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Pitcher

[11] **3,921,400**

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[54] **CRYO-ELECTRIC ENGINE-REFRIGERATOR COMBINATION**

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[52] **U.S. Cl.** **60/517;** 60/660; 60/667; 62/6; 62/190; 62/467; 307/39; 307/155

[51] **Int. Cl.**.. **G05b 11/01;** F25b 49/00; F01k 13/02

[58] **Field of Search** 307/38, 39, 155; 62/6, 62/190, 467; 60/660, 667, 516, 517, 524

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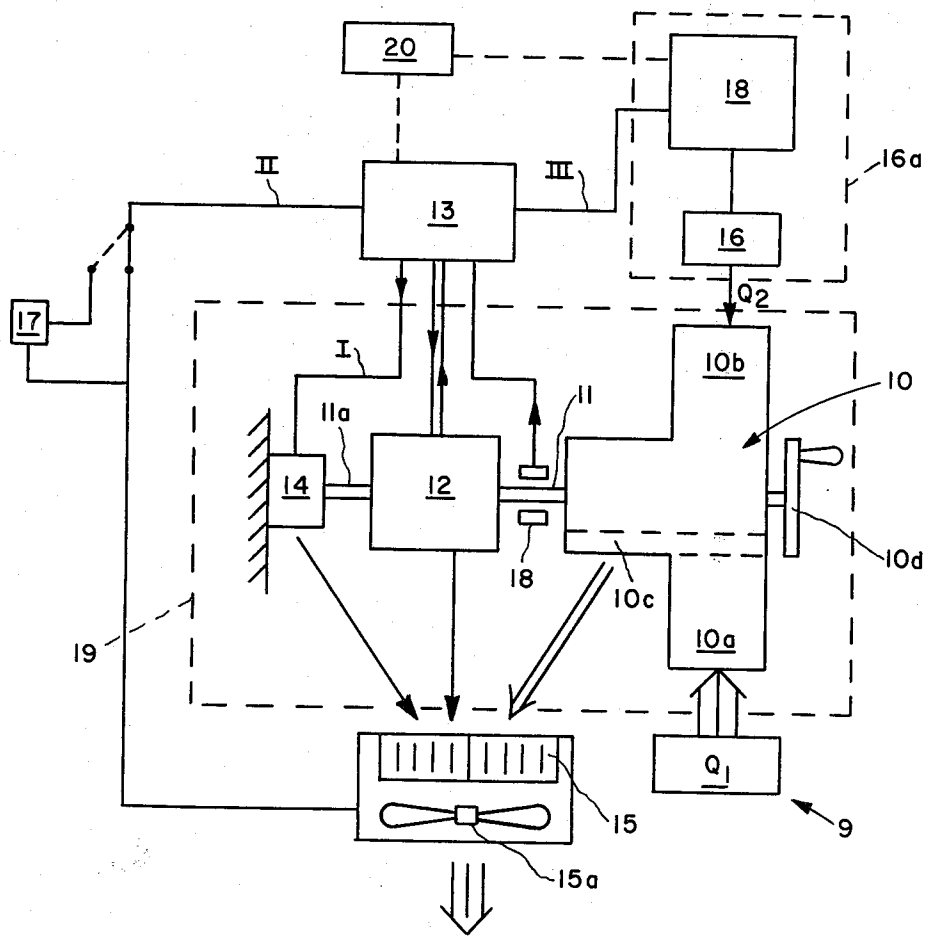
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Assistant Examiner—Allen M. Ostrager
Attorney, Agent, or Firm—Frank R. Trifari; J. David Dainow

[57] **ABSTRACT**

A cryo-electric apparatus converts heat into both refrigeration and electrical power, the apparatus being operable in part according to the Vuilleumier thermodynamic cycle with interconnected compression and expansion spaces for a working gas, each of said spaces formed by a piston-cylinder assembly, the pistons operable through a crankshaft that also provides mechanical output power to drive a generator or alternator producing electrical power; a control system senses refrigeration and electrical output of and demands upon the apparatus and correspondingly regulates the apparatus which is essentially self-running once started.

