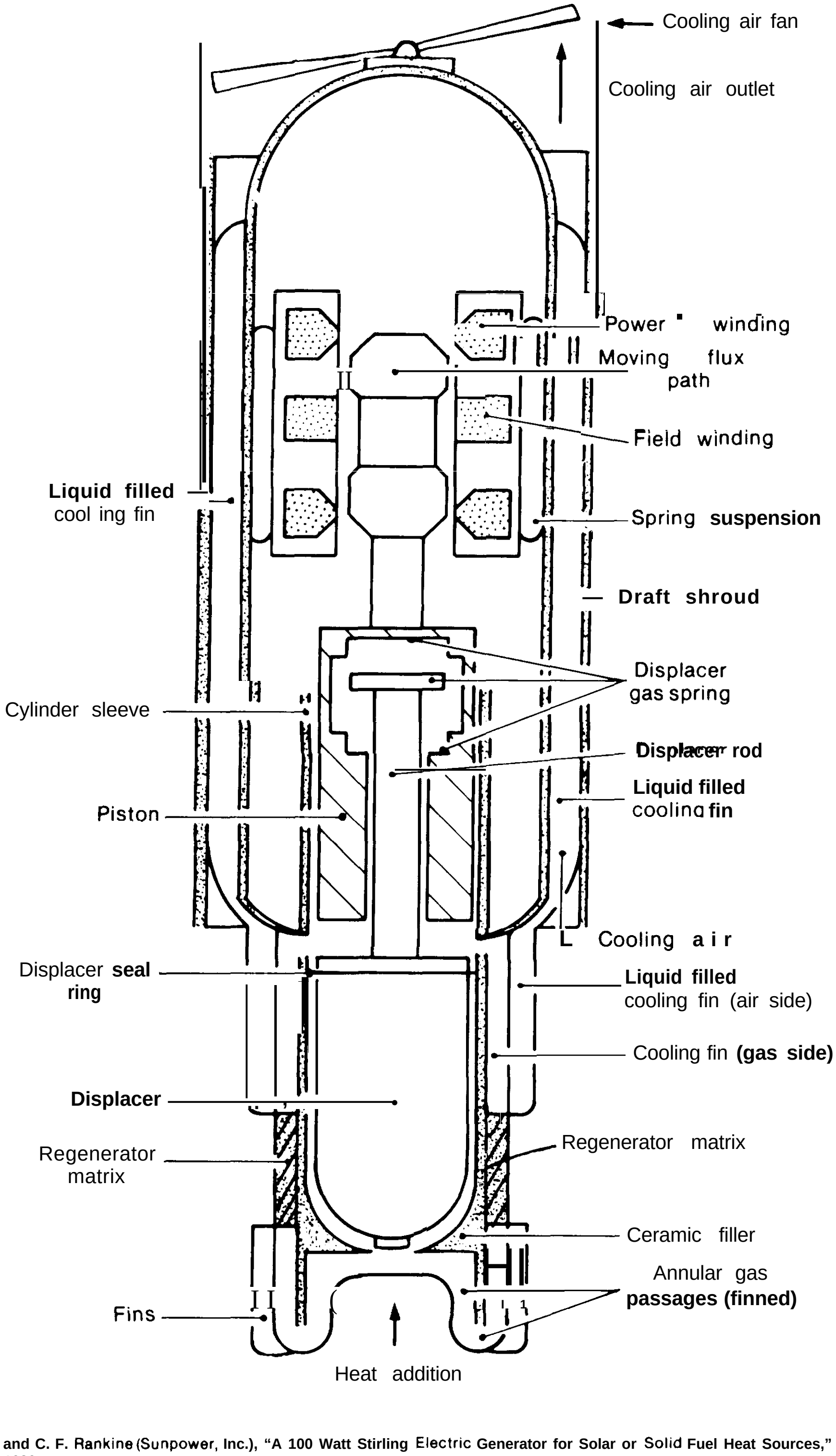
"W A Tomazic **and James E** Cairelli, **Ceramic Applications In** *the* **Advanced** *Stirling Automotive Engine* **(ERDA/NASA 1011/77/2, p 6)**

[48]Paul **R.** *Swenson,* **Consolidated Natural Gas** Service Company, Cleveland, Ohio, "Competition Coming in Heat Pumps: Gas-Fired May be Best in Cold Climate, " **Energy Research Reports,** 3(5), *Mar 7, 1977,* p 2

[49]" Advanced Gas-Fired Heat Pumps Seen Cutting Heating Bills **in Half, "** *Energy Users Report 188 (3/7/77),* p **27, Bureau of National Affairs**

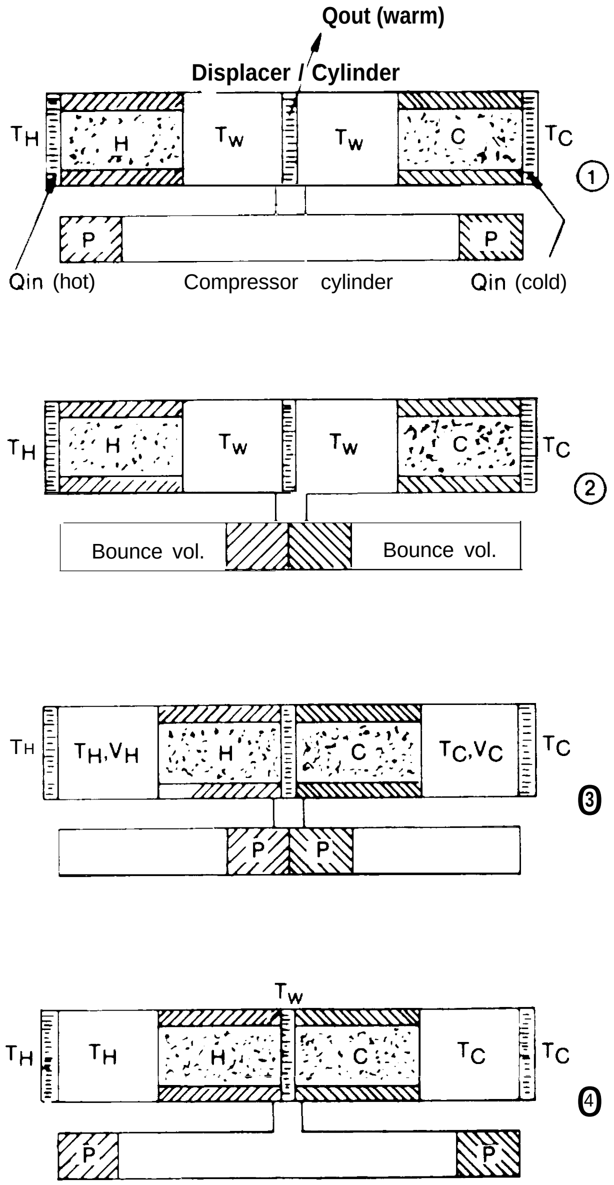
[50]W. **A. Spofford, "Heat-Pump Performance for Package** Air **Source Units,"** *ASHRAE Journal,* April 1959,

Figure IX-34.— Sunpower Systems Free-Piston Stirling and Ericsson Cycle Design Approach



SOURCE: W T. Beale and C. F. Rankine (Sunpower, Inc.), "A 100 Watt Stirling Electric Generator for Solar or Solid Fuel Heat Sources," 10th IECEC, August 1975, *Proceedings*, p. 1020.

