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EVALUATION OF MAGNETOCALORIC CONVERTERS

by

J. DONEA, F. LANZA and E. VAN DER VOORT

1968

Joint Nuclear Research Center
Ispra Establishment - Italy

Physical Chemistry

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Choice is made of a practical cycle for which a preliminary dimensioning and a draft design are presented.

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SUMMARY

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KEYWORDS

POWER
FERROMAGNETIC MATERIALS
SUSPENSIONS
MAGNETIC FIELDS
TEMPERATURE
FLUIDS
THERMODYNAMICS
DESIGN

Contents

EVALUATION OF MAGNETOCALORIC CONVERTERS (+)

Part I: Thermodynamics of a ferrofluid and possible power cycles.

1. The ferrofluids

1.1 - Definition

Present day technological efforts succeed in producing liquids, in the laboratory stage, in which fine ferromagnetic particles of the order of a Weiss domain (100 Å) are brought in suspension in an oil medium. Macroscopically, due to viscosity and thermal agitation, such liquids, which will be called ferrofluids (FF), behave as if they had a reduced magnetization $M = \varepsilon \mathfrak{M}$ where $\mathfrak{M}$ is the magnetization of a Weiss domain of the pure ferromagnetic material and ε is a volumetric factor indicating how much of this material has been brought in suspension in the transporting liquid. The preparation of such a suspension in molten sodium is under study [2].

As a matter of fact, ferromagnetic particles having Weiss domain sizes orient the magnetization $\vec{M}$ with the magnetic field intensity $\vec{H}$ in a quasi-free rotation. Hysteresis effects are thus eliminated and it appears possible in theory to obtain Carnot efficiency for a converter based on the magnetocaloric effect applied to an FF.

1.2 - Ferromagnetic materials.

Ferromagnetic materials having a high saturation magnetization are Ni, Co, Fe and their alloys.

Due to its low Curie temperature, Ni was eliminated. Since none of the concepts in this paper has to be altered if Fe-Co alloys would be used, the discussion only will be pursued on pure iron and cobalt.

(+) Manuscript received on April 29, 1968.

1.3 - Thermal properties.

The bearing liquid of the ferromagnetic particles was chosen to be Na and the volumetric factor, for rheological reasons, has been fixed to $\varepsilon = 0.1$. Although there is a serious problem of physical chemistry to prepare a stable FF of this kind, it further will be assumed that such an FF is available.

The specific heat at constant field zero of these ferrofluids is:

for cobalt: $C_o = 1.27$ Joule/cm^3 - ^oK

for iron: $C_o = 1.24$ Joule/cm^3 - ^oK

The density is:

for cobalt: $\rho_o = 1.62$ gr/cm^3

for iron: $\rho_o = 1.51$ gr/cm^3

Both properties are considered as temperature independent.

The thermal conductivity of the FF is assumed to be that of liquid Na, namely: $k = 0.63$ Watt - cm^{-1} - $^oK^{-1}$.

1.4 - Weiss equation of state.

Considering the FF as incompressible and of invariable composition, its thermodynamical state is pressure independent and can be defined by only two independent variables, e.g. temperature and magnetic field.

Due to lack of experimental data on the magnetization of ferrofluids, the Weiss equation of state is used.

It correlates $\mathcal{M}$, H and T by the transcendental equation:

$$\frac{\mathcal{M}(H,T)}{\mathcal{M}_{sat}} = tgh \frac{\frac{H}{\alpha \mathcal{M}_{sat}} + \frac{\mathcal{M}(H,T)}{\mathcal{M}_{sat}}}{\frac{T}{T_c}}$$

In this equation $\mathcal{M}_{sat}$ is the saturation magnetization that is obtained when all free spins do align (magnetization at absolute zero); α is the molecular field constant and T_c is the Curie temperature. For iron and cobalt the following values were used [3]:

	$\mu_0 \mathcal{M}_{sat}$ (gauss)	α	T_c (°K)
Fe	21,870	710	1043
Co	18,150	1152	1404

2. Thermodynamical relations for a ferrofluid.

It is known that the specific heat at constant field strength of ferromagnetic material is lowered when this material is brought in a magnetic field. This is due to the alignment of the Weiss domains and allows to write the entropy variation of an FF as follows:

$$dS = dS_{th} + dS_{mag}$$

where S_{th} is the entropy due to thermal agitation and S_{mag} the entropy due to the ordering action of a magnetic field.

It has been proved [4] that:

$$dS_{th} = C_0 \frac{dT}{T}$$

and

$$dS_{mag} = \mu_0 \varepsilon \left[\int_0^H \frac{\partial^2 m(H,T)}{\partial T^2} dH \right] dT + \mu_0 \varepsilon \frac{\partial m(H,T)}{\partial T} dH .$$

where μ_0 is the permeability of vacuum.

From the above relations, expressions can be derived for heat input and output as well as for mechanical work [4].

Next it will be shown how to extract mechanical power by cycling the ferrofluid in the presence of a magnetic field through a range of temperatures. Three cycles will be discussed.

3. Power cycle consisting of two isothermals connected by two constant field legs (Type I).

3.1 - Schematic description of the cycle.

A converter has been proposed using the difference of work developed by an FF entering a magnetic field below its Curie temperature and leaving the field slightly above it.

This FF will indeed tend to move towards the highest magnetic field intensity produced in a solenoid. Heating the FF within the high field zone from a low temperature to roughly the Curie temperature of the ferromagnetic material in suspension, and assuming that the FF retains its fluidum characteristics in this temperature range, less energy is required to leave the solenoid than was transferred to the FF entering it. Cooling the FF out of the magnetic field, it can be cycled again towards the solenoid.

When the FF is attracted to the high field zone, kinetic energy is transferred to the FF from the B-H energy of the solenoid due to the fact that for higher field intensities the magnetization is increased. However, when the temperature of the FF is increased, this magnetic energy is returned to the solenoid because the magnetization then diminishes. Due to the magnetocaloric effect, heat must be extracted if the FF is brought isothermally into an increasing magnetic field intensity and added in the reversed case.

The difference in magnetic forces acting on the FF when it moves into the solenoid and when it is removed from it, confers to the FF a kinetic energy which would continuously increase (apart from friction losses) if a work extractor (e.g. MHD duct.) were not inserted in the cycle.

A converter of this kind, subsequently denoted by type I converter, is shown in figure (1) and the cycle the FF is effectuating is shown in the S-T diagram of figure (2).

In order to supply the necessary energy to heat the FF from T_1 to T_2 in the solenoid A, producing a magnetic field H_1, a secondary non-magnetic recuperation fluid (SF) circulates in a counter-current heat exchanger located in the solenoid.

The heat is given back to the SF out of the field in the heat exchanger B where the FF cools from T_2 to T_1.

In order to accomplish the heat transfer, a thermal drop ΔT_R must exist between the fluids in both exchangers. This gives rise to a heat input $2\, C_o \Delta T_R$ to the SF in the hot region and an equal heat output in the cold region. The SF is circulated by an electromagnetic pump P.

