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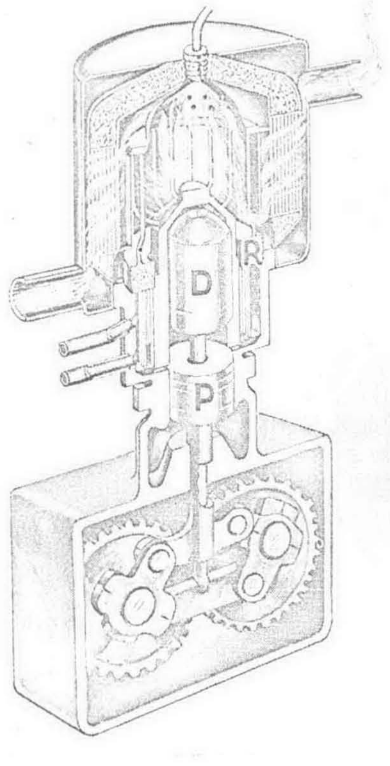
Regenerative Thermal Machines

by Theodor Finkelstein

Invented almost 150 years ago as the Stirling engine, regenerative thermal machines promise efficient power generation and performance of other useful functions for today's technology.



A modern 40-horsepower version of the Stirling engine. Like the original, shown on the next page,, this engine has a displacer (D), a regenerator (R), and a piston (P). In the laboratory, this modern engine was reported to have an over-all efficiency of 39 per cent.

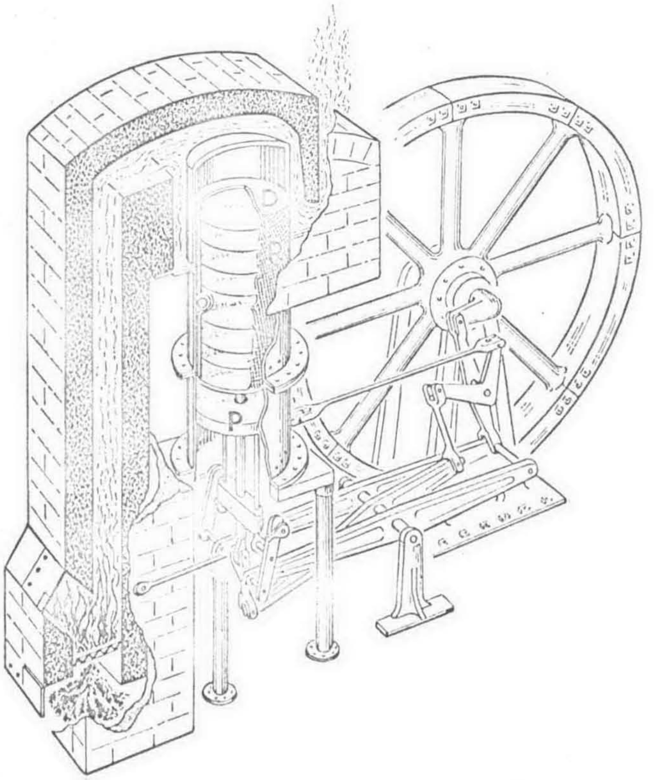
Regenerative utilization of thermal energy is a scientific principle currently under intensive study for applications as diverse as outboard motors and infrared cell coolers, air conditioners and irrigation pumps. Thermal machines based on this principle are extremely versatile. They can convert heat energy to mechanical power or can elevate heat energy to a higher temperature level by a basic process which is much more efficient than that used in conventional devices.

Modern machines are usually quite different from their original prototypes; not only are they more efficient, but almost invariably they have had so much technical development that they no longer resemble the earliest design. With regenerative thermal machines, this is not the case. The original of these machines, built more than 100 years ago, was in many respects superior to later designs and has not been equalled until recently.

In 1816, Robert Stirling, a young Scottish minister who had just been assigned to his first parish, invented the engine shown on page 4. The caloric theory was then still current, but the design was so much ahead of scientific knowledge at the time that about thirty years passed before a theory was developed which could explain how the engine worked. Even today some engines under development still use a nearly identical design, like the very recent example shown on this page, where the only important difference between the prototype and the modern version is merely an improved link mechanism.

