PRINCIPLES AND APPLICATIONS OF STIRLING ENGINES

C. D. West

Oak Ridge National Laboratory

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PREFACE

This book is intended as an introduction to Stirling engine principles, applications, and technology for engineers who have not specialized in the field. For some reason, most textbooks have little to say about Stirling engines, and what little is said often makes the principle seem more arcane than it really is. I have therefore tried to show the basic simplicity of a principle that was actually invented long before the scientific knowledge necessary to explain it became available. On the other hand, it is the imperfections of real, as opposed to ideal, Stirling engines that have had the most influence on the research, development, and engineering work on the subject; I have therefore attempted to relate the major imperfections and losses of real engines to the simple principle of the ideal machine. Finally, the book attempts to show how different engineers have found a variety of ways to put the Stirling principle, complete with imperfections, to use in real engines.

I should like to thank my colleagues in the Stirling field—a friendly, generous, and helpful group of people who have done so much, in so many ways, to help and encourage me. It is difficult to single out a few names, but I have a special feeling of gratitude to William Beale, Bill Martini, Worth Percival, Andy Ross, Jim Senft, Issy Urieli and of course, Joe Walker, the friend and helper of so many Stirling engine enthusiasts.

Jim Crowley kindly allowed me to include his proposals for a standard terminology of Stirling engine power and efficiency parameters; his proposal appears in its entirety in Appendix 2.

Many of the drawings were done, with speed and efficiency, by Karla Bishop of the University of Calgary.

My wife Suzanne typed the entire manuscript, often during weekends and holiday periods. My son Peter took care of many chores that would otherwise have fallen to me, spending hours splitting logs while I wrote in front of the fire. It was not out of ignorance that they agreed to help me work on this book, for they knew exactly what would be involved, and I am truly grateful for their support and encouragement.

C. D. WEST
Oliver Springs, Tennessee

CHAPTER 1

STIRLING ENGINES AND THEIR APPLICATIONS

The basic principle of the Stirling engine is a simple one and easily explained, being no more than the tendency of a gas to expand or rise in pressure when heated, but the attractive simplicity of the principle in no way reduces the complexity and difficulty of the task faced by the engineer who must put the theory into effective practice. This book is an introduction to the principles of the Stirling engine and the application of those principles. This first chapter therefore gives a brief explanation of the operation of the Stirling engine, relates the main features of the operating principles to the advantages and disadvantages of the Stirling compared with other heat engines, and describes how the advantages and disadvantages have helped to define the major current applications for Stirling engines.

BASIC PRINCIPLES

In a Stirling engine, a fixed amount of gas is contained in a working volume consisting of at least one space that is maintained at a high temperature and another at a lower temperature (Figure 1.1). By means of piston movements, some of the gas is transferred back and forth between hot and cold spaces: when more of the gas is in the hot space, the pressure rises and when the gas is transferred back to the cold space, the pressure falls again. The piston that is responsible for transferring gas is called the displacer. The high pressure moves a second piston, called the power piston, increasing the gas volume (Figure 1.2). Only after the gas has been moved back into the cold region, and the pressure has fallen again, is the gas compressed back to its original volume by reversing the movement of the power piston. Because the pressure is lower, the force on the power piston is less on its inward, compressive stroke than it was during the outward, expansive movement and so a net amount of work is gained from it.

Figure 1.3 illustrates the entire cycle, and the indicator diagram, of the ideal Stirling engine. The displacer is situated at the hot end of its cylinder, thus transferring all of the gas to the cold end of the engine before beginning

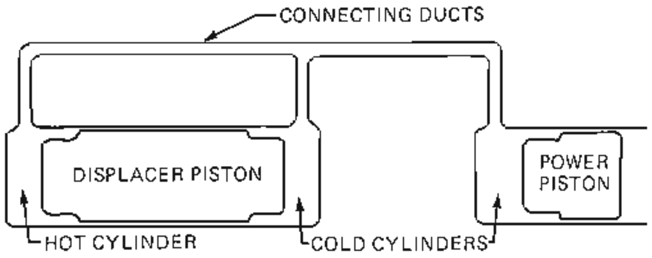

Fig. 1.1. The basic Stirling Engine.

the compression stroke [Figure 1.3(a)]. Then the compression stroke takes place with all of the working gas in the cold region of the engine [Figure 1.3(b)]. After the compression stroke, the displacer is moved to the other end of its cylinder, which transfers the gas to the hot region, thereby raising the pressure in preparation for the expansion stroke [Figure 1.3(c)]. At any given position of the power piston, the pressure is higher on the outward stroke, with some of the gas hot, than it was on the inward stroke, when all of the gas was cold [Figure 1.3(d)]. Therefore, more work is done on

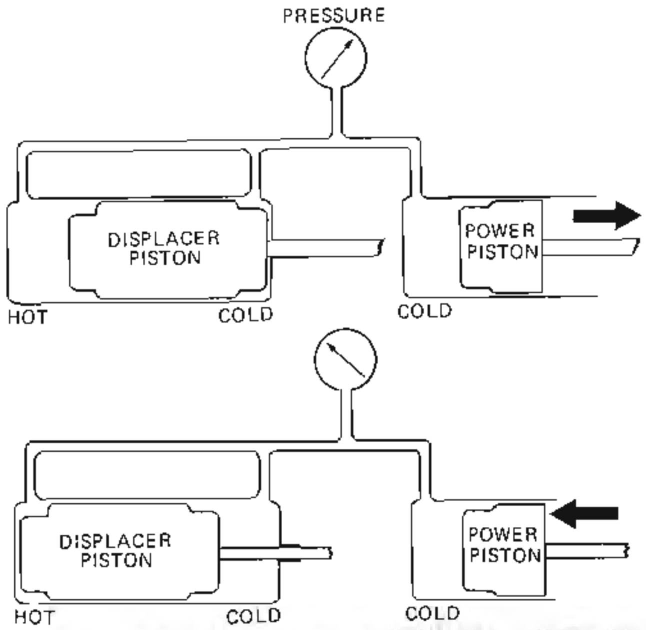

Fig. 1.2. The power piston works on pressure changes caused by the Displacer Action.