To permit isothermal in- and outlet of the FF in the solenoid, cold and hot sources (CS and HS) have to supply respectively:

$$\Delta_{12} Q = \varepsilon \mu_o T_1 \int_0^{H_1} \frac{\partial \mathfrak{M}(H,T)}{\partial T} \, dH$$

$$\Delta_{34} Q = - \varepsilon \mu_o T_2 \int_0^{H_1} \frac{\partial \mathfrak{M}(H,T)}{\partial T} \, dH$$

All heat quantities are expressed per unit volume of FF and per cycle.

3.2 - Efficiency of the cycle.

The total heat input is:

$$Q_{in} = \Delta_{34} Q + 2\, C_o \Delta T_R$$

Due to the fact that the specific heat of the FF is lower in the solenoid than outside, less heat is extracted from the SF in the high field region than is restored in the recuperative heat exchanger.

In order to get the SF temperature equal to $T_1 + \Delta T_R$ at the field exit, a supplementary amount of heat (SHE) has to be extracted from the SF. It has then been proved [4] that the total work extracted is:

$$\Delta W = \varepsilon \mu_0 \int_0^{H_1} \left[\mathcal{M}(H,T_1) - \mathcal{M}(H,T_2) \right] dH$$

Under these conditions, the total heat output is

$$Q_{out} = Q_{in} - \Delta W$$

and the efficiency is

$$\eta_{CF} = \frac{\varepsilon \mu_0 \int_0^{H_1} \left[\mathcal{M}(H,T_1) - \mathcal{M}(H,T_2) \right] dH}{2\, C_0\, \Delta T_R - \varepsilon \mu_0 T_2 \int_0^{H_1} \frac{\partial \mathcal{M}(H,T_2)}{\partial T} dH}$$

Using the Weiss equation of state, Q_{in}, Q_{out} and η_{CF} have been calculated for iron and cobalt.

The temperature range for the cycle was $T_1 = 0.6\ T_2$; $T_2 = T_C$. The magnetic field H_1 was 10^5 Oe.

The integrations were made numerically using the GAL routine (SHARE D1-IP-GAL). The results are given in table I.

Table I : Type I converter heat input and output.

[Joules - cm^{-3}]	Iron	Cobalt
Q_{in}	$9.9 + 2.48\,\Delta T_R$	$9.1 + 2.54\,\Delta T_R$
Q_{out}	$8.7 + 2.48\,\Delta T_R$	$8.0 + 2.54\,\Delta T_R$
ΔW	1.2	1.1

fficiency values are given in figure (3) as a function of ΔT_R. It an be seen that, for ideal heat exchange conditions ($\Delta T_R = o$), iron nd cobalt give the same converter efficiency $\eta_R = 12\ \%$; while for ractical values of ΔT_R, the cobalt cycle efficiency is somewhat lower han the iron converter efficiency.

. Power cycle consisting of two isothermals connected by two magnetic isentropic legs (Type II).

.1 - Magnetic field modulation.

t has been found, that modulating the magnetic field in such a manner o make the magnetic entropy variation dS zero [4], the heat exchanged etween points 2-3 and 4-1 can be made equal and that, with ideal heat xchangers ($\Delta T_R = o$), the Carnot efficiency can be obtained in principle.

The field H^* produced by the solenoid must satisfy the following first order differential equation in T:

$$\frac{\partial H^*(T)}{\partial T} = - \frac{\int_0^{H^*(T)} \frac{\partial^2 \mathcal{M}(H,T)}{\partial T^2} dH}{\partial \mathcal{M}(H^*,T)/\partial T}$$

Fig. (4) shows this magnetic field profile starting with a field of 2.14×10^5 Oe and with a temperature $T_1 = 0{,}6\ T_c$, having a mean field of 10^5 Oe.

The heats $\Delta_{23'}Q$ and ΔQ_{41} being equal in absolute value, one now has:

$$\Delta_{12} Q = \varepsilon \mu_0 T_1 \int_0^{H_1^*} \frac{\partial \mathcal{M}(H,T_1)}{\partial T} dH$$

$$\Delta_{3'4} Q = - \varepsilon \mu_0 T_2 \int_0^{H_2^*} \frac{\partial \mathcal{M}(H,T_2)}{\partial T} dH$$

where H_1^*, and H_2^* are respectively the field values of the modulated field $H^*(T)$ at T_1 and T_2.

4.2 - Efficiency of the cycle.

The total heat input now is:

$$Q_{in} = \Delta_{3'4} Q + 2 C_0 \Delta T_R$$

whereas, due to the vanishing amount of heat in SHE, the total heat output is:

$$Q_{out} = - \Delta_{12} Q + 2 C_0 \Delta T_R$$

giving for the total work extracted

$$\Delta W = - \varepsilon \mu_0 (T_2 - T_1) \int_0^{H_1^*} \frac{\partial \mathcal{M}(H,T_1)}{\partial T} dH$$

It can be shown that

$$\int_0^{H^*(T)} \frac{\partial \mathcal{M}(H,T)}{\partial T} \, dH$$

is temperature independent.

For the efficiency one gets:

$$\eta_{MF} = \frac{\eta_c}{1 - \dfrac{2 C_0 \Delta T_R}{\varepsilon \mu_0 T_2 \int_0^{H_1^*} \frac{\partial \mathcal{M}(H,T)}{\partial T} dH}}$$

where $\eta_c = 1 - \frac{T_1}{T_2}$ is the Carnot efficiency.

Numerical integrations using $T_1 = 0.6\ T_2$; $T_2 = T_{Curie}$, and a magnetic field profile such that its mean value is 10^5 Oe, gave the results of table II.

Table II : Type II converter heat input and output.

[Joules - cm^{-3}]	Iron	Cobalt
Q_{in}	$2.30 + 2.48\ \Delta T_R$	$1.90 + 2.54\ \Delta T_R$
Q_{out}	$1.38 + 2.48\ \Delta T_R$	$1.14 + 2.54\ \Delta T_R$
ΔW	0.92	0.76

Efficiency values are given in figure (3) as a function of ΔT_R. The Carnot efficiency is obtained for ideal heat exchange conditions. For practical values of ΔT_R, the converter based on iron suspension, appears to be more attractive: for a reasonable value of $\Delta T_R = 2^{\circ}C$, one gets $\eta_{Fe} = 12.7\ \%$ and $\eta_{Co} = 10.9\ \%$.

Type II cycle has been drawn in the T-S diagram of figure (2).

5. The Brayton cycle (Type III).

5.1 - Definition and practical advantages.

This cycle differs from type II in that the magnetic field inlet and outlut are no more isotherms but adiabatics (in the sense of thermal and magnetic entropy). The effectuated cycle is indicated on the T-S diagram of figure (2).