Stirling's patent became void due to a technicality, and although similar machines came into use later, no record of the invention was found until recently. When Stirling patented his invention, it was necessary not only to "seal" an invention but also to "enroll" it by copying the specifications onto parchment and stitching this skin to the end of the preceding patent, making one long continuous roll. Stirling's invention is not included in the rolls stored at the Patent Office in London, and the only official record of his invention was the title entered in the ancient "Docquet Book of the Great Seal" for patents granted up to 1852. No mention was made of Stirling's invention in the literature during the next hundred years, though at one time these so-called "caloric engines" were quite common, and 50 U.S. daily papers were printed on presses powered by them. All these later engines had inferior designs and more than 100 years passed before Stirling's specifications turned up again.

The principle of regenerative thermal machines applies to many different designs, and the configuration illustrated is only one example of many possible prac-



Stirling's original 2-horsepower engine, from the drawing in his patent application. This model was used in 1818 to pump water from a quarry. The displacer (D), regenerator (R), and piston (P) are identified.

tical machines. Up to now, research has been confined to a narrow range in a broad subject, and the main purpose of this article is to supply some background information in a field which may provide the answers to several problems of energy utilization and conversion.

WORKING PRINCIPLES

For a better understanding of the working principles, a few notes on general cyclic processes used in thermal machines are given here. To thermodynamicists, a "cycle" simply means that a compressible fluid such as a gas or a vapor (the "working fluid") is repeatedly subjected to variations in volume, temperature, and pressure with a conversion of heat energy to mechanical work or vice versa. Ideally the state of the working fluid at the end of each cycle should be the same as that at the beginning. Typical examples of the two main kinds of machines using thermodynamic cycles are internal-combustion engines and refrigerators.

An important law of thermodynamics states that any cycle has the highest possible efficiency if heat transfer from or to an external source always takes place at the two extreme temperature limits of the cycle. For example, in an engine or a prime mover, heat must be supplied only at the highest temperature and heat must be rejected only at the lowest temperature. Similarly, for a refrigerating or heat-pumping cycle, heat must be supplied only at the lowest temperature and heat rejected only at the highest temperature.

It is usually thought that the only cycle which fulfills this requirement is based exclusively on isothermal and adiabatic processes.* For many years this hypothetical reference cycle has been called the Carnot cycle and, as such, has been widely used in textbooks, although it is rather different from the one described in 1824 by Sadi Carnot in his classic paper, "Reflexions sur la Puissance Motrice du Feu". This concept is an abstraction which involves idealized components as, for example, an enclosure with infinite heat conduction at one stage, and perfect thermal insulation at another. Since large ranges of pressure and volume ratios are also involved, there is no practical mechanism which even remotely resembles this cyle.

Actually the Carnot cycle is only one special case of an infinite number of reference cycles with the same high efficiency, where the adiabatic operations are replaced by polytropic phases. In such processes, the heat removed during compression is equal to the heat absorbed during expansion. If the heat rejected can be stored and reabsorbed later, no external heat exchange is involved during the polytropic phases, and the cycle therefore has the same efficiency as the Carnot cycle. The term "regenerative cycles" used for this process refers to the periodic recovery of thermal energy associated with polytropic processes, and a regenerative thermal machine is an apparatus which attempts to realize such a cycle.

The device which stores the heat during one part of the cycle for use later is a "regenerator". In this application, it is usually a simple component, merely thin wire stuffed into the duct through which the gas flows. Such a regenerator separates two working spaces maintained at different temperatures. A temperature gradient between these is established in the regenerator matrix so that whenever the working fluid is transferred from one space to the other, heat transfer within the regenerator will cause the temperature of the working

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*Glossary of terms commonly used by thermodynamicists:

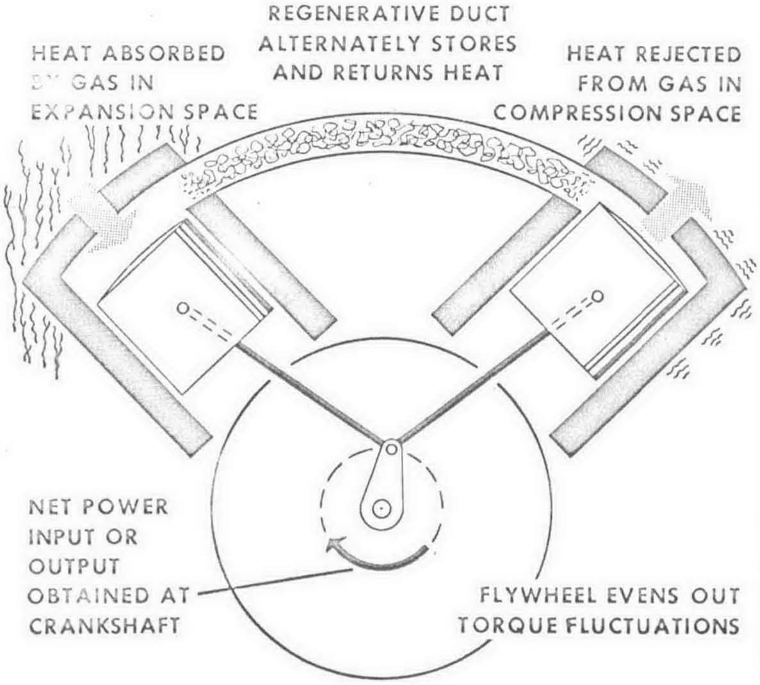
Adiabatic process: Expansion or compression of a substance during which there is no heat supplied to or rejected by the substance; follows the law $PV^{\gamma} =$ constant.

Isothermal process: Expansion or compression of a substance during which the rate of heat exchange is sufficient to keep the temperature constant; follows the law $PV =$ constant.

Polytropic process: Expansion or compression of a substance with arbitrary heat transfer; follows the law $PV^{n} =$ constant.

fluid at the inlet to be approximately equal to that of the space. The over-all effect of this is equivalent to an abstraction of heat during one polytropic phase, storage in the regenerator, and subsequent recovery during another polytropic phase.

In contrast to the Carnot cycle, which is only a theoretical principle and cannot be realized in practice, many real machines operate on regenerative cycles. Only five moving parts are needed for a simple device of this type, as shown on this page. Although in some respects the operation of a regenerative power producer resembles that of an internal-combustion engine, it is rather more difficult to understand. Instead of compressing a charge of air and fuel and igniting it, so that the force of explosion drives down a piston in the cylinder, regenerative machines accomplish the same objective by a more efficient, but less powerful, gradual heat addition.



The two variable-volume working spaces of a basic closed-cycle regenerative thermal machine are connected by a duct which contains the regenerator.

The working fluid is enclosed in a system comprising the variable spaces in two cylinders and a regenerator in a connecting duct. The two pistons produce alternating compression and expansion effects; during compression, heat is rejected by the gas, and during expansion heat is absorbed. Since there is a phase difference between the movements of the pistons, most of the gas is in the right cylinder during the compression phase, and during expansion it is mainly in the left cylinder. The "expansion space", in the left cylinder, therefore, continuously takes in heat from the outside while the "compression space" in the right cylinder rejects it. The volume changes produce a cyclic variation in pressure, and the energy conversion during a cycle is due to the differences in mean pressure when the pistons move into or out of the cylinders. Since torque will be partly positive and partly negative during each cycle, a flywheel is used to even out the fluctuations in energy. Depending only on the temperature levels of these two spaces, there will be a mechanical work output or input equal numerically to the difference between the heat supplied and rejected.

Dr. Finkelstein's current research interests include thermal regenerative cycles and magnetohydrodynamics. Prior to joining the Institute's staff he was active in studies of the Stirling engine at the University of Wisconsin. Still earlier he was Assistant Chief Scientific Officer of the English Electric Company, with responsibilities for determining research studies for various divisions of the British company concerned with hydroelectric, nuclear, and diesel power generation and aircraft manufacture. Holder of a doctorate from the University of London, he is author of papers and articles on the history, theory, and technology of the Stirling engine and of other regenerative thermal machines.