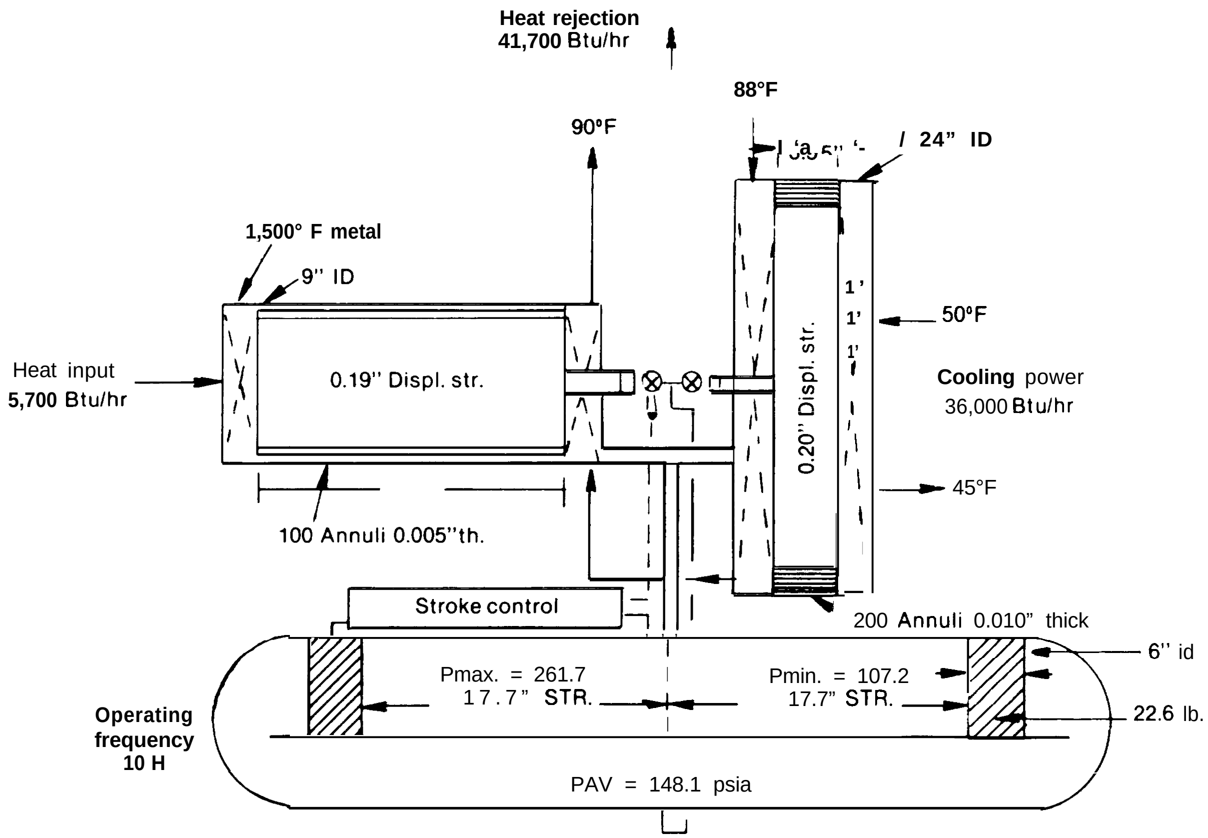
Figure IX-35. — Free-Piston Total Energy System



Note: Only **phasor position determines working and bounce gas pressures (P_w + pb)** since opposed motion of hot and cold displacers (H + C) produces a constant P_w.

SOURCE. G M Benson (ERG), Thermal Oscillators, op cit (U.S. patent No. 3,928,974).

Figure IX-36.— Free-Piston Total Energy System



Optimized preliminary design for **a heat-operated heat pump**

SOURCE W R Martini (University of Washington, Richland), "The Free-Displacer-Free-Piston Stirling Engine—Potential Energy Conserver," 1975 *IECEC Record,* pp 9951,002, 1976.

shown in figure IX-37. Space heat is provided from engine waste heat. Another approach, currently being supported by the American Gas Association, uses the piston of an Ericsson-cycle device to drive a sealed freon compressor.[51] William Beale of Sunpower, inc., has proposed still another alternative which is being investigated by the American Gas Association. His design would use the working piston in a free-piston device as the compressor for a Rankine-cycle heat pump. The working piston contains a mass whose inertia changes the volume available to the refrigerant inside the working piston as the piston oscillates.[52] The refrigerant enters and leaves this compression volume through flexible metal tubes which provide a leak-free path for the refrigerant through the helium-filled spaces surrounding the piston.

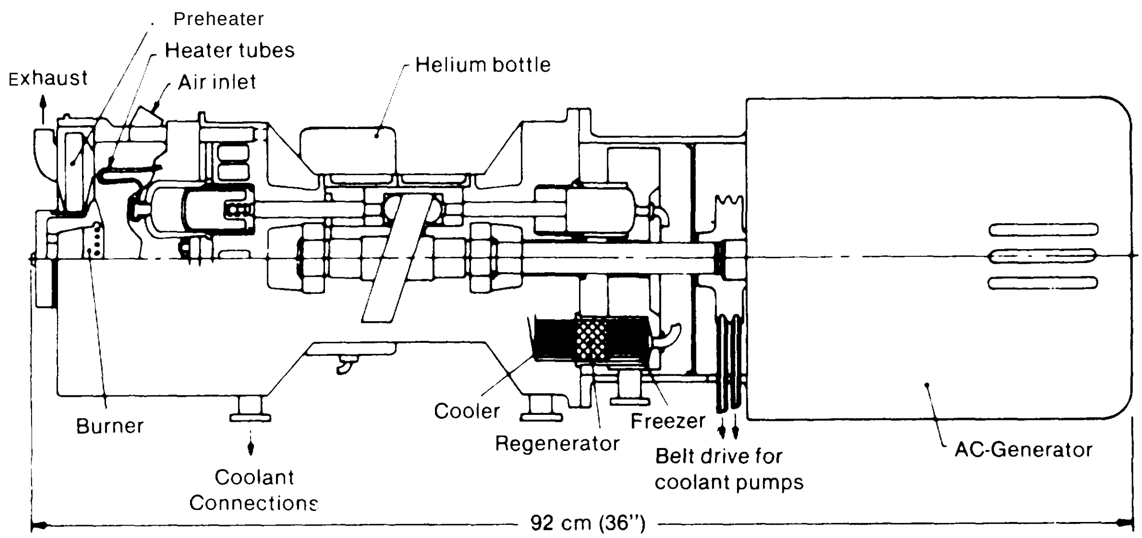
Performance

The performance of a number of the devices surveyed by the Jet Propulsion Laboratory in its review of potential automobile engines is summarized in table IX-8. All of

[51] Dr. C. H. Benson, ERG, private communication, Feb. 2,1977.

[52] William Beale, President of Sunpower, Inc., private communication.

Figure IX-37.—The Philips Design for a Stirling Engine Total Energy System



SOURCE H A Jaspers and F K du Pre, *Stirling* Engine Design *Studies of an Underwater Power System and a Total Energy System, (N* V. Philips publication)

these devices use mechanical linkages of some sort. The efficiency of operating engines averages between 24 and 30 percent (about 45 to 50 percent of ideal Carnot efficiency).

An optimized engine operating at its most efficient speed could, according to these estimates, produce 43 percent efficiency operating between 1,4000 and 1600 F (about 65 percent of ideal efficiency). Achieving this high efficiency, however, would require operating the engine at less than its maximum designed power, thus increasing its cost. The performance reported for free-piston devices has varied considerably because many different heat exchangers, regenerators, and thermodynamic cycles are being examined. Consequently, it is much too early to make a reliable estimate of the **efficiency of commercial systems. The efficiencies** of devices constructed to date by the Sunpower, Inc., group **have been relatively** low (10 to 30 percent cycle efficiency or 16 to 48 percent of ideal efficiencies) (table IX-9).