7 Claims, 3 Drawing Figures



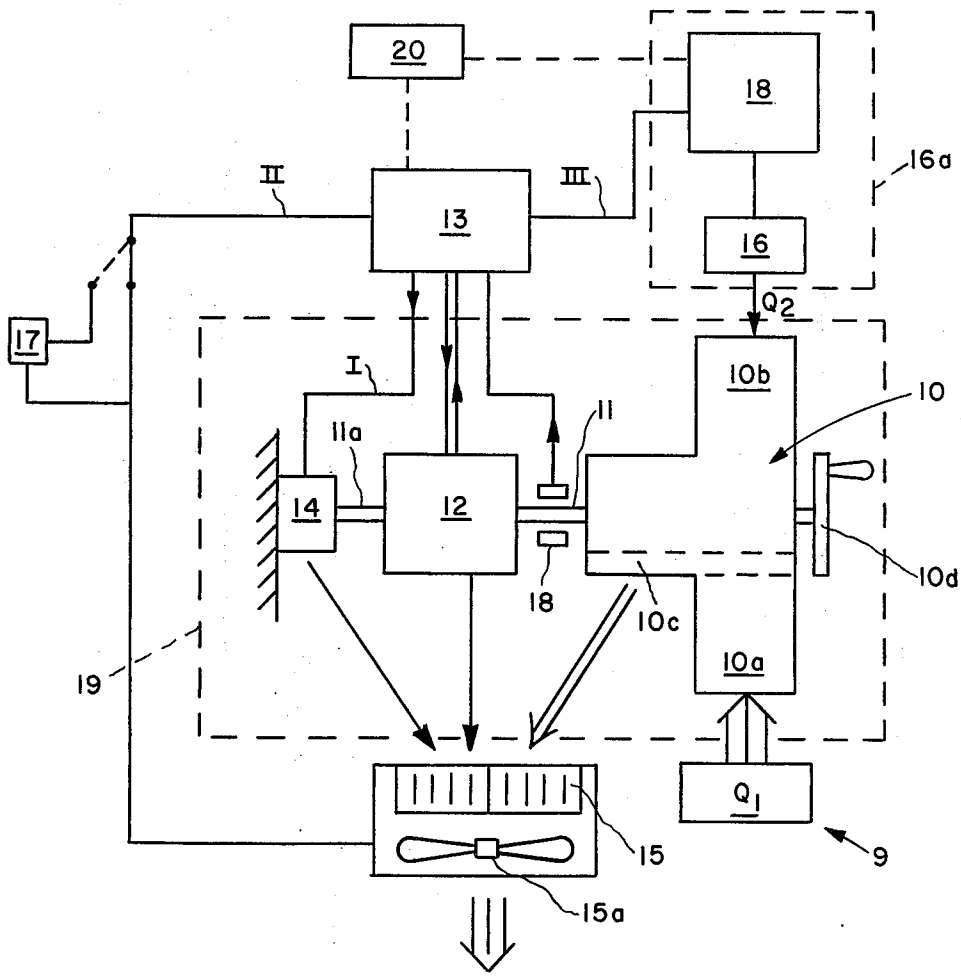

20
18
16a
II
III
13
16
17
Q2
I
10b
10
11a
11
14
12
10d
18
10c
19
10a
Q1
15
9
15a

Fig. 1

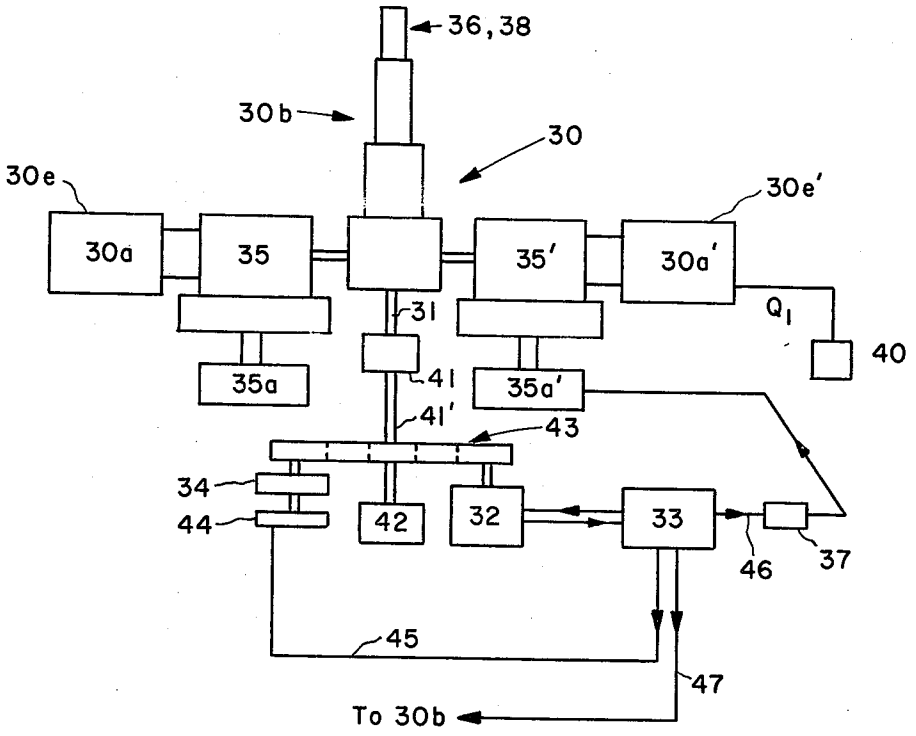

36, 38
30b
30
30e
30e'
30a
35
35'
30a'
31
Q_1
40
35a
35a'
41
41'
43
34
44
42
32
33
46
37
45
47
To 30b

Fig. 2

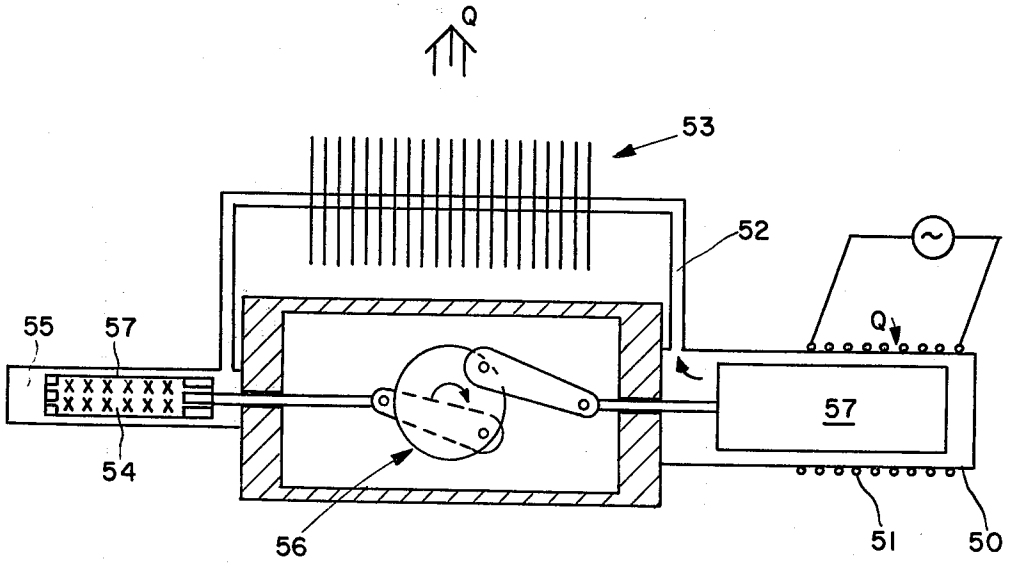

Q
53
52
55
57
54
56
Q
57
51
50

Fig. 3

CRYO-ELECTRIC ENGINE-REFRIGERATOR COMBINATION

BACKGROUND OF THE INVENTION

This invention relates to apparatus for producing refrigeration at cryogenic temperatures, and particularly to a refrigerator operating according to the Vuilleumier (or V-M) thermodynamic cycle. A V-M refrigerator has the significant characteristic that working gas is compressed in its hot-end due to externally supplied heat, in contrast to compression in a Stirling refrigerator by a mechanically driven compression piston in a cylinder; the compressed gas in both types of refrigerators is subsequently cooled and then expanded in the cold-end where useful cryogenic-level refrigeration is produced. Thus, the V-M refrigerator reqires only a small mechanical drive in addition to the thermal input to operate, as compared to Stirling or other refrigerators that require substantial mechanical or electromechanical power input for the gas-compression stage with problems of noise and vibration, and the provision of said power.