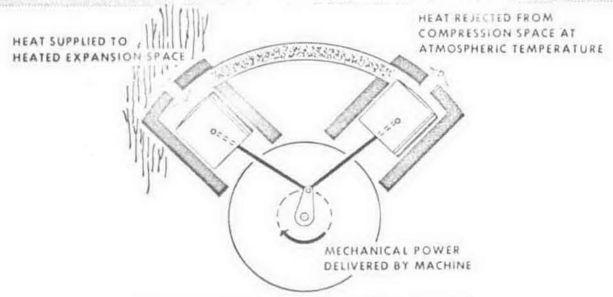
The original design, as shown on page 4, used a different mechanism to achieve the same result. In these models, compression and expansion are performed by only one piston, and the relative distribution of the gas between the compression and expansion space is changed by means of a "displacer". This type has had the most extensive technical development, and recently-described high-efficiency engines and air liquefiers are of this type. There are many alternative designs which may be much more efficient mechanically and thermodynamically. The patent literature is rich in devices which use the same working principle, but with an entirely different mechanical configuration. Most of these machines existed only on paper until recently, and a detailed study of them is in progress to determine their field of application.

THERMODYNAMIC REVERSIBILITY

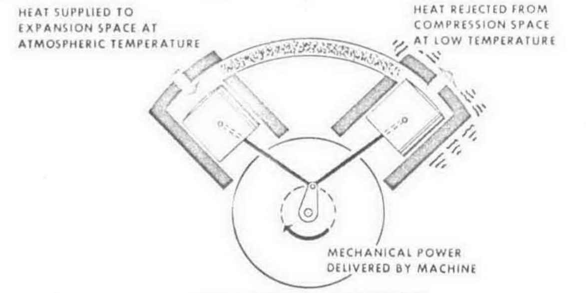
As stated above, regenerative gas cycles can operate both as prime movers and as refrigerators. In fact, this corresponds to only two out of four possible basic functional conditions, differing from each other according to prevailing temperatures and directions of heat and mechanical energy transfer. On page 6, four operational modes are illustrated.

THE FOUR BASIC OPERATING CONDITIONS OF THERMAL REGENERATIVE MACHINES

As prime movers producing mechanical energy by degrading heat energy to a lower temperature level.

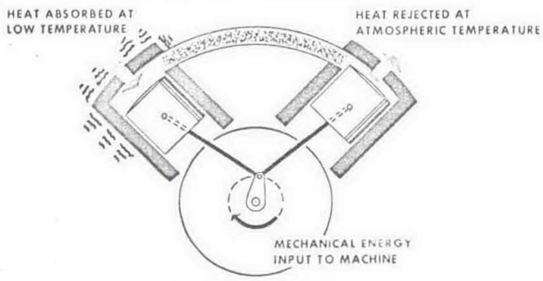


CONVENTIONAL PRIME MOVER

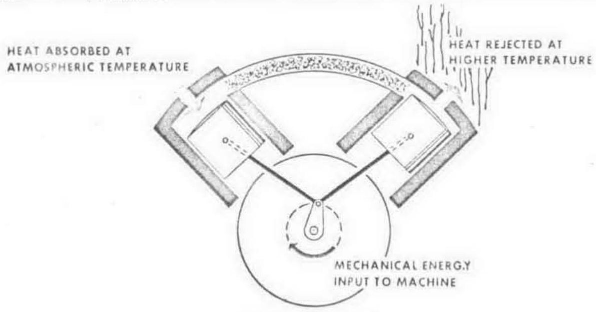


COLD PRIME MOVER

As heat pumps or refrigerators using mechanical energy to elevate heat to a higher temperature level.



REFRIGERATOR



HEAT PUMP

The Four Operating Modes

Prime Mover. When the heat supply is at a relatively high temperature, while rejection is approximately atmospheric, power is delivered by the machine at the crankshaft. The over-all effect, therefore, is that heat energy is degraded from a high to a low temperature level and consequently produces mechanical energy.

Cold Engine. A regenerative thermal machine can also function in a novel way as a "cold" prime mover. In this instance, heat energy is supplied to the machine at atmospheric temperature and rejected at a much lower temperature. This is a case where heat energy is dropped from atmospheric temperature to a low level, so that mechanical energy is produced. Although such machines have not yet been developed, they could be used when liquid gases are evaporated to recover some of the mechanical energy which was expended during their liquefaction.

Refrigerator. When operation corresponds to a conventional refrigerator, heat is absorbed by the machine at a temperature below that of heat rejection which is approximately atmospheric. Here heat energy is being pumped up from a low to a high temperature level, and mechanical energy must be supplied to the machine at the crankshaft to maintain the process.