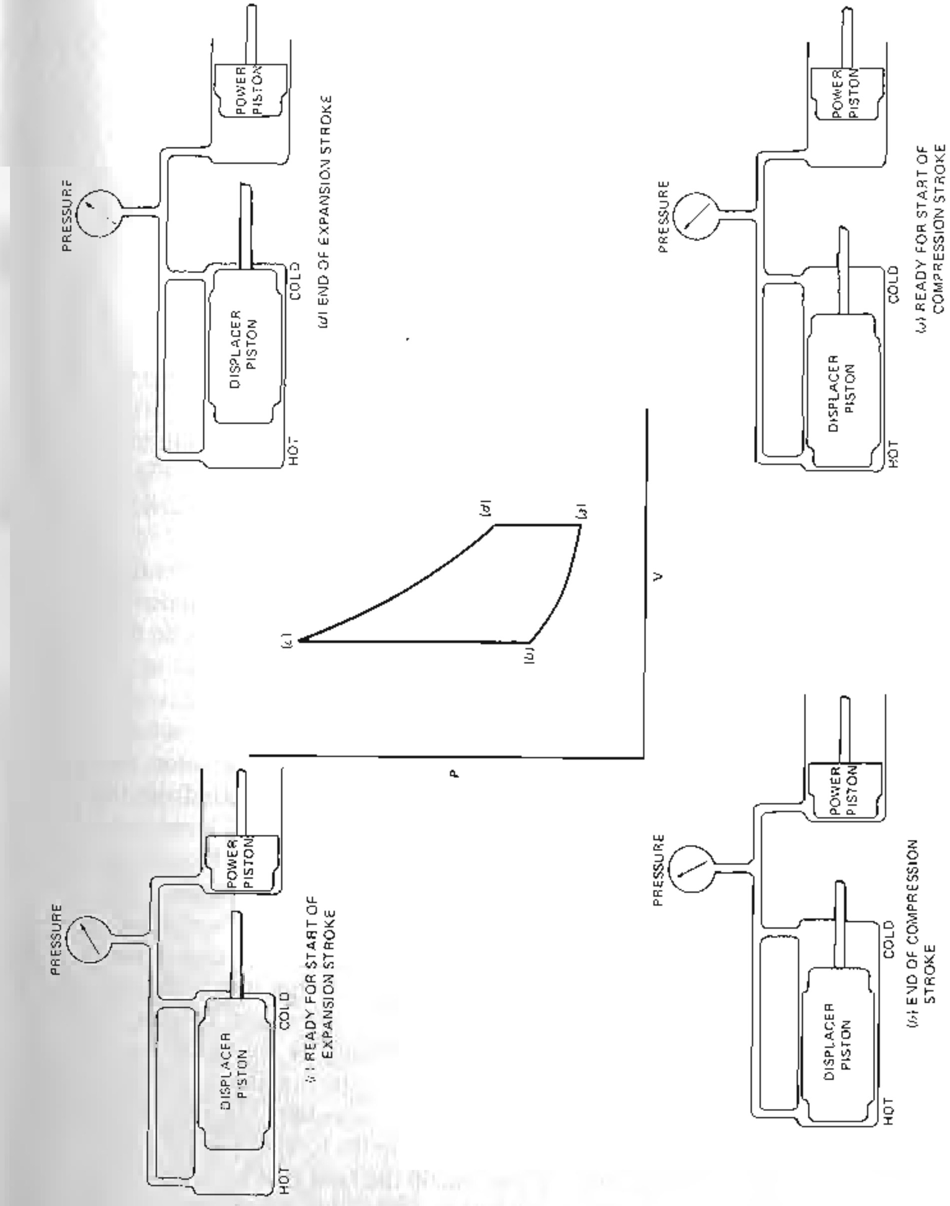

Fig. 1.3. The Stirling engine and its indicator diagram.

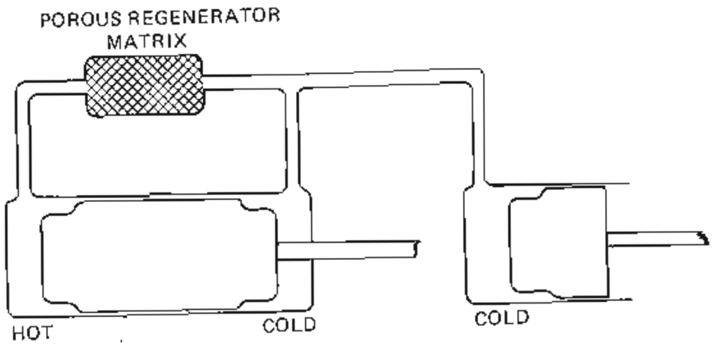

Fig. 1.4. The Stirling engine with regenerator.

the piston during the gas expansion than has to be done to recompress the gas, and the difference is the net work available from the engine. At the end of the expansion stroke, the engine is returned to its initial condition, ready for another cycle, by moving the displacer back to the hot end. Figure 1.3 also shows the indicator or *PV* diagram corresponding to the series of events just described.

Most practical Stirling engines differ from this simplified representation in three important respects. First, a regenerator is placed between the hot and cold ends of the system (Figure 1.4). The regenerator is a heat exchanger and heat store, often made by stacking together a number of fine wire screens to form a kind of metallic sponge, through which the gas must flow during the displacer action. The action of the regenerator is most easily understood by first imagining the gas behavior without a regenerator. Hot gas would be transferred, by the action of the displacer, directly from the expansion space into the compression space, where it would have to be cooled. The heat extracted during the cooling process would be rejected and lost. When the gas was subsequently returned to the expansion space, it would have to be reheated, drawing more heat from the heat source. Extra heat would, therefore, be both added and rejected with a consequent loss of efficiency. The regenerator, however, has a temperature gradient along it; as the gas passes from the hot end (expansion space) toward the cold end (compression space), the gas cools gradually by giving up heat to the metal of the regenerator. Therefore, gas leaves the regenerator already cooled, minimizing the amount of heat to be rejected. On the return journey, the gas is gradually heated as it moves up the temperature gradient toward the expansion-space end by picking up the heat that was deposited during the pass in the opposite direction.Thus, gas emerges into the expansion space already hot, minimizing the heat to be supplied by the external source. The regenerator is characteristic of the Stirling engine, and with its help an ideal engine would have Carnot efficiency. Strictly speaking, a machine without the regenerator should not be called a Stirling engine because the regenerator was part of the Stirling brothers' original patent, although in practice some simple engines have been built without regenerators and are still referred to as Stirling machines.

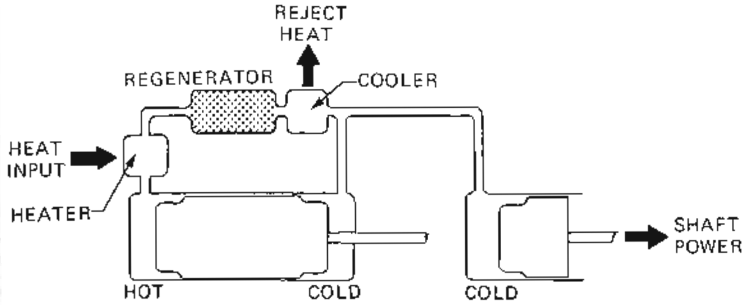

Fig. 1.5. The heater, cooler, and regenerator.

The second difference between practical Stirling engines and the simplified one shown in Figure 1.1 is that most modern engines operate at high speed—typically 3000 rpm—and the gas in the cylinders does not have time to come to thermal equilibrium with the cylinder walls, cylinder head, and piston crown. In fact, so little time is available for heat transfer and the conductivity of even hydrogen and helium is so low, that the gas behavior in the cylinders is often very nearly adiabatic. It is, therefore, usual to fit an external heater and cooler, designed with a high surface area and narrow passages that minimize the heat conduction path through the gas, to add the heat absorbed during the expansion phase and to reject the heat generated during the compression (Figure 1.5). The net difference between the heat added and the heat rejected is, of course, the mechanical work available from the power piston.