Obviously this cycle is more suitable for applications than type II. Indeed, the heat exchangers HS and CS, fig. (1), at the solenoid in- and outlet are no more necessary and only the SF has to circulate through the heat input and output modules. This represents a great advantage from a constructive point of view.

5.2 - Efficiency of the cycle.

Due to the adiabatic entrance in the magnetic field, the temperature of the FF just before entering the solenoid will be $T_1 + \Delta T_1$ instead of T_1 with the type II converter. If the high temperature is T_2, the FF will be at $T_2 - \Delta T_2$ at solenoid exit.

Following the notations of figure (2) and without regeneration, the result is, assuming one goes along the curve $H = H^{*}(T)$:

$$\Delta_{2'3'} Q = C_0 \left[T_2 - T_1 - \Delta T_1 \right]$$

$$\Delta_{4'1'} Q = C_0 \left[T_2 - T_1 - \Delta T_2 \right]$$

In a practical case, the amount of heat:

$$\Delta_{reg} Q = C_0 \left[T_2 - T_1 - \Delta T_1 - \Delta T_2 - 2\Delta T_R \right]$$

can be regenerated (see figure 5).

Hence

$$Q_{in} = \Delta_{2'3'} Q - \Delta_{reg} Q = C_0 \left[\Delta T_2 + 2\Delta T_R \right]$$

$$Q_{out} = -\Delta_{4'1} Q - \Delta_{reg} Q = C_0 \left[\Delta T_1 + 2\Delta T_R \right]$$

giving for the efficiency:

$$\eta_B = \frac{1 - \dfrac{\Delta T_1}{\Delta T_2}}{1 + \dfrac{2\Delta T_R}{\Delta T_2}}$$

The temperature differences ΔT_1 and ΔT_2 can be found expressing that the line integrals of the entropy over the closed curves 122' and 3'4 4' are zero.

This gives, neglecting the exponentials after the third term:

$$\frac{\Delta T_1}{T_1} = \frac{|\Delta_{12} Q|}{C_0 T_1} + \frac{1}{2} \frac{|\Delta_{12} Q|^2}{C_0^2 T_1^2} + \ldots\ldots$$

and

$$\frac{\Delta T_2}{T_2} = \frac{|\Delta_{3'4} Q|}{C_0 T_2} - \frac{1}{2} \frac{|\Delta_{3'4} Q|^2}{C_0^2 T_2^2} + \ldots\ldots$$

It has been shown [4] that

$$\frac{|\Delta_{12} Q|}{C_0 T_1} = \frac{|\Delta_{3'4} Q|}{C_0 T_2} = \alpha$$

and defining α as the common quantity, we may write:

$$\Delta T_1 = \alpha T_1 \left[1 + \tfrac{1}{2}\alpha + \cdots \right]$$

$$\Delta T_2 = \alpha T_2 \left[1 - \tfrac{1}{2}\alpha + \cdots \right]$$

It can be seen that this approximation is fairly good, indeed, in our case we have e.g. for iron, for $T_1 = 0.6\ T_c$, $T_2 = T_c$ and $H_1^* = 2.14 \times 10^5$ Oe (Table II):

$$\alpha = 1.78 \times 10^{-3} \ll 1$$

From this the efficiency results to:

$$\eta_B = \frac{\eta_c - \alpha \dfrac{T_1}{T_2}}{1 - \dfrac{2\, C_0\, \Delta T_R}{\varepsilon \mu_0 T_2 \int_0^{H_1^*} \dfrac{\partial \mathcal{M}(H,T_1)}{\partial T}\, dH} \left[1 + \frac{1}{2}\alpha\right]}$$

Comparing η_B and η_{HF}, one may say that in practice type III converter has the same efficiency as type II, but is much more suitable for realization.

For the Brayton cycle in connection with a constant field, a similar mathematical development can be performed. According to figure 2, we can foresee that adiabatic in- and outlet of the solenoid cause somewhat higher ΔT_1 and ΔT_2, but always of the same order of magnitude. We can therefore conclude that replacing isothermal legs by isentropic ones, does not influence appreciably the efficiency.

6. Choice of the ferrofluid.

The choice of the FF not only has to be based on efficiency considerations. A very important practical parameter is the ratio of the produced mechanical work over the amount of heat transferred between both fluids at zero field per unit volume of FF and per cycle, called working ability:

$$\Lambda = \frac{\Delta W}{C_0 (T_2 - T_1)}$$

Working with the modulated magnetic field, this leads to:

$$\Lambda = - \frac{\varepsilon \mu_0}{C_0} \int_0^{H_1^*} \frac{\partial m(H, T_1)}{\partial T} \, dH$$

Knowing that the integral in the righthand member is temperature independent, and that the same is true for Λ, one may say that with magnetic field modulation, each part of the solenoid has the same working ability.

However, fixing H_1^* , Λ will increase as T_1 approaches T_c but the efficiency will decrease.

Comparing the working ability for iron and cobalt under the same working conditions, one obtains the results of table III for $H_1^* = 2.14 \times 10^5$ Oe; $T_1 = 0.6\ T_c$.

Table III : Working abilities

	$C_o(T_2-T_1)$ [Joule-cm^{-3}]	ΔW [Joule-cm^{-3}]	Λ
iron	517	0.92	1.77×10^{-3}
cobalt	714	0.76	1.06×10^{-3}

Consider now two converters with identical Carnot efficiency having the same solenoid and the same heat exchangers working respectively with Fe and Co based FF's.

Due to the difference in heat transferred between the FF and the SF for Fe and Co, the ratio of the times τ required for cycling the FF's is, according to table III:

$$\frac{\tau_{Co}}{\tau_{Fe}} = 1.38$$

Furthermore, the mechanical work produced by these converters being different too, the ratio of the extracted mechanical power for both FF's is:

$$\frac{\text{Power}_{Fe}}{\text{Power}_{Co}} = \frac{(\Delta W)_{Fe}/\tau_{Fe}}{(\Delta W)_{Co}/\tau_{Co}} = \frac{\Omega_{Fe}}{\Omega_{Co}} = 1.67$$

This clearly indicates that for the same Carnot efficiency, iron has to be preferred.

Further advantage of using iron derives from the fact that it works in a temperature range for which material problems are well solved.

We know that in the cycle using constant magnetic field the relative values for cobalt and iron of the working ability are in the same ratio as the available power. Besides, the absolute value of Ω will increase slightly with respect to the modulated field cycle. In this case the work extracted per cycle is about 10 % higher, while the heat exchanged in the solenoid is only slightly diminished. As a matter of fact, the magnetic field is higher for type I converter in the region (around T_o) where $\frac{\partial \mathfrak{M}}{\partial T}$ has the highest values.

7. Conclusion

The thermodynamical study allows to conclude that iron is the best ferromagnetic material for a magnetocaloric converter.

We are not able to select the best cycle. Each cycle can be characterized by two parameters: the thermodynamical efficiency and the working ability. The constant field system has a higher working ability but a lower efficiency. The reverse is true for modulated field system.