Also relevant to the background of this invention are power-producing engines, particularly external-combustion types as the Stirling heat engines, that utilize a thermal input to produce mechanical output power, but have a closed-cycle operation of working gas between compression and expansion spaces similar to the V-M refrigerator. Both these engines and refrigerators have inherent control difficulties, particularly the problem of varying quickly the amount of external heat-input needed for response to changes in the amount of power demanded in the case of an engine, or varying the quantity of cold produced in the case of a refrigerator.

In operation a typical Vuilleumier refrigerator has the hot-end and cold-end displacers moving reciprocally, but in a 90° phase difference. Increased pressure and resulting compression of the gas occurs as a consequence of heat input to the gas within the hot-end cylinder, which thus functions as a thermal compressor. The pressure variations in the cold volume of this V-M device are produced by the motion of the hot displacer in the following way. If the hot displacer is "down", much of the helium is in the hot area, the average helium temperature will be high, and the pressure will be high everywhere in the working space. On the other hand, if the displacer is "up", very little of the helium is in the hot area, the average helium temperature will be low, and the pressure will be low. Therefore, as long as the hot displacer moves up and down in the correct phase relationship to the motion of the cold displacer, the required pressure and volume variations are produced in the cold expansion space, with a regenerator operative between the hot and cold ends to store heat from gas leaving the hot end and return heat to gas entering the hot end, and cold is produced according to the equation of $Q = \oint pdV$; this equation defines cold production per period in the various thermodynamic cycles, with the same cold produced in a given expansion volume no matter how the pressure variation is produced. A further characteristic of the V-M refrigerator is that the power required to drive the displacers may be small, since the only forces on the displacers are those due to the small pressure drop of the helium flowing through them, and to the nominal mechanical friction.

A further development with respect to V-M refrigerators is that by suitable selection of design parameters, the hot end can be made to heat the gas therein, sufficiently to produce power for driving the hot piston, crankshaft, and cold displacer piston, with the gas experiencing the compression and expansion cycle to produce refrigeration, and the crankshaft having available excess power to drive an accessory such as a generator or alternator to produce electrical power. In such a case the refrigeration apparatus functions partially like a heat engine to produce output power, but the compressed gas is also flowed to the cold end for expansion producing refrigeration. As mentioned above controlling power output of such heat-engines and refrigeration output in V-M and related Stirling refrigerators has been a problem for many years, and existing efforts to solve these problems have resulted in complex systems with undesirable features, one example being the use of internal valves with external ducts and auxiliary spaces for release of the pressure of the working gas.

The new invention constitutes an approach to the "engine-refrigerator" as a whole system instead of the usual approach of considering separately, (a) known methods to regulate heat "engines", and (b) known methods to regulate cryogenic "refrigerators". Accordingly the new invention converts the excess output shaft power to electric power that directly reduces shaft speed and operates other regulatory accessories of the overall system as described below. Further background material on the V-M operation is disclosed in U.S. Pat. Nos. 2,657,553 and 1,275,507.

SUMMARY OF THE NEW INVENTION

The new invention is an apparatus utilizing a heat energy to produce refrigeration and also to produce mechanical power which is converted to electrical power. The apparatus has at least one hot-end cylinder and piston assembly defining a variable volume compression space of higher average temperature, at least one cold-end cylinder and piston assembly defining a variable volume expansion space of lower average temperature, and a rotary crankshaft or other coupling interconnecting the two pistons. The compression and expansion spaces plus an included regenerator constitute a part of a closed system in which a working medium, such as helium gas is cyclically reciprocated between compression and expansion states.