The performance of free-piston devices reported by Energy Research and Generation Corporation (ERG) is shown in table IX-10. These reports claim measured "indicated" efficiencies as high as *87* percent of ideal Carnot efficiency. In the device operating between 1,4000 and 120°F, this results in a cycle efficiency of 60 percent. The feasibility of achieving these efficiencies is corroborated by estimates made by a group studying Stirling engines **in the joint Center** for Graduate Study at Richland, Wash., and by Beale of Sunpower, Inc., although there appears to be some disagreement as to how far development has progressed towards this objective. 5354

The performance, of course, is largely sensitive to design details, including the size and design (and hence the cost) **of heat ex-**

[53] W **R** Martini, *The Thermohydraulic Converter,* **prepared for the joint Center for Graduate Study,** Richland, **Wash , Mar. 4, 1975**

[54] **W .** Beale, Sunpower, Inc **, private communication, July 1976,**

Table IX-8.—Stirling Engine Characteristics

Manufacture	Phillips 4-215	Phillips	United Stirling	GMRL GPU-3	Phillips 4-235	Phillips 40 hp	United Stirling	MAN-MWM 4-400
Status	Proto (Ford)	Analy (opti-mized)	Proto	Proto	Proto	Proto	Analy phase I	Proto
Type	Two-piston	Piston-disp	Two-piston	Piston-disp	Piston-disp	Piston-disp	Two-piston	Piston-disp
Working fluid	H_2	He	H_2	H_2	He	H_2	H_2	He
Max pres P psi	2,850	3,200	2,100	1,000	3,200	2,058	2,100	1,570
No of cylinders	4	4	4	1	4	1	8	4
Max bhp	170	275	49	11	200	40	200	120
Rpm at max power	4,000-4,200	1,600	3,400	3,600	3,000	1,500	2400	1,500
Max torque, ft-lbs	300	1,287	120	19	253	108	520	475
Rpm at max torque	1,400	400	955	1,200-2,400	1,000	900	600	700
Gas temp (hot), °F	1,300	1,400	1,275	1,400[a]	1,260	1,200	1,325	1,170
Gas temp (cold), °F	175	160	160	180	108	60	160	105
Efficiency at max bhp (%)	24	30	24	25	30	30	30	29
Max efficiency, %	32[b]	43[b]	30	26.5[b]	31	38	35	32
Power at max efficiency, bhp	75	100	35	7	175 (approx)	23	76	88
Rpm at max efficiency	1,100-2,000	600	2,000	1,900	1,800	725	1,200	1,000
Weight,[c] lb	750	N/D	N/D	165[d]	1,272	N/D	1,435	N/D
Dimensions,[c] ft	N/D	4.9 x 4.3 x 2.2	N/D	1.3 x 1.3 x 2.4[e]	4.1 x 1.7 x 3.6	N/D	3.7 x 2.7 x 3.1	5.0 x 2.3 x 4.3
Applications	Auto	Bus	Auto	EPS	Bus	LRE	Bus, truck	LRE

[a]Heater tube wall temperature.

[b]Net brake efficiency accounting for all auxiliaries including cooling fan, combustion blower, and water pump, among others.

[c]Includes all auxiliaries except cooling system with fan and transmission.

[d]Engine and auxiliaries less electrical power generator.

[e]Engine only.

Abbreviations:
Proto: operating prototype engine, LRE: Laboratory Research Engine; Analy: computer design projection; N/D: no date; EPS: Electric power supply.

SOURCE: Jet Propulsion Laboratory, "An Automobile Power Systems Evaluation," op. cit., p. 6, 8.

changers used, the gas pressure used in the cycle, the exact thermodynamic cycle chosen, and other variables.

Performance With Waste Heat

As noted earlier, Stirling devices have a great advantage in total energy applications because a very large fraction of the energy not used by the cycle appears in the cooling water. This is shown quantitatively for systems burning fossil fuels in figure IX-38. In a solar application, the percentage of energy recoverable in the coolant water would be even higher, given that there would be no losses in the exhaust. The performance of Stirling- and Ericsson-cycle devices operating at different coolant temperature is shown in figure IX-39 for two different assumptions about engine-generating efficiency.

Table IX-9.—Performance of Free-Piston Stirling Engine Designs of Energy Research and Generation Inc.

	ERG	ERG	Allison
Ind effic* (%)	42	60	50
IMEP/(p_{max} - p_{min})	.32	.37	.41
Head add temp (F)	780	1400	1220
Head rej temp (F)	110	120	170
Carnot effic (%)	54	69	62
Carnot effect (%)	78	87	80
Phase angle (deg)	110	90	118
Press ratio	1.73	1.29	1.79
Displ (in^3)	3.02	1.79	4.81
Max press (psia)	88	2115	1985
Ind work/cycle*(ft lb_f)	3.0	26.1	144
Frequency (Hz)	12.5	60	50
Ind* hp	.067	2.85	13.1

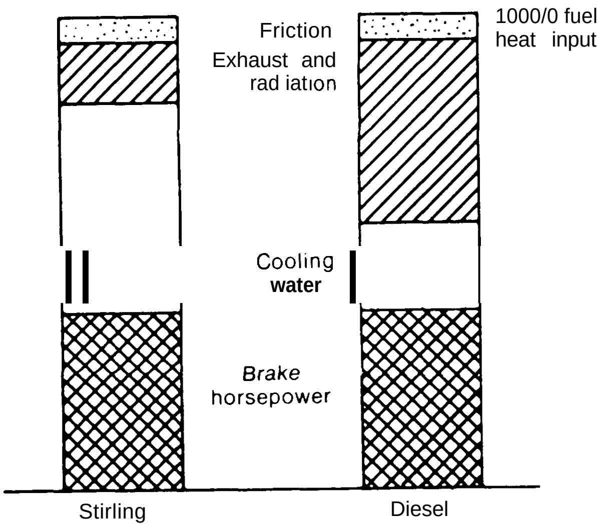
*Indicated work includes gas friction work

SOURCE: Reproduced from "Thermal Oscillators," G.M. Benson, paper presented at 8th IECEC meeting, Aug. 14, 1973.

System Costs

It is **impossible to estimate the costs of Stirling and Ericsson cycles with any precision,** since no practical devices are on the market. The cost will also depend on the efficiency and the lifetime expected of the system. In general, efficiency is improved with large heat-exchange surfaces, but heat exchangers are expensive.

Figure IX-38.— Heat Balance for the Stirling and Diesel Engine



SOURCE R J Meijer (N V Philips), 'The Philips Stirling Engine," De Ingenieur (621 41), page 21

Table IX-10.-Performance of Sun Power Free-Piston Devices

Power (Watts)	Cycle (%) Efficiency ***	% Carnot	T_{hot}(°C)	T_{cold}(°C)
20	10	18	400	25
70	18	30	500	25
100*	15	24	500	25
2000	30**	48	500	25

*Air System
**Expected
***Notice that the efficiencies in this table are complete cycle efficiencies while the ERG efficiencies are "indicated" efficiencies.

SOURCE: W. R. Beale and C. F. Rankin, Jr., "A 100 Watt Stirling Electric Generator for Solar or Solid Fuel Heat Sources," IECEC 75 Record, p. 1021.