Only economical considerations will permit the selection of the best one. In both cases, using Brayton cycles doesn't change appreciably the efficiency or the working ability, and provides an interesting flow sheet simplification.

Part II : Dimensioning of an iron based converter for space use.

1. Introduction

In this part we only shall consider magnetocalorio converters for space use. Other possible applications (topping devices) will be discussed in part III.

For space applications, the most critical parameter is the specific power of the device, i.e. the power per unit weight.

In order to get an idea of the practical size and weight of a magneto-caloric converter, a preliminary evaluation was carried out for iron based converters.

We think that it is too early to optimize the system due to lack of knowledge on practical ferromagnetic suspensions and the continuous improvement existing in the field of superconductors and MHD technology.

A comparison was made only between type I and III. It will be shown that type III is more attractive. However, for computation the formulas developed for type II have been used as they lead practically to the same results. Some general considerations will be made on the main components of the circuit. A pictural view of the proposed assembly is shown in fig. 11.

2. The superconducting magnet.

We have seen in the preceeding part that the work which can be extracted per cycle is directly proportional to the applied magnetic field and to the volume fraction ε of ferromagnetic material in the suspension. The maximum value of ε is determined by the rheological properties of the suspension.

Going to very high magnetic fields (10^5 Gauss) the classical electromagnets using copper coils have unacceptable power consumption: e.g. a solenoid producing a field of 126 K Gauss in a space of $\emptyset$ 2.5 cm x 15 cm requires a power of 1.88 M Watt [5]. We are thus obliged to use a superconducting solenoid.

However, the produced field is limited due to the fact that the field component perpendicular to the current cannot exceed some critical value over which the superconducting properties of the material are destroyed. The critical field of superconductors are 70 K Gauss for coils made with a Nb-Zr alloy, 120 K Gauss for a Nb-Ti alloy and 200 K Gauss for Nb_3Sn [6].

The last material is now the most used for high field solenoids. Another material $V_{2.95}$ Ga is under study and presents by extrapolation a critical field higher than 500 K Gauss [7]. Actually solenoids producing fields of 100 K Gauss are commercially available. It seems, though, that in the near future, fields of 200 K Gauss obtained with Nb_3Sn coils will be available [8].

Up to now these solenoids have been constructed with small diameters but no conceptual difficulties are apparent for increasing the diameter.

Actually there is a gain in using solenoids with larger dimensions. If we look at solenoids having a length-diameter ratio sufficiently high, the high field volume is proportional to the square of the radius, whereas the volume of the superconducting material is directly proportional to this radius due to the fact that coil thickness is radius independent. We therefore have to use the biggest technologically possible solenoids. The first difficulty arises with the wire length. At the beginning it became clear that the critical current - critical field characteristics of long wires were inferior to that of small ones. This was due to metallurgical inhomogeneities. Actually this dispersion has been minimized and 800 m long wires can be obtained with satisfactory characteristics. There do not seem to exist substantial difficulties for obtaining longer ones. The technological limit probably is given by the mechanical resistance of the coil to the magnetic forces. Inside the solenoid an equivalent magnetic pressure P_m is developed equal to

$$P_m = \frac{B^2}{2\mu_0}$$

giving in the coil a mechanical stress directly proportional to the diameter. Such a limit, however, is rather high due to the good mechanical properties of superconductors: e.g. ZrNb wires have a yield stress of 220 kg/mm^2 at 77°K [9].

For the dimensioning of the circuit the solenoid has been assumed with the same dimension (Ø = 15; l = 70 cm) as in [1] for sake of comparison. The total weight of the solenoid has been assumed 100 kg.

3. The heat source.

For space applications of magnetocaloric power, the heat source may be either a nuclear reactor or a radio-isotope source.

The main characteristics of possible radio-isotope sources are given in table IV taken from reference [10].

Co^{60} potential is discussed in [11]. The thermal output being equal, cobalt has advantages over reactor systems, including potentially long operating life, greater reliability and lower weight. That is why we shall use in the following evaluation a Co^{60} source. Furthermore, test quantities of Co^{60} with specific activities of more than 400 Curies/g are now being produced, indicating the feasibility of making very compact heat sources. We can therefore expect in a near future a considerable improvement in the hot source characteristics. Source shielding has not been considered. In case of manned space flights the heat source will be manufactured in a way to have an important self-shielding and it could be located in such a manner to require little shielding. For unescorted flights shielding problems are less important.

Table IV : Characteristics of radioisotopic heat sources.

	Co^{60}	Sr^{90}	Cs^{137}	Ce^{144}	Pm^{147}	Po^{210}	Pu^{238}
Half-life, yr	5.27	27.7	26.6	0.78	2.62	0.38	86.4
Compound form	Metal	$SrTiO_3$ SrO	Glass	Ce_2O_3	Pm_2O_3	Metal	PuO_2
Watts/g compound	2.9	0.22 0.39	0.074	2.7	0.27	140	0.39
Shielding required	Heavy	Heavy	Heavy	Heavy	Minor	Minor	Minor
Present price, $/W	26	30	26	19	558	780	1,600

4. The radiator.

The only way by which heat can be dissipated from a space vehicle is by thermal radiation.

To take advantage of the fourth power relationship between temperature and radiated heat flux, the cold source temperature has been fixed to $T_1 = 0.6\ T_o = 626^oK$.

A lower temperature would give a somewhat higher magnetization variation during thermal cycling of the ferrofluid, but would be prohibitive for keeping the radiator size within reasonable limits.

The Stefan-Boltzmann law gives for the radiated heat flux:

$$Q = \varepsilon_r \sigma_o \left(T_1^4 - T_o^4 \right)$$

Taking

$$\varepsilon_r = 0.9$$

$$T_1 = 0.6\ T_c = 626\ ^\circ K$$

$$T_o = 273\ ^\circ K$$

one has

$$Q = 7.7\ Kw/m^2$$

This last relation gives the radiator surface area as a function of the dissipated power. The wall thickness of the radiator tubes has been taken, according to [12], 2mm in order to minimize tube puncture by meteoroids.

5. The MHD load.

A very interesting characteristic of the proposed cycle is that the available energy is obtained as a liquid pressure or kinetic energy.

Since the suspension medium is a liquid metal and since we are already using very high magnetic fields, we are in the best conditions to use an MHD generator.

We do not want to give a complete design of anMHD generator but to draw only the principal features of such a machine.

The principle of the energy conversion in an MHD generator is the same as in a classical electrical current generator. Both utilize the electromagnetic induction. The current generation is due to the displacement of a conductor in a magnetic field. In the most common design of an MHD generator, the liquid metal flows in a rectangular tube; the magnetic field is perpendicular to the axis of the tube; the electrodes, which collect the current, are perpendicular to both. In practice the main difference with an alternator is that instead of having a rotational motion of a solid conductor we have a traslational movement of a liquid conductor.

The geometry of the duct has a very important influence on the generator efficiency.