The introduction of heat energy to the hot-end compression space compresses the gas therein for later expansion in the cold end according to the Vuilleumier (V-M) thermodynamic cycle. However, the dimensional parameters and the temperatures and pressures of operation are selected such that the gas compression in the hot-end is sufficient not only to drive the hot-end piston, the crank shaft, and cold-end piston displacer for reciprocating the gas in its refrigeration cycle, but also to develop excess power available via the crankshaft. Such excess power will drive a generator or alternator that provides electrical power for energizing all the apparatus operating and regulatory or control accessories, such that the apparatus becomes self-running, once started; also there is excess electrical power for energizing the device to be cooled for its own independent operation.

The control components sense speed of the crankshaft, electrical output of the generator, and refrigeration developed by the cold end (cold-finger), and pro-

duce appropriate reactions on the system to maintain proper temperatures, steady speed and refrigeration, electrical power storage or other function required. The speed regulation in particular, i.e. producing appropriate reactions to correct over or under speed conditions, provides steady frequency of the electrical power output where an alternator is used, and steady voltage where a dc generator is used.

For long term regulation of the apparatus i.e. to establish semi-fixed parameters of operation, an adjustment may be made in the heat input to the hot-end; for short term regulation, i.e. temporary change of operating parameters, an electrically operated brake may be employed, which uses electrical power produced by the apparatus, to apply a greater resisting torque load to restrict excessive speed of the output shaft and a lesser resisting torque when speed drops below the desired steady state speed. The brake provides an immediate effect on the system, in contrast to a slower reaction from a change in the heat input.

The control means also distributes electric current to the electric motor of each cooler (cooling heat-exchanger) of the engine-refrigerator and to the brake, and to the cryogenic device being cooled as mentioned above; heat from these various components, the brake, the generator, and heat of compression of the gas is at least partially dissipated by the cooler.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic drawing of the engine-refrigerator combination of this invention, including a device to be cooled.

FIG. **2** is a schematic view of a second embodiment of this invention having two opposing hot-ends operable with a single cold finger.

FIG. **3** is a schematic view of a Vuilleumier engine alone which produces refrigeration and has a rotary output shaft for mechanical power.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In FIG. **1** is a V-M engine refrigerator **9** which will be described first as regards it component parts and their functions, and then as regards the system's overall operation. The V-M apparatus **10** has hot and cold ends **10***a* and **10***b* respectively and an intermediate cooler **10***c*, and the hot and cold-end displacers are coupled to an output shaft **11.** The structural design and operating parameters including quantity of heat input are selected such that output power will be available at said shaft **11,** in addition to refrigeration being produced at the cold end.

A device **16** to be cryogenically cooled, such as an infrared detector is arranged in thermal communication with the cold end's freezer at **10***b*, whereby a quantity of heat Q_2 flows into said cold end. An electric power producing device **12** such as a dc generator or an alternator is driven by shaft **11,** with the generator's power output conducted to a regulator **13,** which may variably excite the generator's field to control the level of power output. This device also selectively directs current via paths I, II, and III respectively to a brake **14,** to the blower **15***a* of heat exchanger **15,** and to part **18** of the device **16** being cryogenically cooled. Brake **14** may be eddy current, magnetic or other type for applying a resisting torque to shaft **11,** and sensor **18** registers the speed of shaft **11** and communicates same to regulator **13** which may employ the brake to alter said speed.

Heat input to the V-M's hot side **10***a* may be from any convenient source, including a fuel burner, electric coils, waste heat, and isotopes. The heat exchanger **15** may be the forced-air type shown, which receives heat from and thus cools the V-M's cooler **10***c*, and from the brake **14** and the generator **12.** A thermal seal represented by line **16***a* insulates the cryogenic device **16, 18** from heat of the V-M apparatus or from the general environment.

The dashed line **19** represents a hermetic seal enclosing the V-M device **10,** brake **14,** and generator **12,** for the purpose of retaining the working gas (usually Helium) of the V-M, without requiring the use of shaft seals with these components, and associated difficulties. Optionally, the heat exchanger **15** and the regulator **13** can also be included within the hermetic seal.