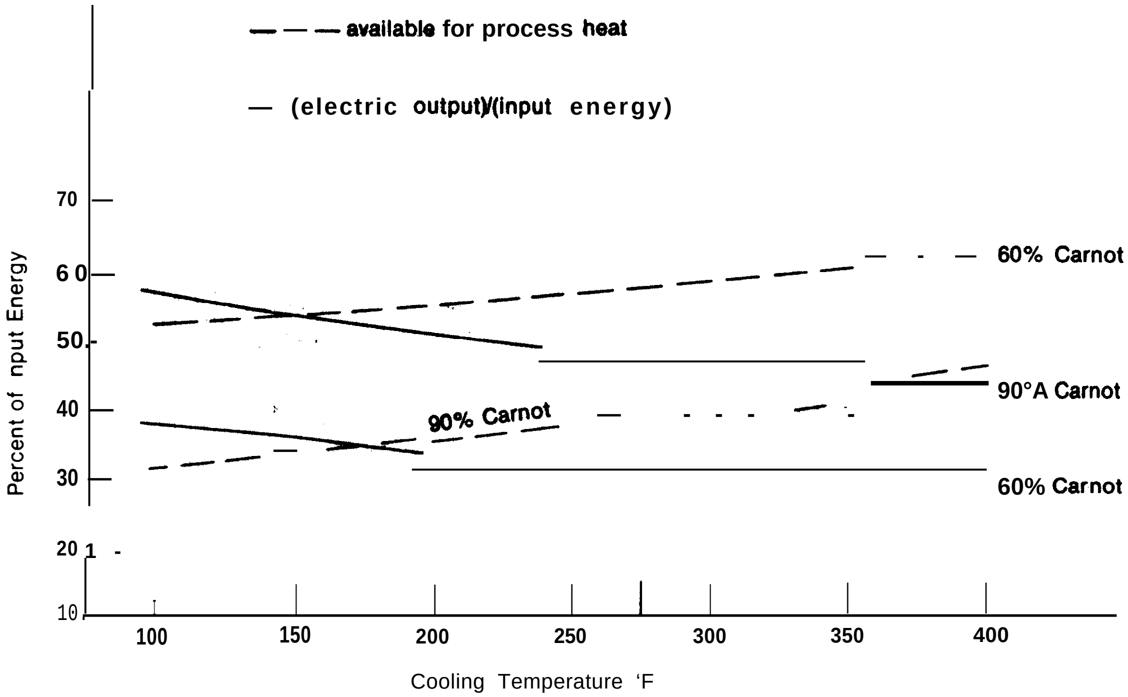
There could be some difficulty in adapting current designs to mass-production techniques since many current designs require complex heat exchangers which would need many separate welds and brazements. **It** should be possible to overcome this difficulty with advanced heat-exchanger designs, but the question of costs cannot be resolved until a production unit is designed.

Estimates made by the Jet Propulsion Laboratory in their survey of automobile-power systems indicate that a "mature" Stirling engine, operating at a temperature of 1,400" F, would cost approximately $14/kW wholesale, and would sell for approximately $18/kW at the retail level.[55] **(This, of course, assumes production on the scale of current automobile product ion.) A further study of the adaptations needed to install a 42-percent efficient Stirling** device **in a solar energy application resulted** in an estimate of about $38/kW for the engine, $27/kW for the alternator (installed on **the** engine), and about $27/kW for miscellaneous switching equipment and controls.[56] This results in a total cost of about **$92/kW**

[55] *An Automobile* **Power S** *ystems Evacuation, Jet* Propulsion **Laboratory, Volume 11, pp 11-12**

"Richard Caputo, J PL, Program Manager, *Comparative Assessment of Orbital and Terrestrial Power Systems, p.24*

Figure IX-39.— Electric and Thermal Output of a Stirling Engine



Assumptions:
inlet temperature = 1400°F
Generator efficiency = 90%
energy not recoverable = 59'0

SOURCE, Prepared by OTA.

(all prices are given in terms of price per-peak- power output; average power would be substantially lower). These prices also do not include the cost of the receiver and heat pipe needed to transmit solar power to the engine.

Another estimate of the cost of a Stirling engine/generator set was made by Philips and Ford Aeroneutronics for their proposal to construct a solar, total energy system in Disney World. This estimate for an engine/-generator and switch-gear amounted to $400/kW, with an aside noting that this could be reduced to $100/kW if large-scale production were undertaken .57

[57]Pons, et al., op. cit., p. 13.

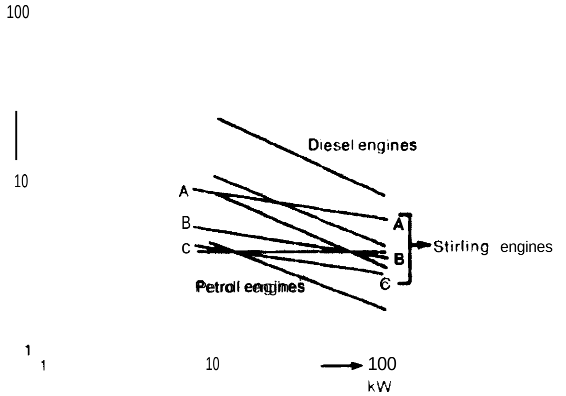
The cost of free-piston devices could be lower than those of the mechanically coupled systems because of their inherent simplicity, but again the lack of commercial devices makes cost estimates difficult. The Energy Research and Generation Corporation has estimated that their free-piston design is amenable to mass-production techniques and could be produced for about $30/kW, with an additional $10/kW for the linear alternator.[58]

Another way of estimating the cost of the Stirling-engine devices, manufactured at moderate production rates, is to compare

[58]Glen Benson, Energy Research and Generation Corporation, private communication, December 1976.

them with the cost of conventional gasoline- and diesel-powered engine-generator sets. Figure IX-40 indicates that the Stirling devices with mechanical linkages should have a weight per-unit-of-power which is somewhere between gasoline and diesel engines. Assuming that the Stirling devices are roughly of the same complexity, figure IX-41 can be used to estimate costs of about $75 to $150/kW for shaft output Stirling engines of about 100 kW capacity.

Figure IX-40. —Weight-to-Power Ratios of Engines With Internal Combustion and of Stirling Engines

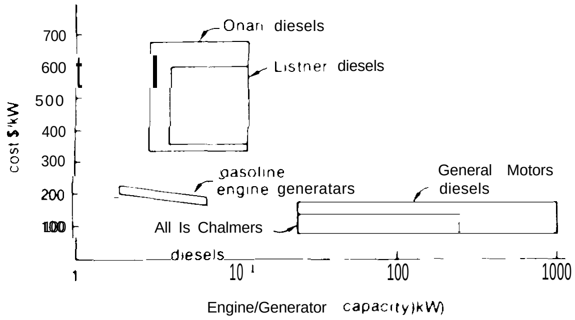


A Stirling engines present laboratory types
B Laboratory models to be expected within a few years
C Stirling engines developed for vehicles

Weight to-power ratios of engines with Internal combustion and of Stirling engines

SOURCE
R J Meyer Combination of Electric Heal Battery and Stirling Engine—An Alternative Source of Mechanical Power, reprinted from Denkschrift Elektrospeicherfahrzeuge ' Volume 1 1/1 969

Figure IX-41.—Cost of Diesel Engines



SOURCE Prepared by OTA using manufacturer's data

Free-piston designs could weigh significantly less than the mechanical devices shown in the figure. Dr. Benson of ERG has estimated that their device could weigh as little as 5 lbs/kW (2.3 kg/kW).[59]

State of the Art

Engines based on the Stirling and Ericsson cycles have been in operation since the early 19th century, The Stirling engine was patented in 1816 by a Scottish clergyman, John Stirling; Ericsson-cycle devices were patented a few decades later. (The Ericsson cycle is named for the Swedish-American inventor, John Ericsson, who, among his other accomplishments, was the designer of the Union ship, The *Monitor.)* These early designs used air as the working medium and were expensive, heavy, and relatively inefficient—since the designers lacked both materials and analytical methods capable of optimizing the design of thermodynamic cycles.