Third, in almost all real engines the piston movements are not sequential and discontinuous as in this example. In most cases, the pistons move simultaneously and almost sinusoidally. With sinusoidally moving pistons the pressure variations and the mass of gas in each of the spaces will also vary almost sinusoidally. Figure 1.6 shows the *PV* or indicator diagram for a hypothetical engine like the one in Figure 1.2 but with the pistons moving sinusoidally with a 90° phase angle between them. Because of the 90° phase, the displacer is at top dead center, leaving most of the gas at the cold end of the engine, when the power piston is in the middle of its compression stroke. Similarly, the displacer is at bottom dead center, having transferred some of the gas into the hot space, when the power piston is in the middle

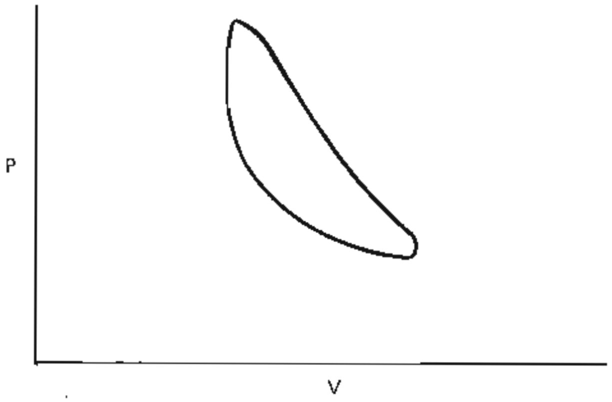

Fig. 1.6. The indicator diagram of a Stirling engine with sinusoidal piston movements.

of the expansion stroke. This phasing (expansion while the gas is hot, recompression when it is cold) is the correct one for an engine (Figure 1.3).

In Chapter 2, the principles of the Stirling engine are discussed more fully, but the brief description already given contains the essence of the machine: an external heat source, a cooler, a fixed charge of gas that is transferred between hot and cold regions by varying the volumes, a power piston to take advantage of the resulting pressure changes and a regenerator to reuse heat that would otherwise be lost. These essential features of the Stirling machine distinguish it from other, more familiar heat engines—for example, from the internal combustion engine, which uses a diffferent charge of gas in each cycle with heat supplied inside the cylinder by burning fuel, or the steam engine in which the working medium begins the cycle as a liquid, only changing to the gaseous form as the heat is added.

CHARACTERISTICS OF THE STIRLING ENGINE

The features that promote the particular characteristics of the Stirling engine make it uniquely appropriate for certain applications. First, external heating means that a wide variety of heat sources can be used, and Stirling engines have been operated from solid, liquid, and gaseous fossil fuel combustion, solar heat, vegetable oil combustion, nuclear heating, heat stored in molten salts, and combustion of biomass waste products. Furthermore, heat is supplied continuously during operation so that if a burner is the source of heat, the combustion process can be well controlled and efficient. As a result, in comparison with an internal combustion engine, the emissions from a well designed Stirling system are lower and the adaptability to different fuels is much greater. The separation of the combustion processes from the internal working parts of the engine also avoids contamination and deterioration of the lubricants.

Second, because the working fluid is retained in the engine, rather than being ejected and replaced each cycle, it can be chosen on the basis of its properties and effectiveness. By a suitable choice of working fluid, efficiency-robbing processes such as flow losses can be minimized, while desirable factors such as heat transfer capability can be maximized. Hydrogen or helium is the usual choice, both gases combining low density and viscosity with good heat transfer properties, although air was used in the earlier engines and is still recommended for applications, such as farm equipment for developing countries, where low cost and ease of maintenance are the major design goals.

Third, the smooth pressure variations that result from moving the working fluid continuously back and forth between the hot and cold regions combined with the continuous, as opposed to explosive, combustion result in a quiet engine, with a very even torque that is almost independent of engine speed.

Fourth, most of the heat rejected from the cycle is carried away by the coolant, and is thus readily available for supplementary use, for example in a cogeneration system; by contrast, most of the heat rejected from an internal combustion engine is in the hot and corrosive exhaust gas and can be recovered only with difficulty.

Finally, the nature of the basic Stirling cycle, with the regenerative process already described, is one that is thermodynamically efficient because heat is added only to gas that is already at the high temperature of the system and removed only from gas that is already at the low temperature. A cycle of this kind—where all the processes are called isothermal—has the highest theoretical efficiency permitted by the laws of physics, the Carnot efficiency. The practical efficiency of a Stirling engine is not so high as that, of course, but the freedom to choose the most appropriate working fluid and the opportunity to incorporate a sophisticated combustor with exhaust heat recuperation means that the Stirling engine can approach its theoretical efficiency more closely than many other engines, at least in the medium- and low-power applications for which the large and complex systems of a central steam power plant are not practical.

Each of the unique characteristics of the Stirling cycle also raises difficulties that are not shared by other common heat engines. First, the continuous high temperature of the heat source promotes materials problems that are absent from an internal combustion engine, where the intermittent combustion process gives little time for heat transfer between the hot gas and its surroundings, which therefore remain relatively cool.

Second, as the working gas is transferred between the high and low temperatures, the pressure will fall and rise about its average value. In order to have a very large pressure change that can produce a large difference between the forces exerted on the power piston in its outward stroke and on its inward stroke, and therefore a large net work output, the average gas pressure must usually be high—more than 20 MPa (3,000 psi) is used in some engines, although low-power machines, and ones in which the highest efficiency is not sought, can operate at atmospheric pressure. To retain the working fluid charge under high pressure from one cycle to the next demands an effective sealing system around the working space. The seal must provide passage for the output shaft, except in a few special circumstances, and must at the same time keep lubricant and other contaminants from entering the working space. It is very important to hold to very low levels the amount of lubricant entering the working space. Hydrocarbon oils are particularly to be avoided: if the oil carbonizes, the fine passages of the regenerator can be blocked; in an air-filled engine, the oil can form an explosive mixture; in a helium or hydrogen-filled engine, contamination by methane formed from the oil at high temperatures can reduce engine performance. Providing a satisfactory long-lived sliding seal for the power piston shaft is one of the most important and intractable engineering problems in Stirling engine development, although progress is being made.

Third, heat must be transferred effectively between the gas that is inside the engine and the heat source or coolant outside the working space. This requires heat exchangers, with the usual difficult compromise between heat transfer effectiveness, pressure drop, and volume. The heater must operate for long periods at high temperature while containing the high-pressure working fluid without physical or chemical ill effects, and it is also subject to thermal cycling when the engine is started up and shut down and to cyclic mechanical forces as the working space pressure rises and falls. The higher the upper temperature of a heat engine, the higher its efficiency can generally be, and the upper temperature of a Stirling engine is usually limited by the creep strength of its heater assembly.

