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# RECENT CRYOCOOLER PROGRESS IN JAPAN

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This paper reviews the recent progress of cryocoolers and its related devices in Japan. Part of the research and development of cryogenic technology including small scale cryocoolers is supported by a number of national projects. The Japanese National Railways has been developing the light weight 4 K on-board refrigerators since 1977 as part of the MAGLEV train program. An investigation of superconducting and cryogenic fundamental technology has been conducted by the Science and Technology Agency since 1982, including high performance cryocooler (related to Stirling cycle), magnetic refrigerator and superfluid refrigeration. A study of space cryogenics such as the cooling systems of IR-detectors was started by the Ministry of International Trade and Industry in 1984. In addition to these national projects, several companies also have done their own activities on cryocooler investigation, for special applications such as cryopump, NMR-CT and JJ devices. Compact heat exchangers, high performance regenerators and reliable compressors are also being investigated as a critical component technology.

Key words: Cryocoolers; heat exchangers; helium; low temperature; refrigerators; regenerators.

## 1. Introduction

The research and development scheme of cryocoolers can be classified into two categories. The first one is related to the investigation of reliability, compactness and cutting costs of the well known cryocooler systems. Stirling or Gifford-McMahon cryocoolers with a JT loop and small scale Claude cycle also belong in this category. The second one is a fundamental approach to the novel refrigeration systems such as a magnetic refrigerator or regenerative cryocoolers which can be cooled down to liquid helium temperature without a JT loop. As a critical component, compact heat exchangers, high performance regenerators and reliable compressors are also important. With this in mind, the recent progress of the relatively small cryocoolers, operated at liquid helium temperature are reviewed.

## 2. Claude Cycle Cryocooler

The Claude cycle has been used for rather high capacity helium liquefiers, however, two on-board Claude cycle cryocoolers with a capacity of 30 watts at 4.4 K and 5 watts at 4.5 K have been fabricated for the MAGLEV project of JNR since 1978 [1, 2]. In this particular case, the following considerations were taken:

(1) The automatic inlet and exhaust valves of the expanders and cylindrical cam for the piston were employed for the compactness of the crosshead.

(2) A direct coupling system of the high speed flywheel was employed as an energy absorber of the expander. This energy absorber system makes the expander unit compact and light weight.

(3) The laminated metal heat exchangers made of aluminum perforated plates and plastic separators were employed for the 5 watt systems.

In the field of industrial electronics, the need for cryocoolers to cool superconducting magnets in such systems as magnetic resonance imaging or the control of the single crystal drawing furnaces has gradually increased. To meet these requirements, the Toshiba Co. developed 4.4 K 5 watt Claude cycle cryocooler, as shown in figure 1. Figure 2 shows the available energy balance of this system. It is reported that the JT valve loss is limited, although the losses due to the heat exchangers and expanders could be decreased.

The research activity for developing smaller Claude cycle cryocoolers has been continuing, however, there are almost no reports about the long term operation to date, and it has remained as a problem for the future.

### 3. G-M Cycle Cryocooler with JT Loop

The G-M cycle or modified Solvay cycle has been developed mainly as a 20 K cryocooler for the cryopump applications. Recently, several companies have been investigating the relatively high power G-M cycle cryocooler as a precooler for the JT loop for the recondensor of liquid helium.

Most of the cooling systems for superconducting magnets require simultaneous cooling of the radiation shield and liquid helium bath. Figure 3 shows the flow diagram of a 4.5 K cryocooler with 77 K additional cooling loop developed by Hitachi Ltd.. This work has been supported by MITI since 1982. The typical cooling power of the G-M cooler is 18 watts at 20 K and 60 watts at 80 K, respectively. The expander efficiency is reported as 44% at first stage and 38% at second stage. The details are shown in figure 4. The layered heat exchangers with perforated aluminum plates are used for the JT loop. It has a scroll type cross section as shown in figure 5. Figure 6 shows the cooling power at 4.5 K and 77 K where the JT flow rate was maintained at 10 $Nm^3$/hr. Indications shows that this system can be applied to both the large cryostat with low heat load at 4.5 K (such as superconducting NMR-CT) and the small cryostat with high heat load at 4.5 K (such as J-J devices).