If we assume, that the liquid motion is laminar and that the length l of the channel is much longer than its width a, and its height b, ($l \gg a \gg b$), an ideal generator with non conducting walls and without end losses has an efficiency of

$$\eta = \frac{1}{1/\gamma + 1}$$

where γ is the ratio between the load resistance R_o and the internal resistance R_i.

We can write also

$$\eta = \frac{R_o}{R_o + R_i} = \frac{R_o}{R_o + \frac{a}{\sigma . b . l}}$$

where σ is the liquid metal electrical conductivity.

We see thus that to obtain a high efficiency we have to use a narrow rectangular duct. The influence of length is more evident when we take into consideration the end losses assuming that the magnetic field terminates sharply at the end of the electrodes; then the efficiency becomes [13]:

$$\eta = \frac{1}{\frac{1}{\gamma} + 1 + 2a \log 2 / \pi l}$$

Some calculations show that for ideal efficiency lying between 80 and 99 %, an $\frac{l}{a}$ ratio of 10 causes a loss of two points but a ratio of 100 causes a loss of only 0.2 points.

The load voltage is given by the following equation

$$V = \eta \, a \, v \, B_0$$

and the total current is

$$I = (1-\eta) \, \sigma \, b \, l \, v B_0$$

The power density in the duct is then

$$P = \eta (1-\eta) \, \sigma \, v^2 \, B_0^2$$

where v is the mean velocity of the liquid metal and B_o is the applied magnetic inductance.

The use of high velocity is unconvenient, because if we have a turbulent flow we decrease the efficiency. To keep the power density high, we will have to use a superconducting magnet.

The parallel plate geometry is not ideal for the superconducting coil, since it requires a considerable amount of iron which increases the weight of the system. The best utilization of a magnet using super-conductor wires, especially if weight is at premium as in spatial use, is the solenoid.

A good geometry allowing the use of the solenoid is the helix. If the conducting fluid flows in an helical duct limited by two cylindrical surfaces, and the magnetic field is parallel to the cylinder axis, like in a solenoid, a voltage is developed between the axis and the surface of the cylinder.

Such a geometry can be obtained with a very simple design. The electrodes are constituted by the two tubes defining the cylindrical surfaces of the helix; the separation between consecutive turns is made with an alumina helix. An absolute tightmess between the tubes and the alumina is not needed.

As a first approximation we can use the formulas developed for the straight duct even for the helicoidal one. This approximation is more valid if the step of the helix is short and if the internal diameter is not very different from the external one.

Let us evaluate the principal dimensions of a MHD helicoidal system to be placed at the entrance of the solenoid for the magnetocaloric conversion using then the maximum field. To avoid turbulent flow, velocity will be very low, 0,2 m/s. The yield is assumed 0.8. If we take a 2°C temperature drop in the heat exchangers, the power developed in the MC converter is 7 Kw of which 5 % is used to pump the suspension. The net electrical output of the MHD will be 5,3 Kw.

Table V gives the general dimensions.

Table V

magnetic field flow	213,000	Gauss
tangential flow velocity	0,2	m/s
total flow velocity	0,21	m/s
electrical conductivity of Na	$5 \cdot 10^{6}$	$^{-1}, m^{-1}$
el. cond. of suspension	$4.5 \cdot 10^{6}$	Ω^{-1}, m^{-1}
power density	10,35	W/cm^{3}
ext. diameter	100	mm
int. diameter	35	mm
height of the cylinders	67	mm
spiral path	10	mm
voltage	0,12	V
total current	4420	A
insulant volume	10	%
efficiency or yield η	78,8	%

The generated voltage is quite low. An increase of the voltage can be obtained by increasing the distance between the two electrodes or decreasing the conductance or the medium, e.g. using Na-K mixture instead of pure Na.

6. The heat exchangers.

The amounts of heat exchanged between the FF and SF into the solenoid and in the regenerative heat exchanger are equal in case of a type II converter and nearly equal in case of a type I converter.

Since the heat exchanger located in the superconducting magnet has the most critical size, we consider only this one.

We shall consider a plate type heat exchanger with counter current flow.

As can be seen from figure (6), the modular unit of the heat exchanger is made of plane sheets separated by corrugated sheets.

The arrangement of the units is such that each triangular cell is in contact through its walls with 3 cells containing the other fluid.

The sheets are assembled in such a manner that the heat exchanger has a polygonal cross section delimitated by a circle which, in first approximation, has the same diameter as the thermal insulation of the superconducting solenoid.

The free space between the polygom and the circle is used to separate the two fluids at the exchanger in- and outlet.

In each unit, the corrugations of the interposed sheet stop at a certain distance from the heads. The interposed sheet is then bent and welded to one of the plane sheets so that the SF can flow through the hole section of the exchanger. The SF is collected axially by a tube welded to the polygonal perimeter.

The FF on the contrary flows out laterally through openings allowing its collection in the annular space between the heat exchanger and the thermal insulation.

Neglecting thermal conductance across tube wall, the heat transfer coefficient for turbulent flow of a liquid metal in a tube of hydraulic diameter d can be evaluated on the basis of a constant Nusselt number [14]:

$$Nu = \frac{h \cdot d}{k} = 8$$

Since there are two films, the film heat transfer coefficient is effectively h/2.

Taking flow cross sections of both fluids equal, and FF and SF velocities such that:

$$\frac{v_{FF}}{v_{SF}} = \frac{c_{SF}}{c_{FF}}$$

i.e. with numerical values of paragraph 1.4 (part I):

$$v_{SF} = 1.24\ v_{FF}$$

The temperature profiles of both fluids are parallel straight lines.

Let l be the heat exchanger length, c the triangular tube side and ΔT_R the temperature drop between fluids to get heat transfer; one must have:

$$v_{FF} \cdot c_{FF} \cdot (T_2 - T_1) \cdot \frac{\sqrt{3}\, c^2}{4} = 12 \sqrt{3}\ h \cdot l \cdot \Delta T_R$$

or

$$\frac{l}{v_{FF}} = \frac{c_{FF} \cdot (T_2 - T_1) \cdot d^2}{16\ k\ \Delta T_R}$$

with $d = \frac{\sqrt{3}}{3} \cdot c$ = hydraulic diameter.

The quantity $\frac{l}{U_{FF}}$ gives the time required to cycle the FF. It clearly appears that, to increase the mechanical power, one has to have the hydraulic diameter d as small as possible and ΔT_R as high as possible.

However, any increase in ΔT_R implies supplementary heat input and reduces accordingly the efficiency of the converter. Furthermore, too small tubes lead to excessive friction losses.

An intermediate solution consists of establishing beforehand the fractional power necessary for pumping.

7. Friction losses.

Assume that the total length of the converter is $3l$, where l is the length of the superconducting solenoid.

The frictional drag on both sides of all pipes gives rise to a net force:

$$F_f = \frac{1}{2} f \cdot \rho_{FF} \cdot U_{FF}^2 \cdot 9 c l$$

where f is the friction coefficient.