The regenerator is also a heat exchange component, and in fact it typically stores and returns several times as much heat per cycle as is added by the heater. This is because, ideally, the heater replaces only the energy that has been removed from the system as work and as reject heat, whereas the regenerator first extracts and then replaces all the heat needed to lower and raise the temperature of the gas within it. The compromise between heat exchange and pressure drop is therefore even more important, and more difficult, in the regenerator than in the heater or cooler.

The cooler has a heavier load than the cooling system of an internal combustion engine, because in the latter only enough heat is removed by the cooling system to keep the engine components and lubricant at a tolerably low operating temperature; the remainder of the heat rejected from an internal combustion engine is carried away by the exhaust gas, although some of the exhaust gas energy may be recovered by adding one, or sometimes two, more heat engines to the system (turbocharging and turbocompounding).

APPLICATIONS

There is an almost bewildering array of mechanical configurations for the Stirling engine, but in the following discussion only one major distinction need be drawn—that between kinematic and free piston engines. In kinematic machines, the pistons are driven through connecting rods by a crankshaft, a swash plate, or some other more or less conventional mechanism. The seal problem referred to earlier is present in full force for kinematic engines. In a free piston engine, the pistons are not rigidly connected to any drive mechanism but are instead moved by the pneumatic forces exerted on them by the varying pressure in the working gas. In some cases a free piston engine can be hermetically sealed, with no power piston connecting rod penetrating the boundary of the working space, thus reducing the seal problem considerably. However, without the discipline imposed by a mechanical drive it is more difficult to control the piston movements for optimum performance. As might be expected, hybrids of the two systems have also been invented; they are discussed in Chapter 4. Stirling engines have been proposed for almost every possible use of a prime mover, but at the present time perhaps the eight applications listed in Table 1.1 are receiving the most attention.

A thorough historical review of these and other applications was published in 1980 (Walker, 1980); the following descriptions therefore concentrate on attempting to relate the important factors in each field of application to the basic characteristics of the Stirling engine, and on more recent work.

Artificial Heart Power

A research effort funded over the last 18 years by the National Institutes of Health has been devoted to the development of an implantable, Stirling

Table 1.1. Stirling Engine Characteristics and Applications.

APPLICATION AREA	EXTERNAL HEAT SOURCE	QUIETNESS AND SMOOTHNESS	HIGH EFFICIENCY	REJECT HEAT AVAILABILITY	VERY LONG LIFE/HIGH RELIABILITY
Artificial heart power	essential	essential	important	essential	essential
Underwater power unit	essential	important	important	important	important
Space power	essential	important	essential		essential
Remote small power sources	essential		essential		essential
Military ground power	important	essential			important
Heat pump driver	important	important	important	important	
Automotive engine	important	important	essential		important
Solar thermal conversion	essential		important		

powered artificial heart. This work began at McDonnel-Douglas, but the project and its staff were later transferred to the University of Washington. It would be difficult to overstate the accomplishment of the researchers who have achieved an overall module efficiency (hydraulic power output divided by thermal input) of more than 25% at an output level of 5 watts and have demonstrated a continuous, maintenance-free run of more than 4 years. (See Chapter 5). The long-term stability and continuity of the program and, especially, the constancy of the objectives sought by the sponsor are certainly major factors contributing to the excellence of the research achievements.

The ability of the Stirling engine to use an external heat source (from a rechargeable thermal store, or perhaps radio-isotopic decay) is obviously crucial in this application. Most of the waste heat from an implantable heart system must be transferred into the blood pump so that it will be distributed throughout the body, thus avoiding local hot spots, and the ready availability of the reject heat in a Stirling engine facilitates this. To allow the recipient as normal a life as possible, the research program has aimed at an engine that would be inaudible when implanted and the ability of the Stirling engine to operate quietly is important in that respect. High efficiency is also important, to maximize the operating period from a given quantity of heat in the heat store, and to minimize the amount of reject heat that must be dissipated in the body. Compared with electrical systems, the thermal store has a very much higher power density and a very much longer life. There is an excellent recent review of this application area (White, 1983) which expresses the view that some of the new technology developed in the heart program can be applied to much larger engines. Figure 1.7 shows the complete implantable Stirling engine unit.

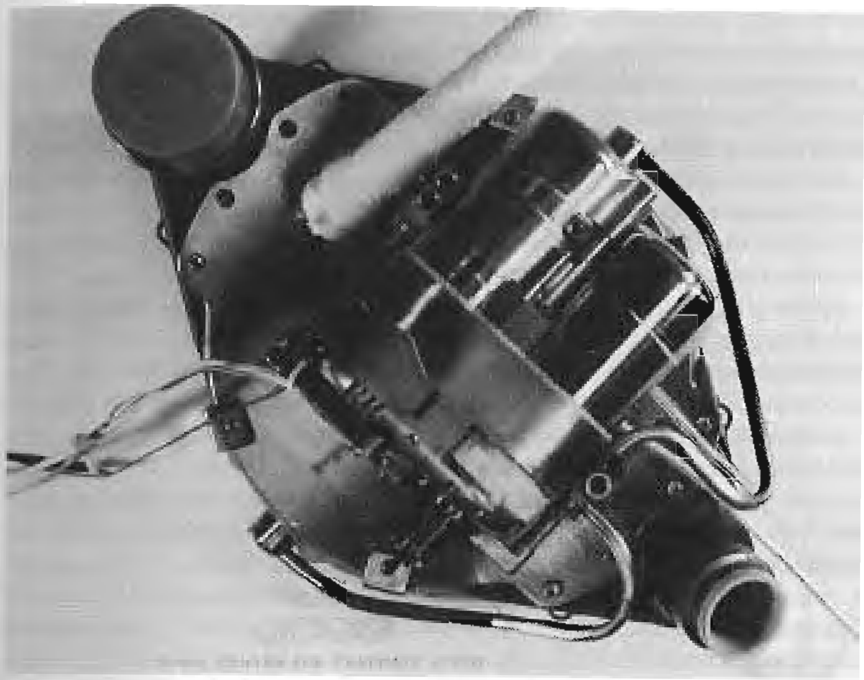

Fig. 1.7. Implantable Stirling engine for artificial heart power. (*Courtesy Joint Center for Graduate Study, University of Washington*).

Other heat engines have been explored in the United States since the beginning of the artificial heart effort in the late 1960s but the only one still active, besides the Stirling program described here, is a thermocompressor that is also sponsored by the National Institutes of Health. The work began at Aerojet in 1967 and was transferred, along with the research staff, to Nimbus Inc. in 1982 (Schneider et al, 1984). There are many similarities between thermocompressor and Stirling engines, the major difference being that the thermocompressor uses valves as well as volume changes to control the movement and position of the working gas.

Underwater Power Units

The German company Entwicklungsgruppe MAN-MWM was formed in the late 1960s to develop Stirling engines, initially on the basis of technology licenced from Philips. Little has been published of the German research and that little has discussed only work aimed at vehicle engines. Nevertheless, it is widely believed that a major interest of the company has always been the development, on behalf of the West German Ministry of Defense, of Stirling engines for marine use, including underwater power systems of up to 1000 Hp. The published papers seem to indicate a broad engineering program of high quality and great depth, but they give few details. Company researchers rarely participate in, or even attend, the various conferences that cover Stirling machines.