The Mitsubishi Electric Co. investigated the 4.3 K 5 watt system, where a G-M cooler was used as a precooler developed by Osaka Oxygen Industries in 1981. They reported the effect of the different ambient temperature on the cooling power of the system. Figure 7 shows that the cooling capacities of G-M cooler decreased about 30% when the ambient temperature was increased to 40 $^{\circ}$C and the inlet helium gas temperature was increased to 50 $^{\circ}$C, (line B in figure 7), compared to the capacities operating at 20 $^{\circ}$C (line A). Figure 8 shows the cooling capacities for the 4.3 K J-T stage. It should be noted that the degradation of cooling capacities, 5.8 to 4.9 watts, is only about 16%. They also studied the effect of the ambient magnetic field on the valve motor up to 1 kGauss.

Sumitomo Heavy Industries Ltd. investigated 4.3 K 3 watts (max. 3.65 watts) cryocooler. The typical cooling capacity of their G-M cooler is 8 watts at 20 K and 20 watts at 77 K. One of their interests is related to the development of a reliable compressor. Three rotary compressors were used at the operating pressure of 1-20 atm for the JT loop (9 $Nm^3$/hr.) and 7-20 atm for the G-M cycle as shown in figure 9. The total input power is about 7 kW. The amount of lubrication oil for each compressor is successfully controlled by the overflow at a constant level which feeds it back to the intake port of the lower pressure stage. The dew point of the working helium gas is initially controlled below -70 $^{\circ}$C, although the pressure drop within the first heat exchanger increased 0.6 -0.84 $Kg/cm^2$ during 1660 hr. operations.

### 4. Fundamental Approach to the Novel Refrigeration Systems

Most of the cryocoolers being commercially used at liquid helium temperature have a JT loop as a final stage of the cooling system. However, a couple of attractive methods are now being investigated. An investigation of superconducting and cryogenic technology was conducted by the Science and Technology Agency in 1982. In this program, studies of high performance cryocoolers (related to Stirling cycle) and magnetic refrigerators were included.

#### 4.1 Stirling Cycle

In the development of the Stirling cycle, there are some similarities between the prime mover and cryocooler. Figure 10 is presented by Ishizaki (ECTI). As a prime mover, he developed the miscellaneous Stirling engines of output power below 50 kW ((a) of figure 10), the cold energy application system of LNG (b), and a hybrid system using LOX and liquid hydrogen (c) [3, 4]. As for the cryocooler, the most popular two stage cycle (d) were used for several applications where the cooling temperature was above 10 K. He also investigated a cryocooler operating at the liquid phase of helium (e).

According to the program of the Science and Technology Agency, the R & D of high performance Stirling cryocooler is now in progress at JNR, in cooperation with the Aisin Seiki Co. and ECTI. Figure 11 shows the single stage Stirling cycle operating below 15 K. The hot end temperature of the regenerator was maintained at a constant, using the evaporating gas from the liquid helium. The relation between the hot and cold end temperature is shown in figure 12. These figures indicate that the rare earth compounds (Gd-Er-Rh) when used as regenerator material improve the regenerator efficiency when it works below 15 K. The lowest temperature achieved in this experiment on the rare earth compounds was 3.74 K at the lower limit of temperature oscillation, when the mean operating pressure was about 0.7 atm and the hot end temperature was about 8K. They also confirmed that the cooling system can obtain near 4 K by using the two stage Stirling cycle when the hot end temperature maintained near 30 K.

### 4.2 Magnetic Refrigerator

The study of the magnetic refrigerator according to the Science and Technology Agency program is divided into three groups, a fundamental study of working materials (Institute of Metallic Material), a fundamental study of the refrigeration cycle (Tokyo Institute of Technology) and magnetic refrigeration systems (Toshiba Co.).

Figure 13 shows a schematic of the reciprocating magnetic refrigerator developed by the Toshiba Co. through this program. It consists of two sets of superconducting DC magnets and pistons with working materials (GGG). A two stage G-M cycle cryocooler (Air Products and Chemicals), USA) was used for the precooler of the working materials. The distance between the maximum and zero magnetic field is about 100 mm, which corresponds to the piston displacement, and is realized using field correcting magnets. All of the magnets are connected in series and operated at a permanent current mode after the initial excitation using detachable current leads. The experimental results of the test run are shown in figure 14 at the excitation current of 80 A and the maximum field of the working material of 4 Tesla. It indicates the increasing liquid helium level within the refrigeration space at each heat absorption process.