The net force on the ferrofluid due to magnetic pumping action of the solenoid is:

$$F_m = \frac{\sqrt{3}}{4} c^2 . \Delta W$$

Putting

$$F_f = \alpha F_m$$

where α is the fractional power necessary for pumping the ferrofluid, one gets the following relation:

$$\frac{l}{d} = \frac{\alpha \cdot \Delta W}{6f \cdot \rho_{FF} \cdot U_{FF}^{2}}$$

It has to be noted that no pump is needed in the FF circuit since a fraction of the pressure rise obtained by magnetocaloric effect is used to overcome wall frictions.

8. Relations between the parameters characterising the converter.

The hydraulic diameter d and the side c of the triangular tubes are obtained by eliminating the velocity U_{FF} between the relations giving $\frac{l}{U_{FF}}$ and $\frac{l}{d}$. The numerical values of f and α are assumed to be respectively 0.01 and 0.05.

Once d is known, the fluid velocities U_{FF} and U_{SF} are easily obtained. Taking the flow cross sections S of both fluids equal, one finds:

$$2S = \frac{\pi D^{2}}{4} - S_{w}$$

where D = inner diameter of the solenoid thermal insulation

S_{w} = wall cross section.

Denoting by e the corrugated sheets' wall thickness, one has approximately:

$$S_{w} = \frac{3\pi D^{2}}{12 + 2\sqrt{3}\, c/e}$$

and for the flow cross section of the fluids:

$$S = \frac{\pi D^{2}/8}{1 + 2\sqrt{3}\, e/c}$$

The total surface of heat exchange is then given by

$$S_{HE} = \frac{3\pi D^2 l}{12e + 2\sqrt{3}\,c}$$

Expressions can now be obtained for the hot and the cold source as well as for the mechanical power:

$$HSP = Q_{in} \cdot S \cdot U_{FF}$$
$$RP = Q_{out} \cdot S \cdot U_{FF}$$
$$MP = \Delta W \cdot S \cdot U_{FF}$$

Values for heat input and -output and for the mechanical work are given in table I for type I and in table II for type III converter.

9. Numerical values.

The numerical values are shown in table VII; for each value of ΔT_R, the first line corresponds to type I converter, the second one is relative to type III converter.

The input parameters are given in table VI.

Fig. (7,8) show the influence of ΔT_R on mechanical power and specific weight of type I and III converters. We can see that increasing the ΔT_R, the mechanical power increases steadily. On the contrary, due to the influence of the heat source and radiator weight the specific weight presents a minimum value for about $\Delta T_R = 2^{o}C$.

10) Conclusions

As we have stated in the introduction the dimensioning of the plant was not intended to be optimized, but only to give a basis of evaluation and comparison between different types of cycle. Table VII shows that with the assumed T_1, the radiator weight has a big influence, much more than the hot source. Hence the thermodynamical efficiency is very important, and as a consequence, the performances of the modulated field cycle are better.

The radiator weight decreases sharply when the temperature T_1 increases. In such a case the optimum may shift towards the constant field system.

For the calculated performances, we have obtained a specific power output of 22,4 W/kg. Such a value can stand a comparison with the performances of the advanced solar cells, around 50 W/kg [15].

We note, however, that on one hand many practical values were assumed rather arbitrarily, on the other hand the system has not been optimized nor specific experimental work has been conducted in order to improve the performances. Furthermore this system uses components, like e.g. the superconducting solenoid, and the MHD, that are still under study, and which only in the near future could benefit from the general progress in the technology.

Part III. Considerations on the use of a magnetocaloric cycle as a topping device.

Up to now we have discussed the applicability of the proposed cycles in connection with spatial use. We will discuss now its use as a topping device, to be coupled to a nuclear reactor. Actually, there are certain types of reactors, like helium cooled reactors (Dragon, HTGR) and sodium cooled fast reactors, which have a very high outlet coolant temperature. Such a temperature cannot be used to increase appreciably the thermodynamical yield of the water cycle, since this temperature is higher than the critical one and the heat stored in the fluid is only that due to the specific heat.

Hence it is worthwhile, to study an intermediate cycle to be interposed between the reactor and the water cycle as a topping device in order to increase the total efficiency.

Fig. (9) shows the proposed flowsheet to be applied in conjunction with a sodium cooled fast reactor.

It is a normal magnetocaloric conversion cycle of type III in which the reactor is the hot source and the classical water cycle the cold source.

The principal characteristic of such a cycle can be determined starting from two parameters: the thermodynamic efficiency and the working ability the last one being inversely proportional to the complexity of the plant.

Let us see how this parameter can be maximized.
In paragraph 6 first part we have seen that the working ability is

$$\Omega = - \frac{\varepsilon \mu_0}{C_0} \int_0^{H_1} \frac{\partial \mathfrak{M}(H,T)}{\partial T} \, dH$$

as a first approximation we can write

$$\int_0^{H_1} \frac{\partial \mathcal{M}(H,T)}{\partial T}\, dH = H_1 \frac{\partial \mathcal{M}(0,T)}{\partial T} = H_1 \frac{\mathcal{M}_{sat}}{T_c} \cdot \frac{\partial \tilde{\mathcal{M}}(0,\tilde{T})}{\partial \tilde{T}}$$

the last derivative can be easily calculated [4] as

$$\frac{\partial \tilde{\mathcal{M}}}{\partial \tilde{T}} = \frac{\tilde{\mathcal{M}}(1-\tilde{\mathcal{M}}^2)}{\tilde{T}(\tilde{T}-1+\tilde{\mathcal{M}}^2)} = \mathcal{F}(\tilde{T},\tilde{\mathcal{M}})$$

We can then write

$$\Omega = -\frac{\mathcal{M}_{sat}}{T_c} \cdot \frac{\varepsilon}{c_0} \cdot \mu_0 H_1 \cdot \mathcal{F}(\tilde{T},\tilde{\mathcal{M}})$$

The first factor is related to the choice of the ferromagnetic material in suspension, it has been yet maximized by the choice of iron.

We can vary only the coefficient ε and the magnetic field intensity. We have seen that it is not unreasonable to foresee in a not too far future the realization of fields of 500 K Gauss. This will increase by more than a factor of 2 the working ability of the circuit.

An increase of the volume percentage of ferromagnetic material seems very difficult if we keep, as a circulating ferrofluid, a suspension. Other methods can be used, for instance circulation of ellipsoids fitting closely into the tubes, and probably coefficients ε of the order of 0.8 can be reached.