Interest in Stirling engines was revived in 1938 by the Philips Corporation of the Netherlands, when that company was searching for an engine to burn a variety of fuels and provide quiet and reliable **power to military radio receivers.**[60] **The company,** one of the world's largest multinational firms, now has over 100 people working on the development of Stirling engines. Many world patents for Stirling engines are held by Philips, and the vast majority **of work which** has been done on Stirling devices in this century has been done either by Philips or under license from Philips. The company has several well-developed engine designs, some of which have operated over 10,000 hours without failures.[61] They have been used to power a number of vehicles including boats and a small bus. The basic development engine

[59] **Benson, ibid.**

[60] R. **J. Meijer and C. L** Spigt, *The Potential of the Philips Stirling Engine for Pollution Reduction and Energy Conservation.*

[61] **Norman** D. **Postma, et** al., *The Stirling Engine for Passenger Car Applications,* **Ford Motor Company publication.**

has been a 25-hp device using two rhombic-drive cylinders. About 30 to 40 of these engines have been built by Philips or are under license from Philips.[62]

The U.S. National Bureau of Standards is testing one of the few Philips engines that is outside of the Netherlands to measure its performance in total energy applications.[63]

The Philips work stimulated interest in Stirling equipment by a number of different companies. The General Motors Company had an extensive program in the development of Stirling engines which began as a cooperative program with Philips. Research and design studies were conducted on a number of different engine designs including free-piston devices. The company had accumulated over 28,000 hours of engine running-time experience between 1959 and the abrupt termination of the project.[64]

In 1972 the Philips Company entered into a contract with the Ford Motor Company to develop a Stirling automotive engine. Work has been underway since then. The program began with an attempt to use a swashplate Stirling engine with a 1973 Ford Torino. Problems have apparently developed with the original approach, however, and progress is slower than had been expected.

The United Stirling company of Sweden has also done extensive development work on Stirling equipment and is apparently planning to have a device ready for field-testing in Swedish iron mines by 1979.[65] The company plans to market 40-, 75-, and 150-kilowatt engines shortly thereafter for use in mine-pumping operations (where their low emissions, fuel economy, and quiet operation should be great benefit), in total energy systems for homes, and for automobiles and buses.[66] The United Stirling devices use a "sliding seal" instead of the "roll-sock" seal employed by most of the Philips engines.

The Thetford Corporation of Michigan recently formed a joint venture with Sweden's Forenade Fabriksverken (FFV) to manufacture a Stirling total-energy system for recreational vehicles which the company hopes to have on the market in 1978.[67]

In addition to Philips and the United Stirling Company of Sweden, **MAN of Germany has accumulated many years of experience with Stirling devices, some of it based on Philips' designs.**

Much less work on Stirling and Ericsson cycles is being done in the United States. The Atomic Energy Commission and the Heart and Lung Institute at the National Institutes of Health initiated a program in 1966 to develop an artificial heart. Several designs were proposed using electric motors and Rankine and Stirling engines. The program attracted several U.S. companies, including Aerojet, Thermo-Electron Corporation, ERG, Inc., Air Products and Chemicals, Inc., and Westinghouse Astronuclear (under contract with Philips).[68]

Work on novel engine designs for transportation and automotive applications is being performed by the Energy Research and Generation Corporation, Sunpower, Inc., and by a variety of university groups. The work at Sunpower is based, in part, on funding from the American Gas Association with the objective of developing a heat pump able to operate from natural gas. The company is also working under an ERDA grant to develop an engine using a radioactive source to provide electric power for

62 Pens, op. cit , p 11.

63 D. Diddion, National Bureau of Standards, private communication, December 1976

64 W H. Percival, Historical *Review of Stirling Engine Development in the United States from 1960 to 1970,* prepared for the ERDA(EPA contract 4-E8-00595), July 1974, page 124,

65 Hallare, Bengt, Director of Corporate Planning and Marketing, United Stirling, et al., "Development of Stirling Engines in Sweden and Their Application in Total and Solar Heated Energy Systems. " Paper delivered to the 1977 International Solar Energy Conference and Exhibit, Palm Springs, Fla., 1977. *Proceedings* published by the Northrop University Press.

66 W. H. Percival, U.S. representative of the United Stirling Corporation, private communication, May 6, 1977.

"Ann Arbor News, Mar. 25,1977.

68 William Beale, *A Stirling-Hydrostatic Drive for Small Vehicles,* provided by Sunpower, Inc.

spacecraft.[69] Figure IX-42 shows the Sunpower device installed in a solar collector.

Work on linear alternators suitable for attachment to Stirling- and Ericsson-cycle devices for electric-power generation has been performed by the Energy Research and Generation Corporation and by the Mechanical Technology Corporation. Both groups have tested operational designs, but neither firm has a unit on the market. Work on the use of Stirling engines for transport is also being done by the Sunpower Corporation, Energy Research and Generation Corporation, and Polster.[70]

[69]G Benson, *Thermal Oscillators,* op cit

[70]N E Polster and W R Martini, "self-starting, Intrinsically Controlled Stirling Engine," *IECEC Record,* pp 1,511-1,518, 1976

Although a number of groups have investigated Stirling- and Ericsson-cycle devices, the engines must be considered to be in a relatively primitive state of development. The alternative cycles have benefited from many years of careful design work, while most Stirling designs have remained in the laboratory. No Stirling engine is being produced on a large scale anywhere in the world.

OTHER HEAT-ENGINE DESIGNS

The Thermionic Converter

The thermionic device shown in figure IX-43 can operate at *very* high temperatures

Figure IX-42.—200-Watt, Sun power Stirling Engine, Mounted in Concentrating Collector