Hitachi Ltd. is also investigating a magnetic refrigerator which is operating between 20 K and 4 K, using a G-M cycle precooler and rotary moving method. Details may be obtained at the end of this year.

### 4.3 Component Technology

A study of regenerators below 20 K is now in progress at Nihon University and is supported by the program of the Science and Technology Agency. Thermal properties of regenerative materials which have a high specific heat below 20 K such as GdRh have been measured. To evaluate the effectiveness of the regenerator, a simple Vuilleumier cycle cryocooler was used. The minimum temperature of 5.4 - 6.5 K was obtained with this VM cooler. The details of these results will be given later in this proceedings.

Most of the compact heat exchangers, which can be used for a small Claude cycle cryocooler or JT loop precooled by a regenerative cryocooler, have been made by the perforated aluminum plates and plastic separators, however, Hitachi Ltd. recently developed a new heat exchanger made by a diffusion bonding method using perforated cooper plate and SUS304 separators, which has a similar cross section shown in figure 5. They reported that the axial conduction loss of this heat exchanger is greater th an that of epoxy bonding type, although the total heat transfer effectiveness is not decreased significantly when it is used at high Re number.

Showa Seiki Industries, in cooperation with Tohoku University and ECTI, developed a small oil free compressor, constructed by three stage reciprocal pistons and swash plate mechanism with a diaphragm for separating oil. Input power is 750 watts and the helium gas pressure at the inlet and outlet are C.1 and 2.0 MPa with the flow rate of 2 $Nm^3$/hr. This compressor can be applied to the JT loop of the small cryocooler system for SQUID or other JJ devices.

### 5. Summary

Most of the cryocooler activities in Japan, at this time, seems to be aimed at the development of a compact and reliable cryocooler having several watts at liquid helium temperature. It will depend on the progress of the small superconducting magnet applications such as super LSI pattern printing devices, the single crystal drawing controller and the superconducting NMR-CT. Due to the improvement of the superconducting materials, the allowable cooling temperature is nearly 10 K, however, in considering the cooling temperature stability, the latent heat of the liquid helium is still attractive.

Miniature cryocoolers for the IR-detector, SQUID or other JJ devices are not being investigated in Japan, except for some fundamental research. However, a conceptual study of the sensor technology for unexplored spectrum has been started by the Ministry of International Trade and Industry this year, which includes the study of IR-detector cooling system for space application. Research will be conducted next year at the Electrotechnical Laboratory.

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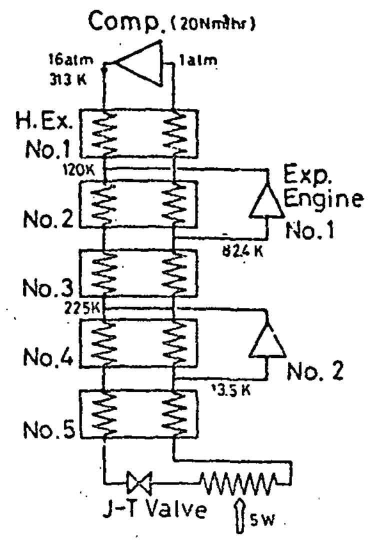