More is known about United Stirling in Sweden and ECA in France, both working on Stirling power packages for underwater operation. United Stirling is a part of FFV, a group owned by the Swedish government. The business of FFV lies in the development and manufacture of defense equipment, although United Stirling's expertise is such that they are also participants in U.S. Government programs for Stirling automotive engine and solar engine development. Over the past decade or more, the company has been developing the Stirling engine for underwater applications, in collaboration with another Swedish Government controlled company, Kockums (who build submarines for the navy) and with development funding from the Swedish Navy. Both military and civilian applications are considered to be important, and a new joint venture—SubPower AB—has been formed by Kockums and United Stirling for the commercialization of their developments in this area.

Like the other major companies in the Stirling engine field, United Stirling initially worked with a license to the Philips technology which at that time (the late 1960s) concentrated on the rhombic drive single acting engine configuration that is described in Chapter 3. Later, United Stirling began to build engines of their own design. The present emphasis is on double acting engines and one of these—the 4-95 or P40 engine, which has four 95-cc cylinders—has been modified for the underwater system. A larger engine, the 4-275 or P75, is also to be used in a further development which is apparently aimed primarily at the naval applications. A paper by Nilsson (1983) gives some details of these projects. The heat source is provided by the combustion of diesel fuel or methanol in pure oxygen at a pressure of 3 MPa, which matches ambient pressure at the maximum operational depth foreseen so that exhaust gases are easily disposed of. Combustion products are recirculated in order to keep the flame temperature, which could be as high as 4000°C in pure oxygen combustion, within reasonable limits. With this combustion system, the overall efficiency of the power unit is only slightly reduced compared with the same engine in its air-breathing form, as is the maximum power (about 35 kW for the underwater 4-95 and 100 kW for the 4-275). Hot water from the cooling system is available for heating living compartments and divers' suits. Within a given storage volume, a Stirling engine and chemical fuels can provide a very much longer operating time than is available from current battery or fuel cell technology.

The French company Société ECA is a world leader in the manufacture of underwater equipment, including electrically powered, unmanned submersibles. In the mid-1970s, the company was seeking ways to improve its submarines; greater endurance and speed were required. For military applications in particular, there should be no gaseous exhaust and silence is important. Company studies, partly funded by the defense establishment, narrowed the choice to electric systems, with fuel cells or sodium-sulfur batteries, or a Stirling engine with either molten salt heat storage or lithium/sulfur hexafluoride combustion. Because of time constraints, a Stirling/heat store combination was chosen since the state of development of Stirling engines was judged to be fairly advanced and ECA already manufactured molten salt heat stores for heating divers' suits.

A lithium fluoride/magnesium fluoride eutectic was chosen as the heat storage medium, and sodium heat pipes are used to transfer heat from the store to the engine heater heads. This part of the development was undertaken by the Grenoble laboratory of the French Atomic Energy Agency, who are experienced in this field and who had, in fact, developed the molten salt heat store for divers in an earlier program with ECA. The use of heat pipes allowed greater freedom in design of the engine layout than is possible with an integral combustor system and an in-line, four cylinder, double acting arrangement was chosen (see Chapter 3 for more details of this configuration) which allowed the use of many parts from a standard Renault automobile engine. Descriptions of the engine and heating system were published in 1983 (Carlqvist et al., 1983; Alleau et al., 1983).

At one time, Philips were working on Stirling power units for underwater use; the heat source would be metal combustion (lithium/freon or lithium/sulfur hexafluoride), an approach investigated earlier by General Motors and found to show great promise. However, the General Motors work terminated in 1970, and nothing has been published about the Philips program, now believed terminated, since 1975; however, a new company, Stirling Thermal Motors, founded by the former leader of the Philips research team, is continuing to work in this area (Meijer et al, 1985).

The ability to choose the external heat source on criteria largely independent of the engine itself is obviously crucial to the selection of the Stirling engine as an underwater power unit. For military applications, quietness is a very important factor. Ready availability of the reject heat is a significant advantage in some cases. Although the very highest efficiency is not needed, the fact that efficiency is good enough to make effective use of the stored heat or fuel energy is significant, and results in a usable energy density much higher than can be achieved with current batteries. Accordingly, the Stirling systems can fit into the underwater scene at intermediate power levels, leaving short term, low energy applications to batteries and the high energy, long duration missions to nuclear reactors.

Space Power

During the 1960s, much effort was devoted by NASA to the development of nuclear space power systems. Both Rankine and Brayton turbines were pursued as multikilowatt power sources, but the NASA program involved no work at all on Stirling engines. The reason, or reasons, for NASA's decision not to include Stirling machines have not been made public, although Walker (1980) speculates that the only U.S. company with extensive Stirling experience at that time (General Motors) was unable to participate fully in an open U.S. Government program because of confidentiality restrictions imposed by Philips' licensing agreement with General Motors. Walker adds that other U.S. companies who might have been interested felt unable to break into the field because of the commanding legal and technical position held by Philips and their exclusive U.S. licensee. In any event, some small programs funded by the U.S. Air Force and ERDA, a predecessor of the U.S. Department of Energy, were the only attempts to develop Stirling engines for space power.

Recently, however, a major initiative to provide high power spaceborne systems has begun. For one system, an initial power level of 100 kW(e) is specified, with the possibility of multimegawatt systems being required later. A liquid metal cooled fast reactor is proposed with either a turbine or free piston Stirling engine power convertor. The reactor itself will be a major project, with many technical difficulties to overcome, but there is little doubt that success could be achieved. However, the schedule set is very short—flight testing by 1989, with the first major contracts not let until 1984! The Stirling system appears to offer, on paper, a good efficiency and light weight while operating at an upper temperature that does not demand exotic or untried materials even with a reject temperature high enough (250–300°C) to keep the heat rejection radiator size within reasonable bounds (Stochl and Green, 1984). However, the decision of 20 years ago not to pursue Stirling machines for this application means that the knowledge base for the Rankine and Brayton systems is now much greater than for Stirlings. The first step for Stirlings is to build within 18 months a demonstration free piston engine producing 25 kW with an efficiency not less than 50% of Carnot with heat source and sink temperatures of 650 K and 325 K (377°C and 52°C), respectively, a difficult task within the time limit specified. By contrast, the turbine systems are considered to be already at about the stage that would only be reached by the Stirling after that first phase. Nevertheless, the potential performance advantages foreseen for the Stirling system in this important application are such that one must wish every success to the researchers involved.

The ability to use an external heat source (nuclear heating in this case) is crucial. The relatively high efficiency even with a high reject temperature is also very important, because it minimizes both the heat input and the reject heat, thus minimizing the weight and size of the overall package, which includes heat radiators and reactor shielding. Low vibration is desirable because of the need to aim accurately the instruments and other equipment on board the spacecraft.