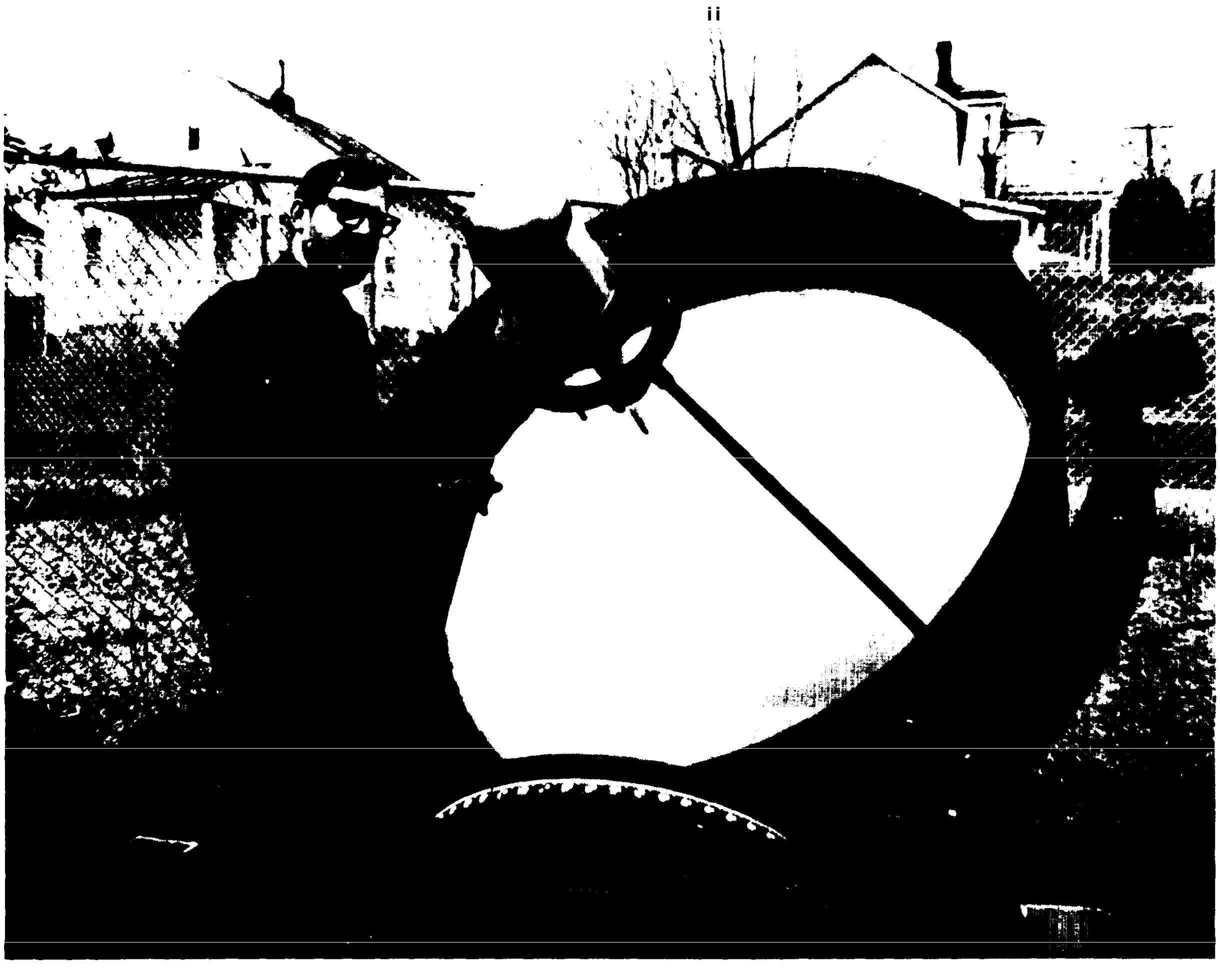
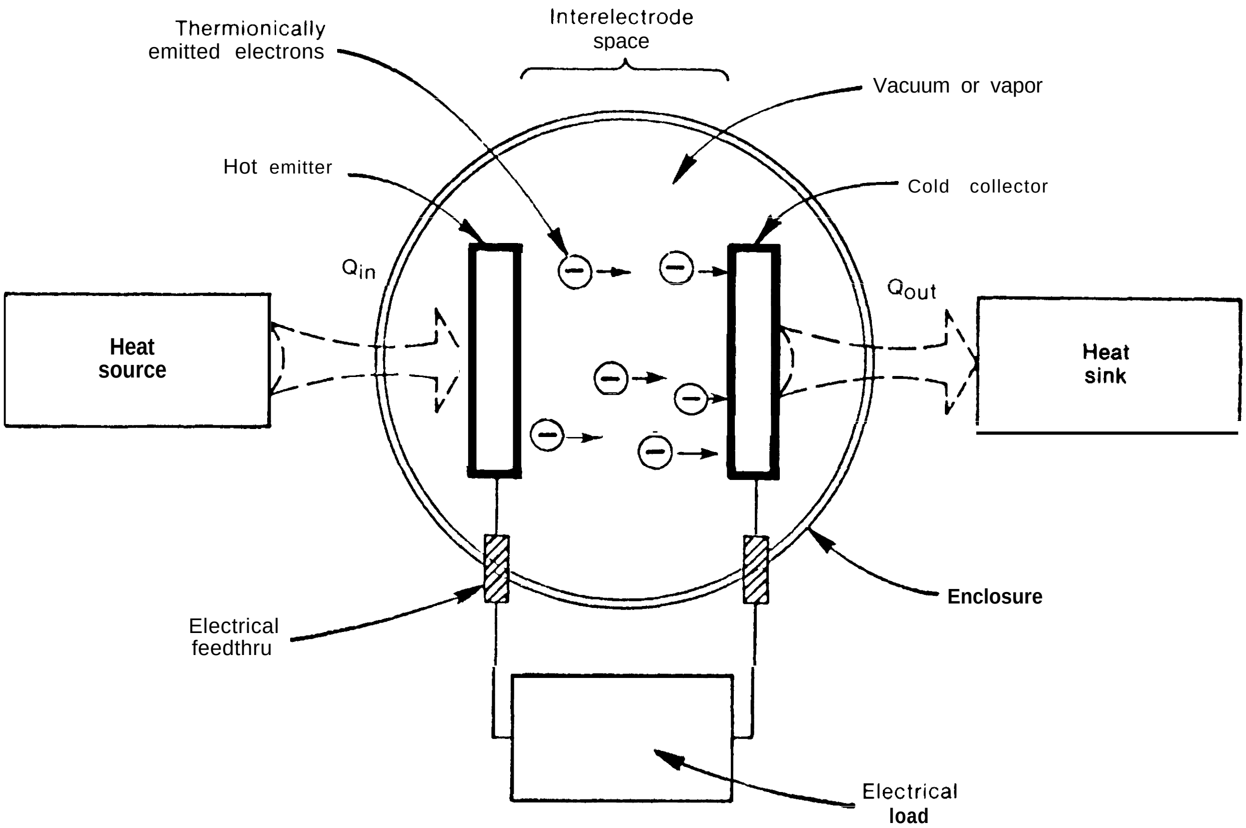


Photo credit Sunpower, Inc

Figure IX-43.— Identification of Thermionic Converter Components



SOURCE Thermoelectron Corporation

and can achieve extremely high-power densities (on the order of 2 to 10 watts/cm^2 of receiver surf ace).” The hot emitter and the cooler collector of a therm ionic converter are separated by a vacuum or by an ionized gas. A current can be sustained if the hot side of the diode emits electrons at a greater rate than the cold side. Electrons evaporated from the emitter flow across the interelectrode gap to the collector, where they condense and are returned to the emitter via the electrical load. Some of the thermal energy transferred from the hot to the cold side of the diode is carried directly by electrons, which are the “working fluid” of this engine. The heat flow is thus translated directly into a flow of electricity.

Therm ionic energy conversion has a number of desirable characteristics: 1) no moving parts, 2) heat rejection at relatively high temperatures, 3) lends itself to modular construction, 4) potential for efficiencies up to 40 percent, 5) heat input in an intermediate temperature range (1 *,2000* to 1,8000 K), 6) the mechanical simplicity associated with no moving parts implies reliability, and 7) the high temperature of heat rejection makes therm ionic converters well suited for topping steam powerplants, because the heat rejected from the collectors is available at a high temperature to generate steam for conventional turbomachinery.