Heat Pump. This is a machine which takes in heat near atmospheric temperature and rejects it at a high level. By analogy with a hydraulic system, it is called a "heat pump", since mechanical energy must be supplied to the machine at the crankshaft to "pump up" heat to a higher temperature level. Machines of a similar type, but with vapor-compression cycles, are in use for space heating.

A Demonstration of Versatility

This unique versatility, of not only a theoretical thermodynamic cycle but also of an actual mechanism, has already been shown in practice. In a demonstration, a standard machine substantially of the same design as originally conceived by Stirling was used. The cylinder head was exposed so it could either be heated or cooled, and a water jacket kept the compression space near atmospheric temperatures. The crankshaft was coupled to an electric armature which could function either as generator or motor.

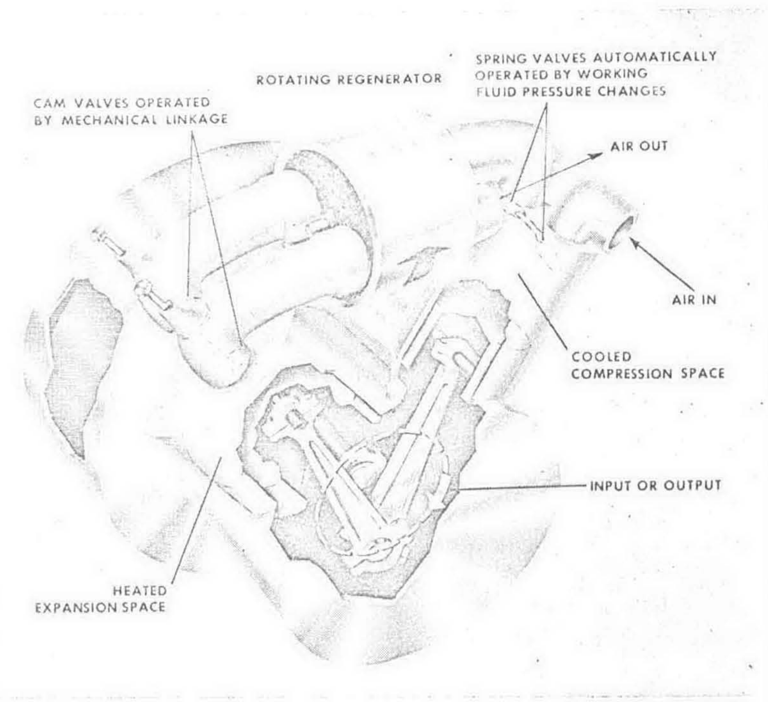
When the cylinder head was made red-hot by heating it with a burner, it would drive the generator and produce electricity. When the burner was removed and the armature was supplied with electric current to continue driving the machine in the same direction, the hot end of the cylinder would continue to absorb heat. As a consequence, the temperature dropped to below atmospheric conditions and ice formed on it by condensation from the atmosphere. Eventually, the temperature became so low that air liquefied on it. These two experiments correspond to operation as "prime mover" and "refrigerator", respectively. With the power disconnected at this stage, the temperature differential between atmosphere and the very cold cylinder head would cause heat to be absorbed at the lower temperature and the mechanism functioned as a "cold prime mover". The machine then rotated in the opposite direction and generated electricity until the temperature between the two cylinders was equalized. If the motor were then again supplied with electrical energy to continue to drive it in the same direction, heat was elevated to a higher level. The cylinder head could again be made red-hot by the mechanical energy supplied to it by the electric motor instead of heat energy supplied by the burner, and the same device now functioned as a heat pump.

Different Designs

The two basic arrangements with either two cylinder-piston assemblies, or with a piston and a displacer in one cylinder, are only the two simplest configurations out of many possible alternatives. In more sophisticated machines, oscillating or rotary cylinders, vane-type assemblies, or free-piston devices could replace the moving pistons in stationary cylinders. It is also possible to use totally sealed systems with bellows or diaphragms for the volume variations. All these designs have been applied to regenerative thermal machines on paper, and some are extremely promising.