Remote Power Sources

Underwater or, especially, space locations might well be counted as remote. However, this section is concerned with applications requiring a few tens of watts to a few kilowatts of electricity, primarily in unmanned stations that call for a highly reliable, long term source of power. Examples include navigation beacons for aircraft and shipping, lighthouses and telemetry stations.

Early work was sponsored at the University of Calgary and at Sunpower (a company founded by the inventor of the free piston engine, William Beale) by the Canadian Atomic Energy Agency and in England by the United Kingdom Atomic Energy Authority. At that time, isotopic decay heat was considered to be the ideal source for the kind of application mentioned in the previous paragraph, a judgment which still appears to be faultless on economic, technical, environmental and safety grounds. Unfortunately, decisions regarding the use of nuclear materials are no longer made on the basis of those criteria and the emphasis in thinking about the use of Stirling engines for small remote civilian power sources has now shifted to fossil fuels.

The small free piston Stirling engine has a well proven longevity and freedom from maintenance, continuous operation for several years without intervention having been demonstrated by the heart engines described previously and the Thermomechanical Generator (TMG), an engine using a diaphragm power piston and spring-suspended moving parts to avoid all the problems of moving seals and sliding parts (see Chapter 9). The TMG was invented and developed at the Harwell Atomic Energy Research Laboratory specifically as a remote small power source, originally for isotope heating. An early, isotopically heated TMG has been in operation for more than 10 years, running for almost 100,000 hours with no failures or maintenance required to run the engine—although the ^{90}Sr isotopic heat source has, of course, decayed noticeably.

Later models of the TMG, and the commercial version that is now marketed by a private company, HoMach Systems, are propane heated. In flame heated Stirling engines, the combustion products are still hot after leaving the heater, because heat is accepted by the engine only at one, high, temperature. To avoid the loss of efficiency that would result if the hot exhaust gas were simply vented to the atmosphere, a counterflow air preheater or recuperator is fitted which cools the exhaust by using it to preheat the incoming fresh combustion air.

In this lower power range, the alternative to specialized Stirling machines for conversion of heat to electricity appears to be thermoelectric modules. Thermoelectric modules are completely solid state devices and certainly have the potential for long life (although poisoning of the semiconductor material by atmospheric contaminants has been a problem), but thermoelectric efficiency is very low: overall efficiency for converting the chemical energy of the fuel to direct current electricity at a high enough voltage to be useful is seldom more than a few percent, compared with 10–15% for the TMG. This is a very important difference for remote locations: to provide 50 Watts of electricity for one year at a 15% conversion efficiency requires 400 kg of propane cylinders, which can easily be carried in by helicopter or Land Rover. To do the same thing at a 3% efficiency requires 2,000 kg, which is not so easily delivered, and batteries for the same mission would be equally, or more, heavy and bulky. A strontium radioisotope source with a TMG operated at 12% efficiency would weigh, complete with radiation shielding, about 700 kg, and would last for 20 years. Reviews of the Thermomechanical Generator and its performance have been given by McBride and Cooke-Yarborough (1984). An interesting point is that, because of the complete lack of sliding and static friction, the TMG is self starting on the application of heat.

The external heat source of a Stirling engine was an essential factor in the early development of the TMG, because it permitted the use of isotopic decay heat, and later permitted the use of the technology developed for the isotope engine in a propane fired system. The first propane heated TMG, which produced 25W(e), was specifically developed as the main power source for the United Kingdom National Data Buoy; deployed in the Atlantic 120 miles from the nearest land the buoy was powered by the TMG continuously for 21 months. The design was subsequently uprated to 60W(e) and served as the main power source for a major lighthouse off the Irish coast. These are thought to be the only Stirling engines put into operational use, as opposed to field testing, in recent years. The TMG is described in more detail in Chapter 9.

Remote in another sense are the villages and smallholdings of the underdeveloped nations. The need there is for engines that can run on low grade fuel (usually biomass waste or coal) and produce a few hundred watts to a few kilowatts for water pumping or to drive small machines. Low material cost and ease of manufacture are perhaps more important than maximum efficiency. For water pumping, no rotary output is necessary and various kinds of free piston engine have been tested for this purpose (West and Pandey, 1981; Beale et al., 1980). A rotary output is more convenient for driving machinery, and a 5 kW air engine of a simple design that does not require either exotic materials or precision manufacturing techniques has been developed by Sunpower, under the sponsorship of the U.S. Agency for International Development, (Wood et al., 1982) and has been tested in Bangladesh—a description of this engine is given in Chapter 9.

On becoming aware of the mechanical simplicity of free piston engines, especially the liquid piston systems discussed in Chapter 9, many people suggest that solar heated versions would provide an ideal power source for the Third World, but it is not clear why, when solar power is too expensive for the affluent West, it should be considered ideally suited to people so poor that a bag of fertilizer is a major investment.

Military Ground Power

The U.S. Army Mobility Equipment Research and Development Command has long sought to develop and improve a reliable and quiet electrical generator of a few kilowatts output and capable of using any one of the liquid fuels (diesel, JP4, gasoline) already supplied for military vehicles and other equipment. High reliability is required and only infrequent maintenance, although the requirements (750 hours mean time between failures and 3,000 hours operation without overhaul) are not nearly as stringent as those for the smaller remote power sources described earlier. However, the tolerance of the Army generator to load transients and load changes must be very high. A further requirement not shared by most remote power needs is silence—to avoid masking possible sounds of enemy activity, the generator must be inaudible at a distance of 100 meters even in quiet surroundings. Silence and low emissions will also reduce the obtrusiveness, and therefore detectability, of the generator set.

As we have seen, the Stirling engine has all of the characteristics needed for the application, as the Army soon recognized. Working under Army sponsorship in the 1960s, but building also on the knowledge gained from their own company funded Stirling engine research, General Motors produced the GPU-3 (Ground Power Unit). Some outstanding research was done, and has been described in an important and highly recommended report by Percival (1976).

The GPU-3 generator met the military specifications but did not go into service because although its major advantage over the less expensive gasoline or diesel engines (silence) was recognized by the Army, silence was not at that time actually written into the specifications on which procurement decisions must legally be based. The high—and still unfulfilled—expectations held of fuel cells were apparently a contributing factor in the Army decision not to proceed further with the GPU development at that time. The Army's recently renewed sponsorship is now devoted to four developments. Mechanical Technology Inc. (M.T.I.) and Sunpower are both working on a 3 kW free piston Stirling engine generator set, and Stirling Power Systems, an American Subsidiary of the Swedish company FFV, are to demonstrate and evaluate their V160 10 kW kinematic Stirling engine for this application. Simultaneously, the University of Washington group is working to scale up the artificial heart technology to a power level that would meet the military requirements.

The military specifications for ruggedness and reliability are very stringent, and a generator satisfying them would almost certainly find industrial and commercial buyers as well, although in the military form it would probably be overengineered and too expensive for the consumer market.