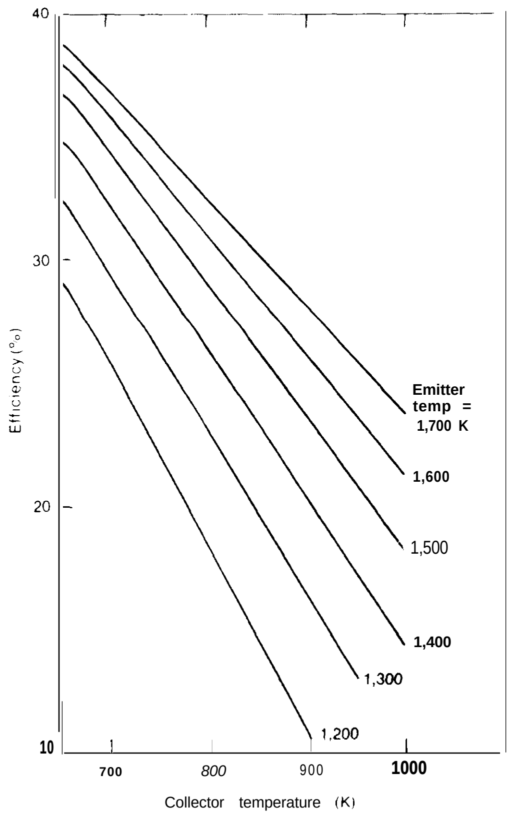
Efficiencies as high as 5 to 15 percent have been reported for devices working be-

“William C. Reynolds and Henry C. Perkins, Engi- *neering Thermodynamics,* **McGraw H ill, 1970, p. 309.**

tween 1,160" and 2200 F (13 to 38 percent of ideal Carnot efficiency) .72 A curve of performance predicted for advanced designs of therm ionic converters is shown in figure IX-44. It can be seen that high efficiencies are possible if the losses which now limit performance can be reduced.

The feasibility of therm ionic conversion has been demonstrated with a variety of hydrocarbon, solar, radioisotope, and reactor heat sources. Stable in-pile operation has been achieved for over 16,000 hours. The Soviet Union has progressed to the third generation in-core therm ionic reactor with electrical outputs of over 7 kilowatts.

Figure IX-44.— Effect of Collector Temperature on Thermionic Efficiency



SOURCE Thermo Electron Corporation

While a good base of high-temperature, thermionic-conversion technology exists, thermionics has yet to achieve practical application with fossil fuels because the emitter temperatures currently required for competitive power densities and efficiencies limit the operating life of the "hot shell" (i.e., the protective structure which isolates the converter, per se, from the combustion atmosphere) to several hundred hours. In order to reduce the operating temperatures of converters to levels where the hot shell will have greatly extended life while maintaining converter efficiency, it is necessary to develop improved emitter and collector surfaces, as well as decrease the plasma losses occurring as the electrons flow across the interelectrode space. Reasonable progress is being made in both areas.

Thermoelectric Conversion

Electricity can also be generated directly from a source of high-temperature thermal energy using a solid-state "thermoelectric" junction. 73 These devices, which operate on the same principle as thermocouples, are frequently used to power spacecraft using isotopes as power sources. Devices operating with an isotope source of 1,000"C (1,832 °F) are capable of efficiencies on the order of 3 to 6 percent. 74

The Nitinol Engine

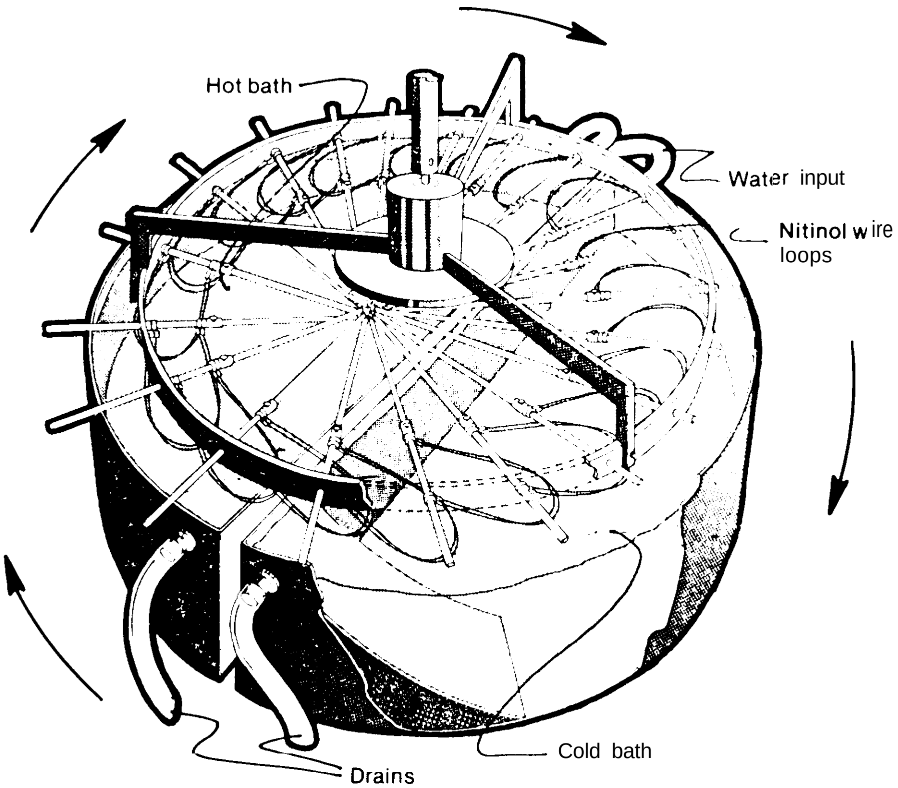
Thermal energy is converted into mechanical work when a heated metal expands, A nickel titanium alloy called Nitinol developed by the Naval Ordnance Laboratory (Ni + Ti + N. O. L.) in 1958 has unique thermal properties which can be used to construct a primitive heat engine— one design is shown in figure IX-45. Nitinol deforms easily at low temperatures but returns to its original shape with considerable force when heated. Several working devices have been

[72] Huff man, Thermo-Electron Corp , private communication, January 1977

[73] P Rouklove, *Tests and Evaluation of Multi-hundred Watt Thermoelectric Generators at JPL*, 12th IECEC Conference, p 1,287

[74] J E Boretz, *Reactor Hybrid-Organ/c Rankine Cyc/e Electric Power Sys terns for Space Applications*, 12th I ECEC Conference, p 1,318

Figure IX-45.—The Nitinol Engine



SOURCE *The CoEvolution Quarterly*, Spring, 1975, p. 70

constructed by Ridgeway Banks at the Lawrence Livermore Laboratory.

Osmotic-Pressure Engine

Thermal energy can also be converted to mechanical energy in the osmotic-pressure cycle. The heat is used to distill a dilute solution into pure solvent and a concentrated solution. Energy can be recovered if the solvent and concentrated solutions are pumped into different sides of a chamber separated by a semipermeable membrane. The solvent is forced across the membrane with a pressure equal to the difference between the osmotic pressures and hydraulic pressures of the fluids on either side of the membrane. The osmotic pressures can be quite large. A saturated solution of NaCl in water, for example, has an osmotic pressure of 380 atmospheres (about 4,000 m of water). Every cubic meter of water sent into the reaction chamber with a saturated NaCl solution, therefore, has a potential energy of about 11 kWh. The fraction of this energy which can be retrieved in a practical system has not been established, although some preliminary design work has been done on membrane reaction chambers.[75] [76] Membranes suitable for use in these systems are commercially available. Du Pont, for exam-

[75] S. Loeb, "Production of Energy From Concentrated Brines by Pressure-Retarded Osmosis: 1, Preliminary Technical and Economic Correlations," *Journal of Membrane Science 1* (1976), p. 49.

[76] S. Loeb, et al., "Production of Energy From Concentrated Brines by Pressure-Related Osmosis: 11. Experimental Results and Projected Energy Costs," *Journal of Membrane Science, 1* (1976), p. 249.

pie, has a membrane called "Permasep," designed for use in desalinization plants, which costs about $4/m^2 of active surface. One square meter of this surface is able to pass about 0.16 m^3/day when a pressure difference of 400 atmospheres is developed across the surface. 77 Waste heat can be recovered from the system via the condenser of the distillation unit.