Even the more elementary mechanism with reciprocating pistons in stationary cylinders can be made much more efficient with a double-acting design. By using both sides of each piston in a multicycle machine for producing the volume variations in two different constituent cycles, only one major moving element is used per cycle instead of two. The efficiency could be greater since there are fewer working parts and because net forces are more equalized. This is particularly important in machines where the working fluid is a highly compressed gas, such as hydrogen.

The preceding discussion of thermal machines was based mainly on so-called "closed" thermodynamic cycles. This term indicates that, apart from incidental leakage past the piston, no inlet or exhaust process is involved, and an identical mass of gas is used again and again. In contrast, open-cycle machines replace at least a substantial portion of the working fluid during each cycle but, in all other respects, the thermodynamic cycle is the same as in closed-cycle machines. The only significant difference is that one or more phases are now performed outside the mechanism, for example, in the atmosphere. An example of a typical open-cycle machine is shown above. While closed-cycle machines usually have no valves, all open-cycle machines need them to regulate the flow process. In the design shown here, the valves in the compression space are automatic, and those in the expansion space link operated. A rotary regenerator is used where the matrix can change position between the two gas streams.



This open-cycle regenerative thermal machine differs from a closed-cycle machine in that it has a rotary regenerator and an intake and exhaust to the atmosphere.

Two "caloric" engines with 14-foot-diameter cylinders of this type powered the famous "Ericsson", a 2200-ton vessel built in 1853; however, power production is apparently not a good application for open cycles, as specific output is low. There are, nevertheless, other promising possibilities. Since a continuous stream of heated or cooled gas is delivered by the machines, they can function as cooling, warming, or dehumidifying devices or even as air compressors, and some attractive designs have been proposed.

The main object in enumerating all of these various possible systems is to demonstrate that only a narrow range in a vast field has been explored. Out of dozens of different technically feasible alternative configurations and applications, only the first mechanism to be invented had been investigated up to the stage where modern prototype designs and test data were available. This means that much research remains to be done before a sound assessment of regenerative machines becomes possible. A substantial portion of such research is basic and amounts to feasibility studies for new and untried systems, and the research must start from first principles, since no previous experience or data are available.

Many new prototypes will have to be constructed and tested before their full capabilities and limitations can be evaluated.

Up to now the greatest obstacle in the development and application of the regenerative principle has been a lack of understanding of the interrelations between the basic physical parameters which influence the operation. Although the individual phenomena of heat transfer, aerodynamic friction, and regenerator losses are well understood, they interact in so complicated a way that individual contributions of any changes made are hard to assess or to interpret.

Recently, this has been overcome by the application of modern digital and analog computers to the problem. It is now possible to conduct analytical studies of the thermodynamic processes of heat transfer and energy conversion. The procedure used is to formulate an extensive system of simultaneous differential and algebraic equations which are adequate for describing the physical situation in a realistic manner and which can be solved numerically to yield integrated results for the energy conversions and the performance. By such methods, it is now possible to predict the cyclic variations under specified conditions in such significant parameters as pressure and temperature. Since it is possible to compute a complete heat balance, one can, therefore, test the operation of various devices without actually constructing a prototype. It is hoped that such studies will soon lead to the development of improved as well as new types of regenerative machines and hasten their practical application to a number of purposes.

SOLAR, NUCLEAR, AND OTHER APPLICATIONS

Although at present most power is still generated by burning fossil fuel, an intensive search for suitable power converters using solar and nuclear heat sources is in progress. In these new technological areas, regenerative cycles have considerable potential. Referring first to small-scale power production, the main difficulty with regenerative machines is the necessity to transfer heat from the outside of an enclosure, such as a cylinder wall, to the inside. The creep strength of engineering materials at elevated temperature thus limits the temperature and pressure which can be used. Output is also restricted by the area available for heat transfer and by the unavoidable temperature differential between the outside and the inside. All these drawbacks are summed up in the term "external-combustion engine" which is sometimes used.