Heat Pumping

This is a major area of work at present with a small program in the United States, a substantial effort in Japan, and work reported from Denmark, Holland, Sweden and Finland. There are basically two ways in which a Stirling engine can be involved as part of a heat pump system. In the first, and most straightforward, a Stirling engine is used to drive a Rankine heat pump. The Stirling engine is fossil fueled (natural gas is the usual choice) and the advantage of the system is that the reject heat from the power unit is available to add to the output of the heat pump; in an electrically driven heat pump, on the other hand, the reject heat at the utility power plant is simply wasted. The overall result is that much more efficient use is made of the gas by the heat engine/heat pump unit. The ready availability of the engine reject heat is crucial to this application, but good efficiency is also necessary if any gain is to be made over an electrically driven heat pump or an advanced gas furnace. It is very important, especially for domestic applications, to have low noise and to burn the fuel with low emissions, since the complex pollution control equipment of a central power plant would be prohibitively expensive for small scale systems.

In the United States, programs within this area have been sponsored by the Department of Energy, the Gas Research Institute (GRI) and private industry (CNG and Mechanical Technology, Inc (MTI)). The only substantial program active at present is at MTI (Moynihan and Ackermann, 1984), with funding from the Department of Energy, GRI, and MTI company funds. The program is based on a free piston engine which has no solid power piston; instead, the working gas pressure variations are transmitted to the refrigerant by a hydraulic fluid that is sealed from the engine working space by means of a metal diaphragm. Actually, it is not a true free piston engine but is one of the hybrid types mentioned earlier in which the displacer is controlled by an electric motor; such a system is now called a "Martini Displacer." Under the same DOE/GRI program, General Electric developed a free piston engine driving an "inertial compressor," which is a heavy piston inside a casing that is moved back and forth by the engine (Chiu et al., 1983). The massive piston does not move as far as the casing, which therefore oscillates relative to it, thus providing a pumping action. This effort has now been terminated.

The Japanese work is, on the whole, concentrating more on kinematic engines for this application, perhaps because kinematic machines are more highly developed in this size range and, as a result, have at present higher overall efficiency figures than free piston engines. However, as indicated earlier, the seal and wear problems may be much more severe in kinematic engines. Most of the Japanese program is sponsored by the government and based on kinematic engines (Nakatani et al., 1984), but the Kawasaki company are using their own funds to pursue free piston engines based on technology transferred from Sunpower. The entire Japanese program is relatively new but it is well founded in the U.S. and European technology and it will be extremely interesting to watch the literature and the marketplace over the next few years.

Just as a Rankine cycle can be used as a heat engine or, if driven mechanically, can work as a heat pump or refrigerator, so can a Stirling cycle. A Stirling engine driven from an external mechanical power source (such as an electric motor) will pump heat from the expansion space—that is, the part of the volume that would be hot in the engine—to the compression space. It may therefore be used as a heat pump or refrigerator. In fact, the major commercial application for Stirling machines at present is for low temperature refrigerators and air liquifiers; most guided missiles with infrared detection systems carry some form of Stirling cryocooler (Walker, 1983).

A major advantage of the Stirling heat pump, by comparison with a conventional Rankine system, is that the performance is much less dependent on the temperature difference between the heat source and the heat rejection. In a domestic heat pump application, for example, heat can be effectively extracted from the outdoor air down to much lower temperatures, thus reducing the need for inefficient electrical resistance backup heating.

From the perspective of a book on Stirling engines, however, the most interesting possibility is to drive a Stirling heat pump with a fossil fuel (gas) fired Stirling engine. There are many technical advantages to this arrangement, which has come to be called a duplex Stirling, perhaps the most important being that a free piston system can be designed with the same working gas in both the engine and the heat pump/air conditioning sections. This eases the sealing problem immensely. However, because the power output of the engine section and the power needed by the heat pump do not vary in the same way when the ambient temperature or the heat load are changed, load matching of the engine and heat pump sections to achieve stable operation may be a difficult problem—as indeed it is for the Stirling/Rankine system. Despite the advantages of the duplex design, and the success of some demonstration machines built by Sunpower (Penswick and Urieli, 1984) there appear to be no significant programs on the duplex Stirling at present, although it is not clear why.

If, as seems to be the case, Stirling engines and heat pumps are unfamiliar and technically obscure devices to most engineers, the Vuilleumier (VM) cycle is even more so. For our present purposes, however, it may be regarded as a kind of Stirling machine that has already proven to be an excellent cryogenic refrigerator and is being extensively investigated in Europe, but not the United States, as a heat pumping system. A description of the Vuilleumier or VM machine is given in Appendix 1. Philips recently revealed that they are working on a 10 kW heat pump of good performance. However, this program has not yet been reported in the open literature. The Technical University of Denmark have been working on a VM machine with an output of up to 10 kW of heat; their machine has a pressurized crankcase, which eases the sealing problem but involves a large, and heavy, pressure vessel. Little has been published, for there is hope of commercial exploitation of the machine.

Many domestic central heating systems in Europe use hot water rather than warm air to distribute the heat, which greatly simplifies the problem of designing effective heat exchangers for the output of a Stirling heat pump. This difference may be important: a report by the Technical Research Center of Finland (Nykyri and Hiismaki, 1981) indicated that the temperature drop across the cold and warm heat exchangers of the particular VM heat pump they studied was likely to be an important factor in degrading performance.

Automotive Engines

The largest single Stirling engine development program is probably the U.S. Department of Energy's Automotive Program, although the application is in many ways the least promising of all the ones discussed here. The reason for this is not that the Stirling engine would make a poor automobile engine—it would actually make an excellent one—but that the internal combustion engine is already so good and is still being improved.

The program has its origins in U.S. Public Law 95-238, the Automotive Propulsion Research and Development Act of 1978. For reasons that need not concern us here, the program is managed by NASA acting on behalf of the Department of Energy. The major remaining participants are a team involving Mechanical Technology Incorporated, United Stirling, and the automobile company AM General Corporation. At one time there was also a project under way at the Ford Motor Company, but in 1978 Ford decided to channel their resources into other areas. The main objective of the MTI project, which began in 1978, is to demonstrate a 30% improvement on the EPA gas mileage (27 mpg) that was projected at the time for a comparable production vehicle. The Stirling must also meet stringent emission requirements (as do conventional engines) and have the ability to use a variety of alternative fuels. These goals will probably be met, but the difficulty of making a significant impact on automobile use is easily seen by considering a few figures for average annual mileage at 1983 prices: the average owner of a 27 mpg car would spend less than $450 on fuel and a 30% improvement in fuel economy would save him only $100 per year. In other words, the fuel savings are not a strong economic justification for the individual consumer. Of course, not all car purchases are made on the basis of rational economics (witness the market for a diesel engined VW Rabbit that cost $1600 extra and used perhaps 75 gallons of fuel less per year than the standard version) but some bigger advantage than a $100 per year saving may be needed to lead to a large scale switch to Stirling engines and thereby make a sizable difference to U.S. oil imports. It is worth remarking that the large private organizations who have sponsored Stirling Engine research, such as General Motors and FFV, have not chosen automotive engines as an early area for development. Nevertheless, the DOE program has sponsored some very high quality research and has led to solutions for many of the problems of kinematic Stirling engines and to substantial progress even on those problems not yet completely solved—including the development of much improved seals, better power control techniques, and proposals for cost reduction. Indeed, the most recent designs are estimated to cost less to manufacture and install than a standard diesel, although more than a gasoline engine (Corey et al., 1984). The potential of medium or high power Stirling engines for almost any purpose will be greatly enhanced by the knowledge gained in the automotive program, regardless of the future of the Stirling as an automobile engine.