Fig. 1 Flow diagram of 4.5 K 5 watt Claude cycle

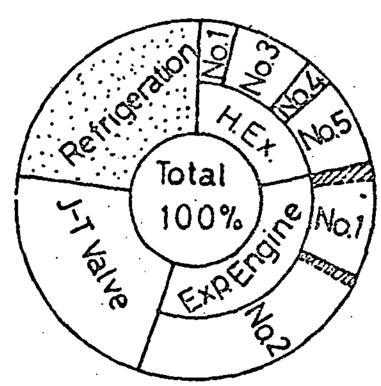



Fig. 2 Energy balance of the Claude cycle

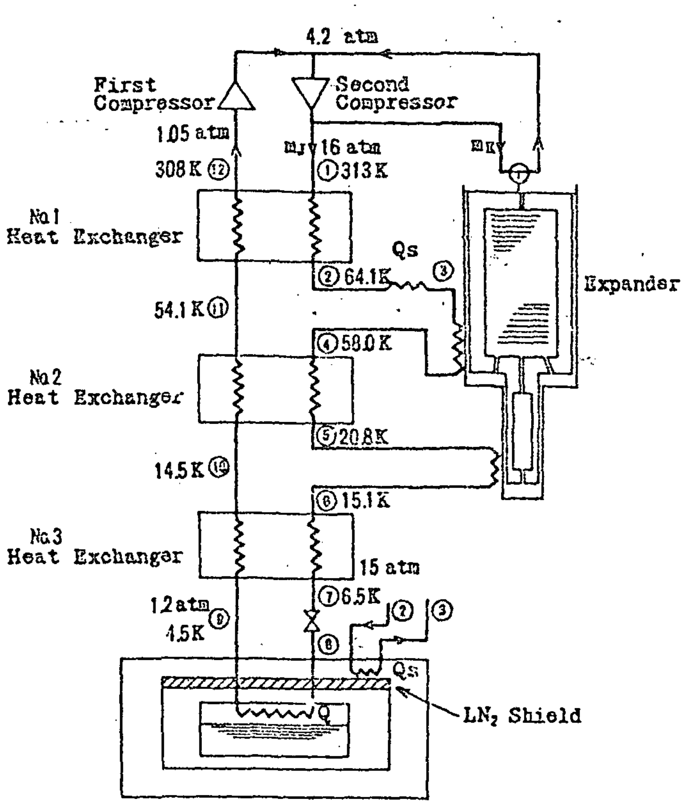



Fig. 3 4.5 K 6.5 watt cryocooler with JT loop precooled by G-M cycle

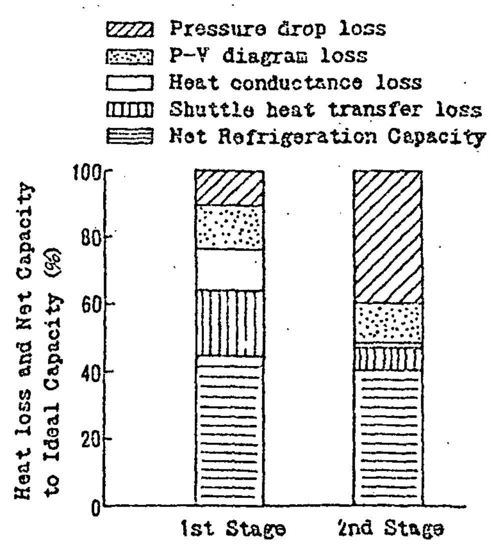



Fig. 4 Expander loss analysis of G-M cycle