With nuclear- and solar-energy inputs, it is possible to avoid these disadvantages and to apply the source of heat directly inside the engine. One system, which uses the heat produced from the decay of isotopes, incorporates these materials inside the engine structure. They may, for example, be installed in the form of a grid or matrix which heats internally and through which the working fluid passes. Similarly with solar machines, it is possible to concentrate the solar energy not on the outside of the envelope, but beam it through a quartz window and generate heat right inside the working-fluid system. There are no heat losses apart from the transmission loss at the window, and the radiant energy is absorbed by a matrix or a grid for transmission to the gas. Both methods give a compact unit with practically no direct heat losses from the hot end, which operates with an effective upper temperature limit appreciably higher than that permitted by the creep strength of the engine enclosure. One obvious application is for space probes and satellite auxiliary power plants where such units have all the desired qualities of compactness, efficiency, and reliability.

A more down-to-earth application of solar engines, which may have considerable economic importance in such countries as Pakistan, India and others, is a simple and reliable prime mover which could be operated by unskilled and uneducated farmers. If such machines were produced cheaply and made available in large numbers for irrigation, they might considerably increase the living standard of rural communities in nonindustrialized power-starved countries. Where natural fuels are more readily available than solar energy, as in some regions of Africa and South America, a simple, low-efficiency, but fool-proof power producer could also be built to run on peat, vegetive waste, or other combustible material. This would make available a simple small source of power for lighting, corn grinding, etc., for primitive communities.

Since there are so many different possible designs and so little is known at present about their capabilities and limitations, it is difficult to forecast future commercial developments. Many possible uses of regenerative machines can be foreseen, but apart from considerations of technical feasibility, economic conditions will determine more definitely whether certain applications will materialize. The commercial prospects in fields where conventional machines are available are particularly difficult to assess. It is obvious that a radically novel design for all types of equipment will be much more readily accepted for purposes where no alternative devices with similar performance characteristics are available. When conventional machines can be obtained that offer adequate performance and that have already gone through a lengthy process of technical development, it is not so easy to establish a revolutionary new type of product in direct competition. This would be the case even if certain marginal or even substantial advantages in performance, cost, or other features can be obtained, especially since most new machines must initially be more expensive with small production quantities. The first large-scale practical applications of Stirling engines might therefore be in fields where no alternatives are available with corresponding performance.

This situation already exists, and the first modern device of this type to be used in substantial numbers is as an air liquefier. This is a single-cylinder displacer machine, also similar to Stirling's original prototype, but driven by an electric motor, so that the cylinder head cools down sufficiently to condense the atmospheric air in contact with it. Although the coefficient of performance is lower than that of larger conventional machines, small quantities of liquid air can be produced more readily and conveniently. Since no alternative method for producing liquefied air in laboratory quantities existed before, this was a natural opening for regenerative machines.

Many other applications that are perfectly feasible at this stage of technical development have been proposed at various times. One example is power units for small boats which could use bottled gas as fuel. The almost uncanny silence of these prime movers should make them most attractive. The use of regenerative thermal machines as road transport power units will require first the development of a better method for control with a short response time. The main advantage of these units is that the property of thermodynamic reversal can be used during braking, so that the energy stored every time the vehicle is slowed down or stopped can be recovered during the subsequent acceleration.

Open cycle machines could form part of the coolant loop in gas-cooled nuclear reactors to convert the heat generated during the fission processes. They can also be designed on a smaller scale as simple and compact air conditioners which are fully reversible at a flick of a switch, so that they can be used either for warming in winter or for cooling in the summer. This apparatus need not have any size limitation and it is possible to design them as miniature localized refrigerators. Such systems might have considerable importance with the new types of electronic equipment. In the past, when large numbers of vacuum tubes were used in electronics, a considerable amount of heat had to be dissipated, and the whole cabinet or enclosure containing this equipment had to be cooled, or ventilated. Transistors develop less heat than vacuum tubes, but may be closely packed so that local cooling by regenerative thermal machines could be advantageous.

Some electronic components, for example, infrared detectors and masers, can operate only in an ultralow temperature environment. Again, the solution may be the use of small devices to produce such local cooling effects, and equipment has already been developed for this purpose. On a more trivial plane, it is also possible to construct very small gadgets such as "cocktail coolers" with which one could cool individual drinks without diluting them by using ice.

Regenerative cycle studies are still in a very preliminary stage, and much research remains to be done to make an adequate evaluation of the best practical use. The above list is therefore largely speculative and not complete or inclusive, and its main purpose is merely to outline a very wide range of uses and to indicate the practical significance of the substantial research effort devoted at present to this area.