Another optional feature of this system is an energy storage device such as a battery **20** which would be placed between the power regulator **13** and the cryogenic device **16.** Such a storage device would act as a buffer to make sure that unsteady power demands by the device **16,** if such is the case, would not directly effect the power regulator and the generator/alternator. In other words the cryogenic device could demand and receive energy at any steady or unsteady rate, and the power regulator could obtain electric power from the generator at a predetermined steady rate chosen for optimum operation of the machine. Alternatively, where power demands of the cryogenic device or other components of the system are relatively constant, such power is readily obtained by exciting the generator field to the extent needed. In the event the power generating device **12** produces ac current and it is found desirable to use a dc motor **15***a* in the heat exchanger **15,** a converter **17** would be added on the output side of the regulator. While the V-M would be essentially self-running once in operation, starting is required, which could be done by a simple hand crank **10***d*, which includes a rack and gear, and a spring recoil.

The system of FIG. **1** operates as follows. When the V-M has begun to function, and the cold side **10***b* has reached its cryogenic operating temperature, full engine shaft power becomes available to drive the generator **12.** Regulation of the V-M shaft speed is required to assure steady refrigeration, steady frequency of the electrical power produced where device **12** is an alternator, and steady voltage produced where device **12** is a dc generator. Also steady power may be needed by device **18** for which the regulator will appropriately excite the field of device **12.**

The system has features (a) for short-term or primary power regulation, i.e. to act immediately and directly upon the output shaft for affecting speed and refrigeration produced, and/or upon the generator for affecting electric power produced, and (b) for long-term or secondary regulation, i.e. to act on the V-M apparatus by altering the heat input Q_1 which has a delayed effect, but relates to overall efficiency.

Primary speed regulation is achieved by regulating the torque presented to shaft **11** of the V-M. As indicated earlier a certain resisting torque is applied to shaft **11** by generator **12** when its field is excited as a consequence of a demand for electric power from device **18** through regulator **13.** Because the V-M is designed to produce torque in excess of the generator's requirements, the auxiliary torque-resisting brake **14** is

provided, which is activated by the regulator to operate in conjunction with the braking-effect of the generator to regulate shaft speed.

In the secondary regulation, the long-term power requirements of the cryogenic device **18** will be known, such that all components can be adjusted to operate in steady-state conditions. This includes heat transfer to the heat exchanger **15** from the V-M cooler, the generator and the brake. Heat input Q_1 to the hot-end **10***a* can be manually controlled or connected back to regulator **13** for the purpose of establishing maximum efficiency conditions for operation.

FIG. **2** shows a second preferred embodiment of the invention. Numerous components of FIG. **2** are essentially the same as in FIG. **1** and these will have identifying reference numerals that differ from FIG. **1** by a factor of **20,** such that generator **12** for example in FIG. **1,** will become equivalent generator **32** in FIG. **2.** Accordingly the V-M apparatus **30** has hot-ends **30***a* and **30***a'*, each including a piston and cylinder (not shown) within heat insulating jackets **30***e* and **30***e'* respectively. A variac **40** controls the electrical power input to the electrical heating coils adjacent the hot-end cylinders within these jackets, unless other heating means are employed. Forced air heat exchangers **35** and **35'** respectively include electric-motor driven blowers **35***a* and **35***a'*. The V-M's output shaft **31,** a coupling **41** connects shafts **41'** with flywheel **42** and belt drive unit **43** for driving alternator **32.** Brake **34** with assocciated speed sensor **44** are coupled via belt unit **43** to control the speed of the power generator **32** and the output shaft **31.** Power regulator **33** is in circuit via path **45** to the brake, path **46** to the heat exchanger blowers with optional ac-dc converter **37,** and path **47** to the cryogenic device. Operation of the FIG. **2** system similar to and follows the same principles of the FIG. **1** system.