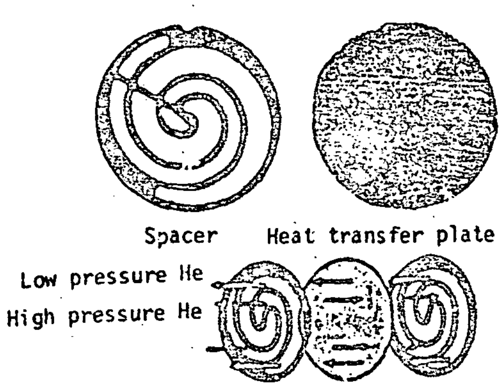



Fig.5 Cross section of scroll type heat exchanger

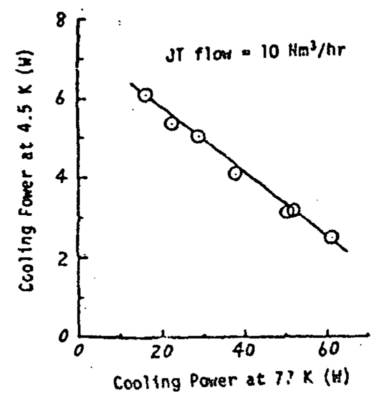



Fig.6 Cooling power dependency of 4.5 K and 77 K

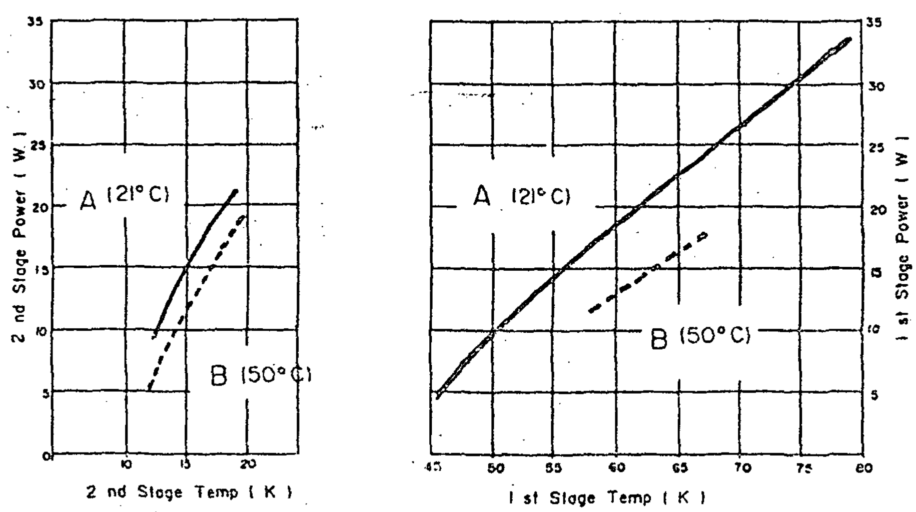



Fig.7 Ambient temperature effect of the G-M cooler performance

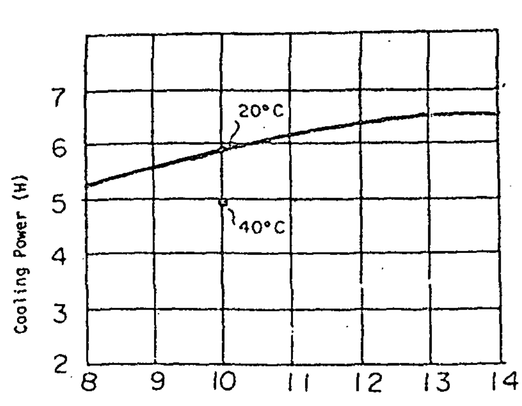
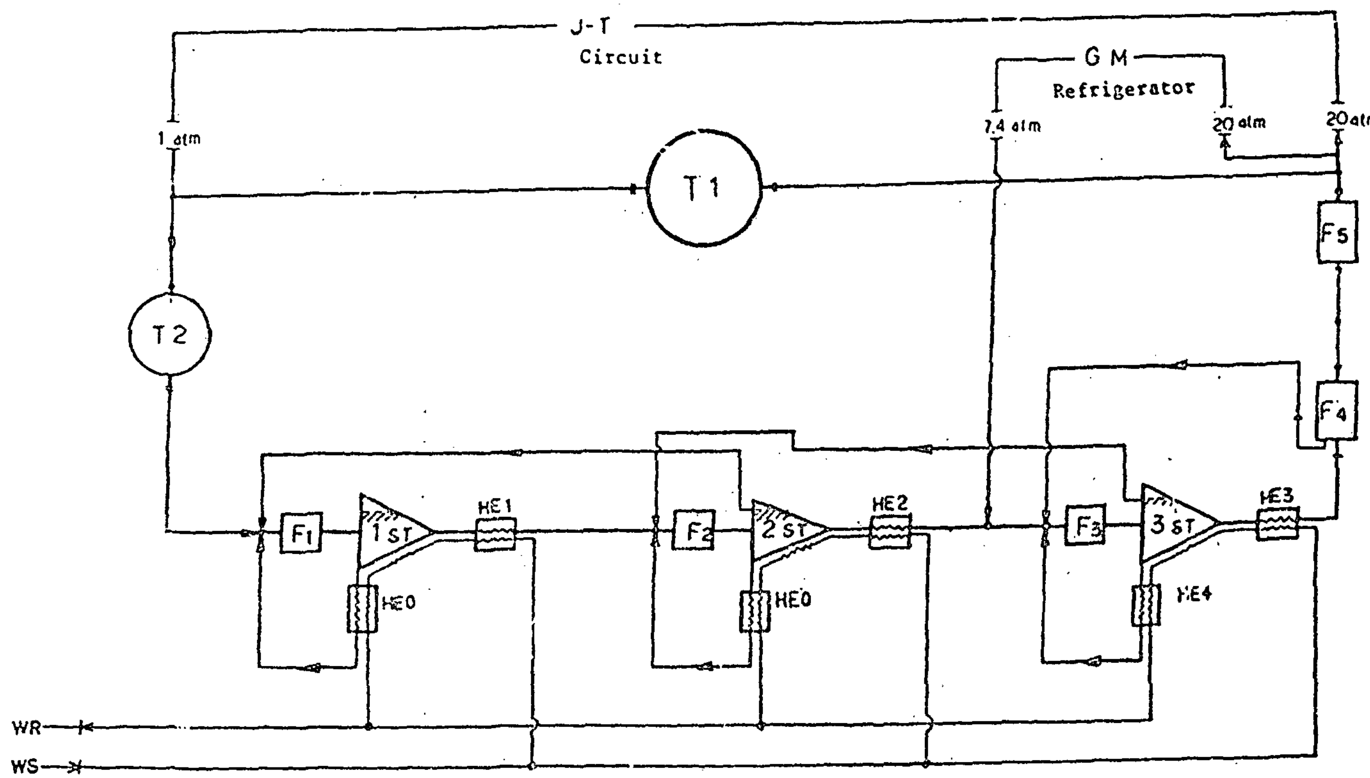