Something more can be obtained from the $\mathcal{F}$ function. If we keep constant the maximum applied magnetic field, the $\mathcal{F}$ function increases with the increase of the low temperature (Fig. 10). However, in the same time the thermodynamical efficiency decreases. The final value of $\mathfrak{F}$ and as a consequence of Ω will come thus from an economical optimization. In a system of fixed power output the cost C of the Kwh will be

$$C = A_1 + A_2 \cdot \eta (T_1, \Delta T_R) + A_3 (\Delta T_R) \cdot \Omega (T_1)$$

A_1 depends principally on the cost of the system used to extract power i.e. from the MHD system. A_2 is related to the cost of the calories (we remember that also for a topping device the calories have a cost, it depends principally on the additional cost of the reactor system to increase the outlet temperature); A_3 depends on the cost of the heat exchangers and is a function of ΔT_R; also the solenoid cost has to be put in A_3 as the solenoid dimensions are determined by the heat exchanger.

We can see that we have to conduct an optimization based on two parameters, ΔT_R and T_1.

In order to evaluate the possibilities of such an application we have calculated the general characteristics of two topping devices, one based on high but actually feasible value of the magnetic field and the other on more futuristic parameters.

Table VIII gives the general characteristics of the two plants. The comparison has been made taking the main parameters of the heat exchanger, i.e. ΔT_R and U_{FF}, constant. The increase of H and ε not only causes a considerable increase of the working ability of the circuit but also of the thermodynamical efficiency.

The first plant presents a very high thermal flow in the heat exchanger while the power produced per unit volume of the solenoid is quite low. The future solution presents a decrease in the circulating heat, and in the fluid of the secondary circuit. It gives rise to a reasonable power density.

The solenoid volume seems always very large but can be surely diminished by a careful optimization.

Concluding, the future of the magnetocaloric topping device is strictly connected with the high magnetic field technology and depends on the possibility of obtaining a high volumetric factor.

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Table VI : Input parameter for converter dimensioning.

l	70 cm	Solenoid length and heat exchanger length
D	15 cm	Solenoid thermal insulation inner diameter
T_1	$353^{\circ}C$	Cold temperature
T_2	$770^{\circ}C$	Hot temperature
H	10^5 Oe	Magnetic field mean value
ε	0.10	Volume concentration of iron particles in sodium.
ρ_{SF}	0.81 gr-cm^{-3}	Secondary fluid density
e	0.2 mm	Heat exchanger plates wall thickness
t	2.0 mm	Radiator tubes wall thickness
p_s	2.9 Watt-gr^{-1}	Hot source specific power (Co^{60})

Table VIIa : Iron based magnetocaloric converters: dimensioning for types I and III.

ΔT_R	TYPE	d	c	U_{FF}	U_{SF}	S	$S_{H.E.}$	RSA	η
°C		mm	mm	$m\text{-}sec^{-1}$	$m\text{-}sec^{-1}$	cm^2	m^2	m^2	%
1	I	1.15	1.99	1.04	1.29	65.7	16.1	9.9	9.6
	III	1.21	2.10	0.94	1.16	66.5	15.4	3.1	19.2
2	I	1.52	2.63	1.20	1.48	70.0	12.9	14.8	8.0
	III	1.60	2.77	1.08	1.34	70.8	12.4	6.3	12.7
3	I	1.78	3.08	1.30	1.61	72.2	11.4	19.6	6.9
	III	1.88	3.26	1.17	1.45	73.0	10.8	9.7	9.4
4	I	2.0	3.46	1.38	1.71	73.6	10.3	24.4	6.0
	III	2.11	3.65	1.24	1.53	74.3	9.9	13.4	7.5
5	I	2.19	3.79	1.44	1.78	74.7	9.6	29.3	5.3
	III	2.30	3.98	1.29	1.60	75.4	9.2	17.4	6.3

ΔT_R	Thermal drop between FF-SF
d	Heat exchanger tubes hydraulic diameter
c	Triangular tubes side
U_{FF}	Ferrofluid velocity
U_{SF}	Secondary fluid velocity
S	FF and SF flow cross section
S.H.E.	Total surface of heat exch.
R.S.A.	Radiator surface area
η	Cycle efficiency

Table VIIb : Iron based magnetocaloric converters : dimensioning for types I and III.

ΔT_R	TYPE	FFW	SFW	TW	HSW	RW	TTW	MP	HSP	RP	SP	SW
°C		kg	kg	kg	kg	kg	kg	kw	kw	kw	$Watt\text{-}kg^{-1}$	$kg\text{-}kw^{-1}$
1	I	20.7	11.0	76.5	29.1	158.6	395.9	8.2	84.5	76.3	20.7	48.3
	III	21.0	11.2	73.6	10.2	49.8	265.8	5.7	29.7	24.0	21.4	46.6
2	I	22.1	11.7	61.9	42.8	236.8	475.3	10.1	124.2	114.2	21.0	47.5
	III	22.4	11.9	59.3	19.0	100.1	312.6	7.0	55.1	48.1	22.4	44.7
3	I	22.8	12.1	54.3	55.9	313.6	558.7	11.2	162.2	151.0	20.1	49.9
	III	23.0	12.2	52.0	28.5	155.2	370.9	7.3	82.6	74.8	21.1	47.6
4	I	23.3	12.4	49.4	69.1	390.4	644.6	12.2	200.3	188.3	18.9	52.8
	III	23.5	12.5	47.2	38.6	214.4	436.2	8.5	111.9	103.4	19.5	51.3
5	I	23.6	12.5	45.8	82.4	470.4	734.7	12.9	239.0	226.1	17.6	57.0
	III	23.8	12.6	43.8	49.2	278.4	507.8	9.0	142.7	133.7	17.7	56.4