ENVIRONMENTAL AND SAFETY PROBLEMS

FLUOROCARBONS

Many of the currently available low-temperature heat engines employ fluorocarbons identical to the refrigerants now used in home and small industrial refrigeration and air-conditioning equipment: F-1 1 (CCl_3F), F-12 (CCl_2F_2), and F-22 ($CHClF_2$). These substances have great chemical stability at low temperature, but this very chemical stability may lead to severe environmental problems. Because fluorocarbons do not decompose once released into the environment, they remain in the atmosphere and eventually react chemically with the Earth's ozone layer, possibly reducing the ability of the ozone to shield the Earth's surface from the Sun's ultraviolet light.[78]

The environmental, biological, and health effects of stratospheric ozone changes are only now being discovered. Some scientists suggest that changes in stratospheric ozone levels could cause changes in the Earth's climate, including changes in temperature and wind patterns. 79 The health effects of changes in the stratospheric ozone are not fully understood. The decreased ozone layer results in an increased incidence of ultraviolet radiation on the Earth's surface. Some evidence supports a correlation between ultraviolet radiation and malignant melanoma, the most serious, often fatal, form of skin cancer.[80] Studies have indicated that increased ultraviolet irradiation results in increased incidence of nonfatal, nonmelanoma types of skin cancer in humans.[81] Increased ultraviolet radiation may also have some adverse effect on human eyes and eyesight,[82] and possibly on growing plants, as well.

In addition to the ozone depletion caused by the release of fluorocarbons into the environment, and the coincident human health effects, direct health effects from exposure to fluorocarbons have been reported in various animals. These effects include influences upon the respiratory and circulatory systems in mice, rats, dogs, and monkeys. 83 Research into the environmental and health consequences of fluorocarbons has received impetus from concern over the widespread use of fluorocarbon propellants in aerosol sprays.[84]

Some fluorocarbons leak into the environment from facilities which manufacture refrigeration equipment and from abandoned or malfunctioning units. Estimates indicate, however, that less than 3 to 6 percent of the fluorocarbons lost into the environment come from this source, even though the refrigerants market constituted 28 percent of

77 S Loeb, op cit , II, p 254.

78 M. J Molina and F J Rowland, "Stratospheric Sink for Cholofluoromethanes Chlorine Atom Cata lyzed Destruction of Ozone, " *Nature* 249.810-812, 1974.

79 NAS Report, pp. 72-78

80 NAS Report, pp 81-89

81 IMOS Report, p. 70.

82 I bid., p. 74,

83 D. M. Aviado, "Toxicity of Aerosol Propellants in the Respiratory and Circulatory Systems IX, Summary of the Most Toxic: Trichlorofluoromethane (F11)," *Toxicology,* 3:311-319, 1975.

84 See e g , M. B. McElroy, "Threats to the Atmosphere, " Harvard *Magazine,* 78:1 9-25, 1976; J E igner, Unshielding the Sun... Environmental Effects, *Environment, 17:1* 5-18, 1975; A.K.A. ed, Unshielding the Sun. . .Human Effects, *Environment, 17:6-14, 1975*

the total fluorocarbon market in *1972.*[85 86] Recent studies indicate that losses from refrigeration equipment can be reduced, especially those from automobile, home, and commercial air-conditioning units. 87

The use of a freon-based heat engine to provide solar air-conditioning would increase the amount of freon in a typical home by a factor of 2 to 3. A house using a freon-based engine to provide 100 percent of residential electrical and air-conditioning needs would need *5* to 6 times more freon than a conventional house.

The environmental impact of this increase in fluorocarbon use (independent of other fluorocarbon uses such as aerosol propellants) is yet to be fully evaluated, but because of the possibility of severe environmental damage either from fluorocarbons or their consequent ozone depletion, these impacts are being analyzed. "

Although ozone levels fluctuate worldwide, it is believed that an overall depletion has occurred, perhaps because of fluorocarbon usage.[89] The effect of this level of depletion is still controversial. It appears, however, that the use of fluorocarbons in onsite energy production will not be a major problem. This is because only a low percentage of environmental fluorocarbons result from loss due to use as a refrigerant. Until a replacement fluid for fluorocarbons is found, an attempt should be made to minimize their escape into the environment.

[85] *Halocarbons: Environment/* **Effects of** Cholofluoromethane **Release, National Academy of Science, Committee on Impacts of Stratosphere Change, Washington, D. C., 1976 (hereinafter, NAS Report), p. 16.** ***Fluorocarbons and the Environment,*** **Report of Federal Task Force on Inadvertent Modification of the Stratosphere (I MOS), June 1975, (hereinafter, IMOS Report), p.91.**

[86] IMOS Report **at page 88, P. H.** Howard and A. **Hanchett,** "Cholofluorocarbon **Source of Environmental Contamination, " Science, 189:21 7-219, 1975.**

[87] IMOS **Report, p. 93**

[88] Manufacturing **Chemists Association,** *Research Program of Effect* **of** *Fluorocarbons on the Atmosphere,* **Dec. 31, 1976, and NAS Report,**

[89] IMOS **Report, P.** 380.

Under the Toxic Substances Control Act (Public Law 94-469), the process of regulating use of fluorocarbons is beginning because of the possibility of extremely severe environmental effects. **In the** *Federal Register* of March 17, 1978, the Environmental Protection Agency, Food and Drug Administration, and Consumer Product Safety Commission issued regulations stating that it will be illegal to: a) manufacture aerosol cans containing fluorocarbons after December 15, *1978,* and b) introduce such containers via interstate commerce after April 15, 1979. Uses of fluorocarbons in refrigeration, including onsite solar energy systems, will be regulated later. Use **of** fluorocarbons in onsite solar energy systems is merely one category of use in refrigeration units, however, and as such will not be **subject to im**mediate regulation.

NOISE

Because the equipment for onsite energy production may be located in or near living or working quarters, the noise emitted by these systems must be considered as an environmental impact. Solar collectors and energy-storage systems are silent except for the low rumble of intermittent pumps and flowing water, but in systems which employ gas turbines and other types of heat engines, noise could be a problem. Without noise suppression, a gas turbine of a size sufficient to generate all electricity for a single home would emit about as much noise as an unmuffled internal combustion automobile engine at full throttle. '" However, the noise from gas turbines is readily suppressible to levels quieter than a common household furnace fan– less than 40 decibels." This suppression is a normal part of commercial turbine installations. In a total energy system (a system which employs waste heat from energy production for space heating uses), noise suppression of the gas turbine

90108-1 20d Ba, at 10 feet,

"Patrick G. Stone, Garrett Corporation, Washington, D. C., personal communication, Feb. 11, 1977,

can be accomplished using a waste-heat boiler, reducing the noise to acceptable levels without added installation costs.

WATER USE IN STEAM CYCLES

The **solar energy systems of a small community or industrial plant, on the order of 15 MW(e), may employ water or steam in** energy conversion.

Although this water will not be polluted by chemicals during this process, it will return to the environment with added heat. **In areas of water shortage, the requirement** for replacing the amount of water lost could constitute a major problem. This is particularly true in dry, sunny climates where solar systems have other advantages, and should be considered prior to installation of such a system. Water requirements would be about the same as for a fossil steamplant of similar capacity.

SODIUM AND POTASSIUM VAPOR

Some of the proposed high-temperature storage schemes require heat pipes which use sodium or potassium vapor as their working fluid. While only very small quantities of these substances are required, they could have minor adverse environmental impacts, although both of these vapors are presently employed in street lighting, and no adverse use impacts have been reported.