FIG. **3** shows a V-M device of the type used in FIGS. **1** and **2.** Hot-end **50** receives heat from electric coils **51.** Compressed gas flows through duct **52,** heat-exchanger-cooler **53,** to regenerator **54** and expansion freezer **55.** Coupling **56** maintains the compression and expansion displacer **57, 58** in a 90° phase relationship. The parameters of operation were described in earlier sections above.

I claim:

1. A self-regulating apparatus for use with a Vuilleumier (V-M) refrigerator for refrigerating a cryo-device which is in thermal communication therewith and which uses electric power, the refrigerator having a hot-end operable to receive heat from a source of heat, a cold-end where refrigeration is produced, working gas alternately compressed and expanded in said two ends, a cooler for discharging heat from the compressed gas, and a power output element with refrigeration produced corresponding to the speed of said output element, the gas compression being excessive for the refrigeration produced with a resulting output power through said element, the regulating apparatus for controlling both long and short term operation of the V-M refrigerator according to predetermined operating parameters, comprising: electric power generator means driven by said shaft, means for monitoring the speed of said output element and registering the occurrence of either excessive or insufficient speed causing unsteady frequency, voltage, power or refrigeration, brake means operable with electric power from said generator for applying a resisting torque on said output element for controlling the speed of said element, control means responsive to said monitoring means directing an amount of said electric power to said brake means corresponding to the amount of excessive or insufficient speed of said output element as a short term control, the control means also directing electric power to said cryo-device when so demanded, the apparatus further comprising a heat exchanger for absorbing heat from said generator, brake, and cooler, the control means further comprising means for varying the heat received by said hot end as a long term control.

2. Apparatus according to claim **1** wherein said V-M refrigerator has two hot-ends operable with a single cold end, the two hot ends being spaced apart in opposing relation.

3. Apparatus according to claim **1** further comprising means for storing electrical power from said generator, said cryo-device in circuit to receive electric power from said generator via said storage means.

4. Apparatus according to claim **1** wherein said generator is a dc generator.

5. A Vuilleumier-cycle refrigerator apparatus operable with a source of heat for refrigerating a cryo-device which uses electric power, the apparatus having a hot-end for receiving heat from said source, a cold-end where refrigeration is produced, a quantity of working gas alternately compressed and expanded in said ends, a cooler for discharging heat from the compressed gas, and a rotary output shaft, the gas compression being excessive relative to the refrigeration produced such that shaft output power is available, the apparatus including means for regulating both short and long term operation of said apparatus comprising: first means for converting shaft output power into electrical power, second means sensing excessive or insufficient shaft rotation speed causing unsteady frequency, voltage power or refrigeration output and providing a corresponding signal information, third means using electric power from said first means for applying a resisting torque to said shaft, control means first for receiving information from said second means and directing electric power corresponding to said excessive or insufficient speed to said third means to maintain steady shaft speed by compensating for excessive or insufficient shaft speed as short term control, and second for varying the heat received by said hot-end as long term control, said control means also directing electric power to said cryo-device as needed, the apparatus being self-regulating according to predetermined operating parameters.

6. Apparatus according to claim **5** wherein said first means is an alternator.

7. An engine-refrigerator apparatus operable with heat from a source for refrigerating a cryo-device, comprising: a Vuilleumier-cycle (V-M) device which when operated produced both refrigeration and output power, the V-M device having a hot-end for receiving heat, a cold finger part for communicating said refrigeration, and a rotary shaft for communicating said output power; means for communicating said heat to said hot-end of the V-M apparatus; first means driven by said shaft for converting said output power to electrical power; second means for sensing any variation above or below the design speed of the rotation speed of said shaft and providing corresponding signal information; third means operable by electric power from said first means for applying a resisting torque to said shaft; a heat exchanger for absorbing heat from said V-M apparatus and from said first and third means; fourth means

communicating refrigeration from said cold finger to said cryo-device; fifth means for regulating said assembly, this fifth means receiving electrical power from said first means and signal information from said second means, and selectively, according to predetermined parameters, conducting electric current to said cryo-device, to said third means directing samme to apply greater or lesser resisting torque to said shaft, and to said heat exchanger, whereby the assembly is self-regulating to maintain steady shaft speed.

* * * * *