Fig. 8 Performance of 4.5 K cooler with JT loop precooled by G-M cycle




1ST.2ST.3ST; Compressor
HE; Heat Exchanger
F ; Filter
T ; Tank

WR; Water return
WS; Water supply

Fig.9 Flow diagram of three stage compressors

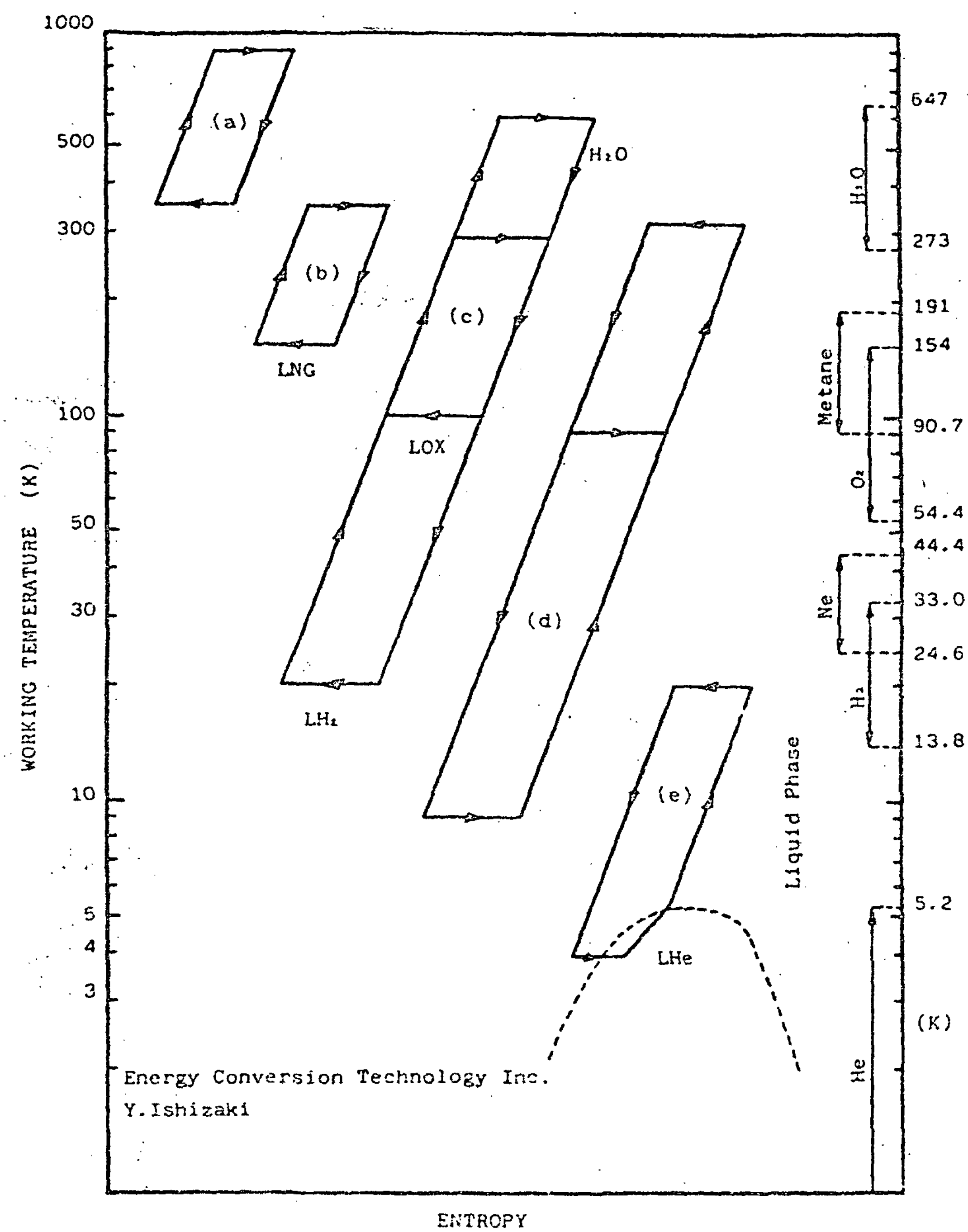



Fig.10 Schematic T-S diagrams of the Stirling cycle machines

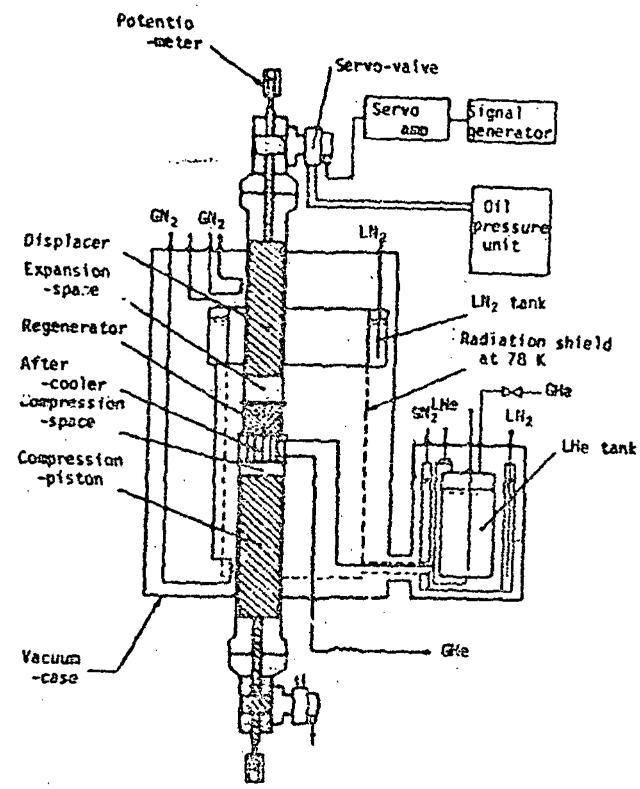



Fig.11 Single stage Stirling cycle operating below 15 K

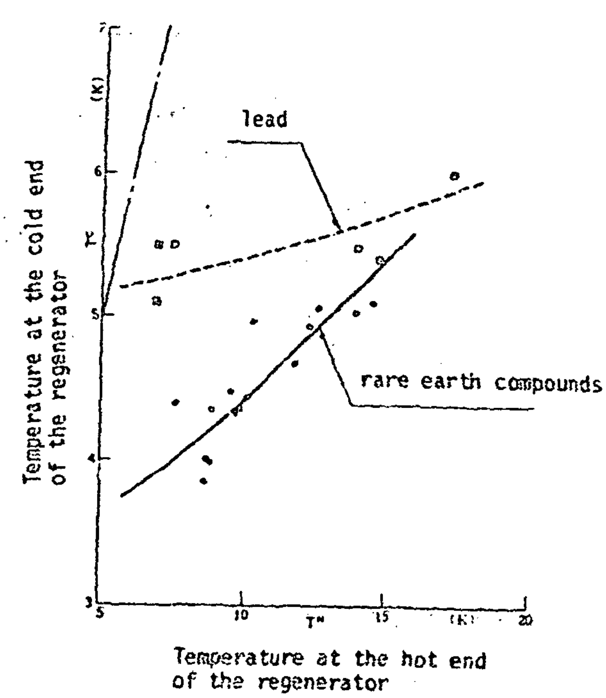