The factors behind the choice of the Stirling engine as one of the propulsion systems to be encouraged under the Act (others were the gas turbine and the advanced diesel engine) were its potential for high efficiency with low emissions, two factors essential to meeting the intent of the law. With regard to efficiency, it may be noted that because of the flat torque curve of the Stirling engine, a given vehicle performance (acceleration) can be achieved with an engine of lower maximum power than would be needed in a normal gasoline engine. By contrast, the torque/speed characteristics of the diesel engine are such that it gives poorer performance in a vehicle than a gasoline engine of the same maximum power.

The external combustion system of a Stirling engine is more easily adapted than an internal combustion engine to burning a range of different fuels without loss of efficiency or increase in emissions. The quietness and smoothness of the Stirling engine may also be a significant advantage when compared with the small, rough running gasoline engines that have become accepted since the inception of emission standards and fuel economy measures.

Solar Thermal Conversion

The direct conversion of solar energy into electricity with photovoltaic cells is much less efficient, with presently available and foreseen technology, than the use of a mechanical heat engine driven by focussed sunlight. Considerable effort has therefore been devoted to the development and testing of suitable heat engines for solar power conversion. Stirling, Rankine, and Brayton cycles have been pursued, and at present the Stirling engine, in the form of a relatively small [25 kW(e)] module combining an engine and parabolic tracking dish, has shown the best efficiency (Washom, 1984): Figure 1.8 shows the solar engine (described in Chapter 8) ready for installation on the collector dish.

Obviously any engine for this application must be able to make use of externally supplied heat and must, because of the relatively high cost of concentrating solar collectors, have a good efficiency. The Stirling is therefore an obvious contender. The solar energy is focused directly onto the heater of the engine, which therefore needs no combustion system or air preheater, two costly components of fossil fuel fired engines. Certain parasitic losses associated with the combustion air and fuel supply, the control system, and the emission controls are also avoided, so that a solar engine should have a somewhat higher efficiency than a fuel fired version operating at the same temperature.

There are a number of problems associated with large scale solar electric generation, whatever kind of conversion system is adopted. The low load factor resulting from the intervention of night and clouds is only the most obvious. Because of the low load factor, either energy storage or a backup supply is needed. If a good commercial energy storage system were available, it could be used for load levelling at the utility coal and nuclear

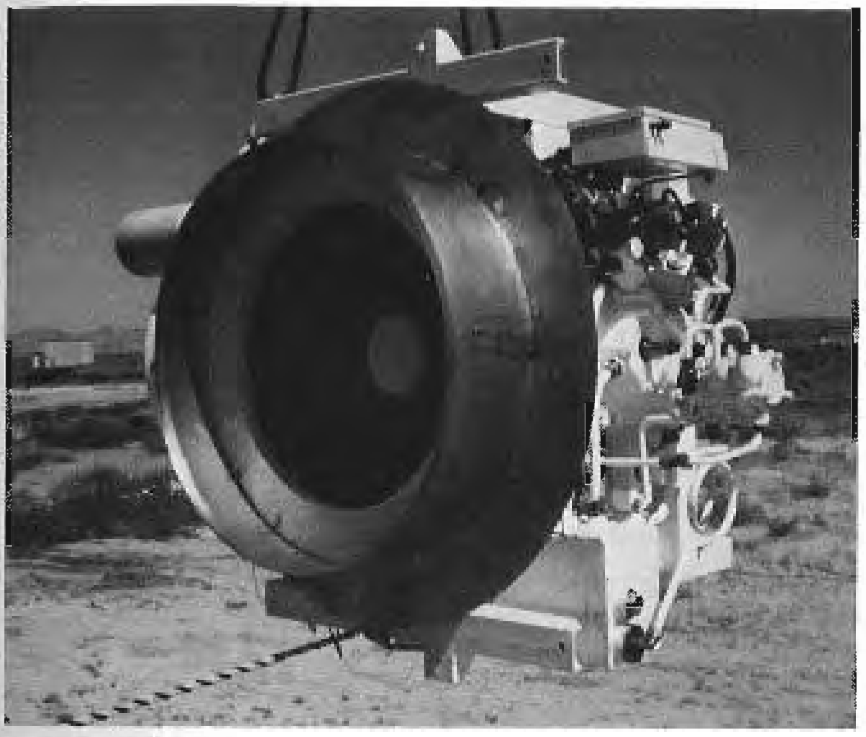

Fig. 1.8. United Stirling solar engine ready for installation on the parabolic collector dish. (*Courtesy United Stirling, Inc.*)

base load power plants, thus reducing the cost of conventional electricity and stiffening the competition for solar. If the utility power plants themselves were used as the backup, then to the capital cost of the solar system should be added the capital cost of a new or existing conventional plant that could function perfectly well without the solar unit. Superficially, the fact that solar is almost a "free fuel" system is attractive, but it must compete with other systems—specifically hydroelectric and nuclear plants—that also have negligible fuel costs. With these and other facts in mind, it is hard to see how solar power could make a substantial inroad into the nation's electricity supply without a major technical breakthrough in at least one field. Nevertheless, even a very small fraction of the 650,000 MW United States electricity supply system represents a huge amount of power, and an enormous potential market for solar electric generation systems.

SUMMARY

The basic operating principles of the Stirling engine give it a number of characteristics that may provide, according to the application and the circumstances, significant advantages. In some cases, the Stirling engine has such obvious and marked advantages over the technical alternatives that it seems bound to make its way, and this is reflected in the breadth and continuity of the research efforts aimed at these applications: the artificial heart engine and underwater power systems are perhaps the best examples of this. Then there are some other areas, such as heat pumping and military ground power, where the potential generic advantages are very clear, but the knowledge base and research background are not yet adequate to prove that the practical difficulties and costs will not outweigh the promise. For some very specialized applications, for example, space reactor power conversion and small, remote, long life power units, only very specific development efforts can lead to a sound judgment as to the applicability of the Stirling engine; in the case of remote power sources, the research has been done and the answer is positive. Another class of application—exemplified by automobile engines and solar thermal power conversion—will not stand only upon the technical success of Stirling engine development, but will in the long term depend on the soundness of the basic goals that the engine would help to meet.

RECOMMENDED FURTHER READING

Stirling Engines by G. Walker, Clarendon Press, Oxford, 1980.

Stirling Cycle Engines by M. A. Ross, Solar Engines, Phoenix, 1981.

Stirling Engines by G. T. Reader and C. Hooper, E. & F. N. Spon, London and New York, 1983.