Fig.12 Test result of the Stirling cycle

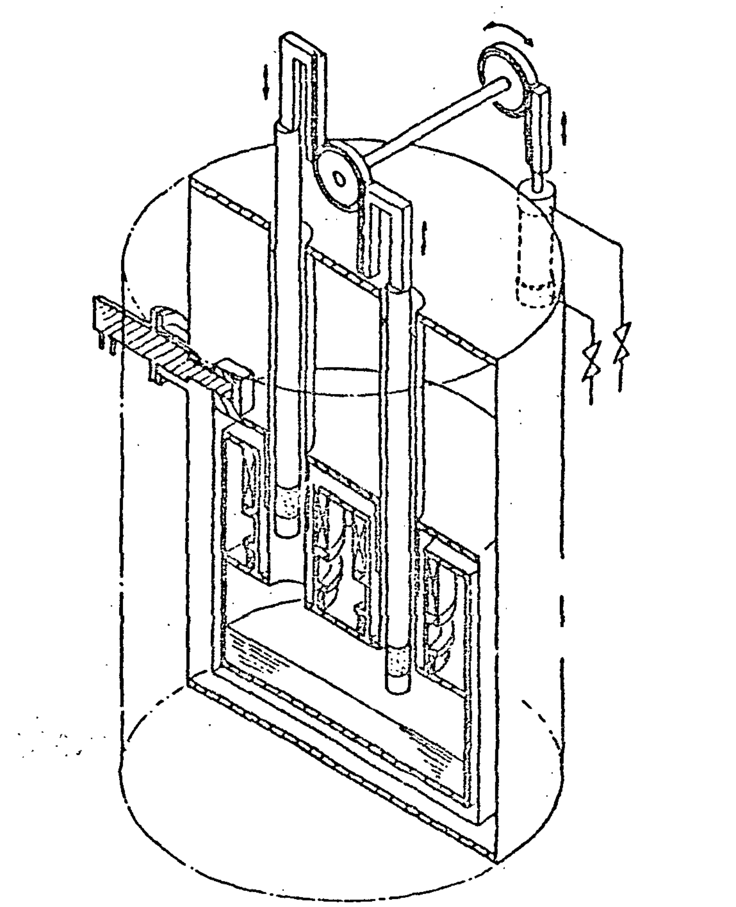


Fig.13 Schematic of the reciprocating magnetic refrigerator

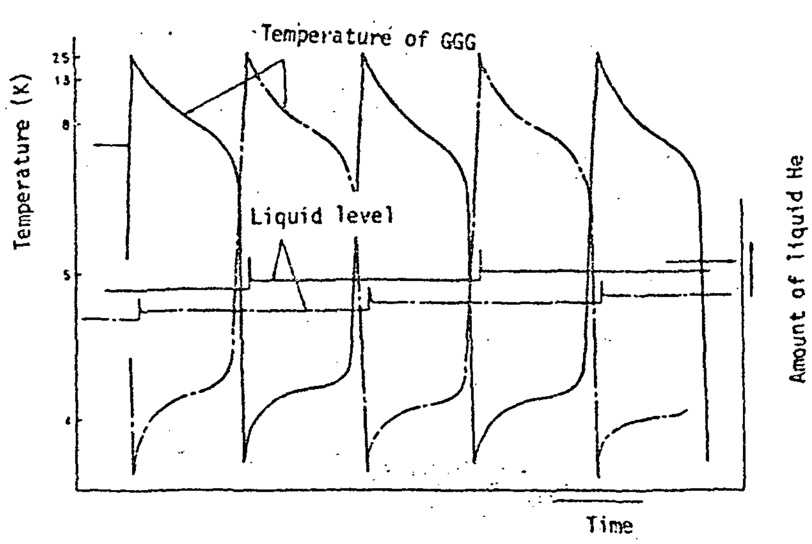



Fig.14 Test result of the magnetic refrigerator