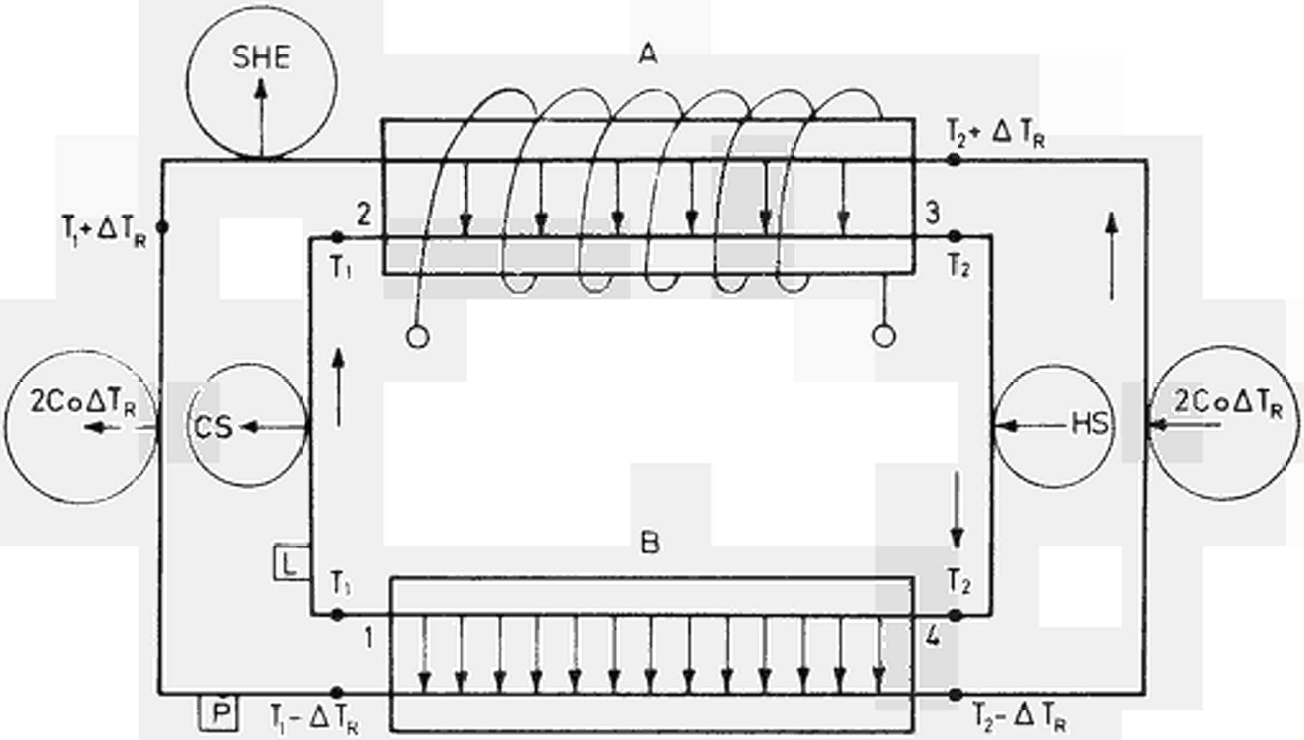
ΔT_R	Thermal drop between FF-SF
FFW	Ferrofluid weight
SFW	Secondary fluid weight
TW	Tubes weight
HSW	Hot source weight
RW	Radiatior weight
TTW	Total weight including 100 kg for the solenoid.
MP	Mechanical power
HSP	Hot source power
RP	Radiated power
SP	Specific power
SW	Specific weight

Table VIII

	actual feasible solution	future solution
Thermal power	1000 MW	1000 MW
Hot temperature T_2	770°C	770°C
Carnot effioiency (ηc)	0.4	0.4
Maximum magnetio field (H_1^*)	214 K gauss	500 K gauss
Volumetric Factor (ε)	0.1	0.8
Exchanger temperature drop (ΔT_R)	2°C	2°C
Thermodynamical efficiency	12.7 %	31.5 %
Electrical power (η_m = 0.76)	97 MWe	240 MW
Working ability (Ω)	1.73×10^{-3}	$1.33 \cdot 10^{-2}$
Thermal flow in heat exchangers	73 400 MWth	23.800 · MWth
Surface of heat exchanger	$5.25 \times 10^5 m^2$	$1.7 \times 10^5 cm^2$
Flow of ferrofluid	169 m^3/s	19.2 m^3/s
Assumed flow velocity	1 m/s	1 m/s
FF flow cross section	169 m^2	19.2 m^2
N_a flow cross section	210 m^2	55.2 m^2
Solenoid equivalent diameter	22 m	9.8 m
Power extr. per m^3 of solenoid	0.356 MWe/m^3	4.6 MW/m^3

Figure 1

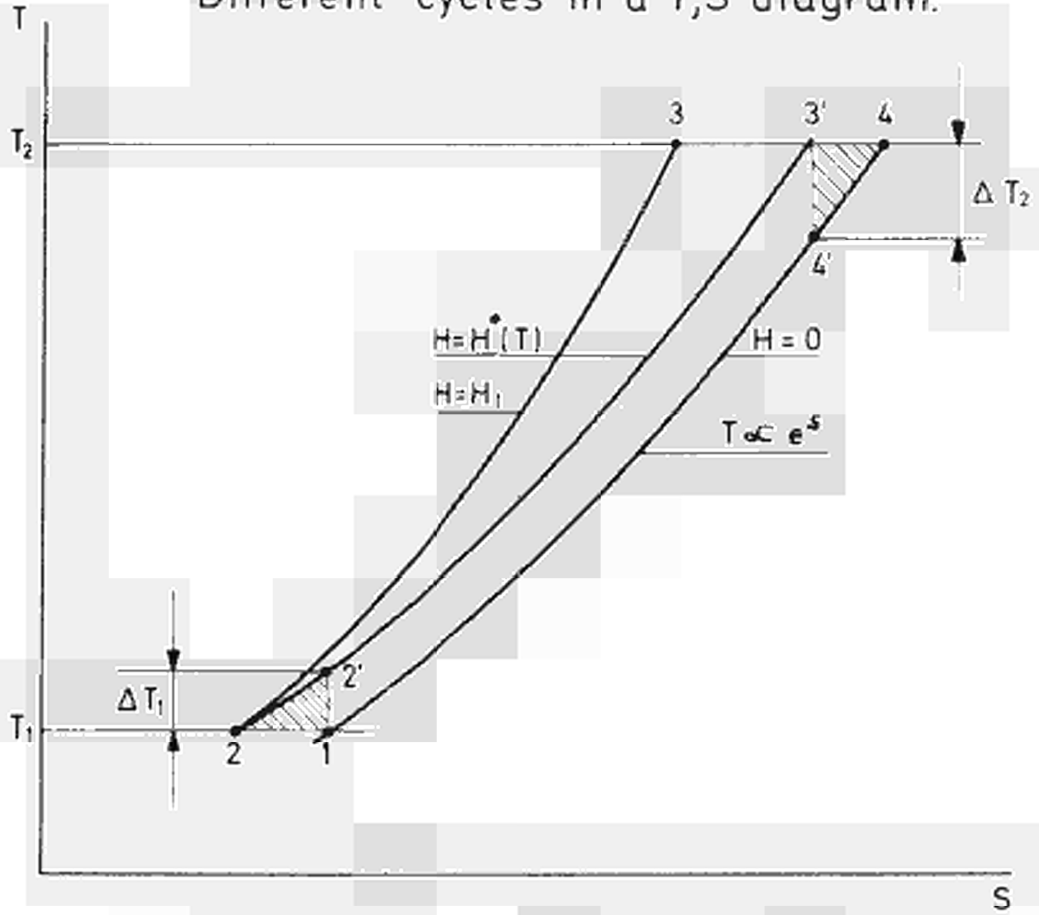
Type I Converter.



A	Solenoid plus heat exchanger
B	Heat exchanger
HS	Hot source
CS	Cold source
SHE	Supplementary heat exchanger
$2Co\Delta T_R$	Heat I/0 to effect practically heat transfer
L	Load
P	Electromagnetic pump

Figure 2

Different cycles in a T,S diagram.



1	2	3	4	Type	I	cycle
1	2	3'	4	Type	II	cycle
1	2'	3'	4'	Type	III	cycle

The paths 1 4 and 2 3' are congruent.

Figure 3

Efficiency of the Converters ($\varepsilon H = 10^4$ Oe).

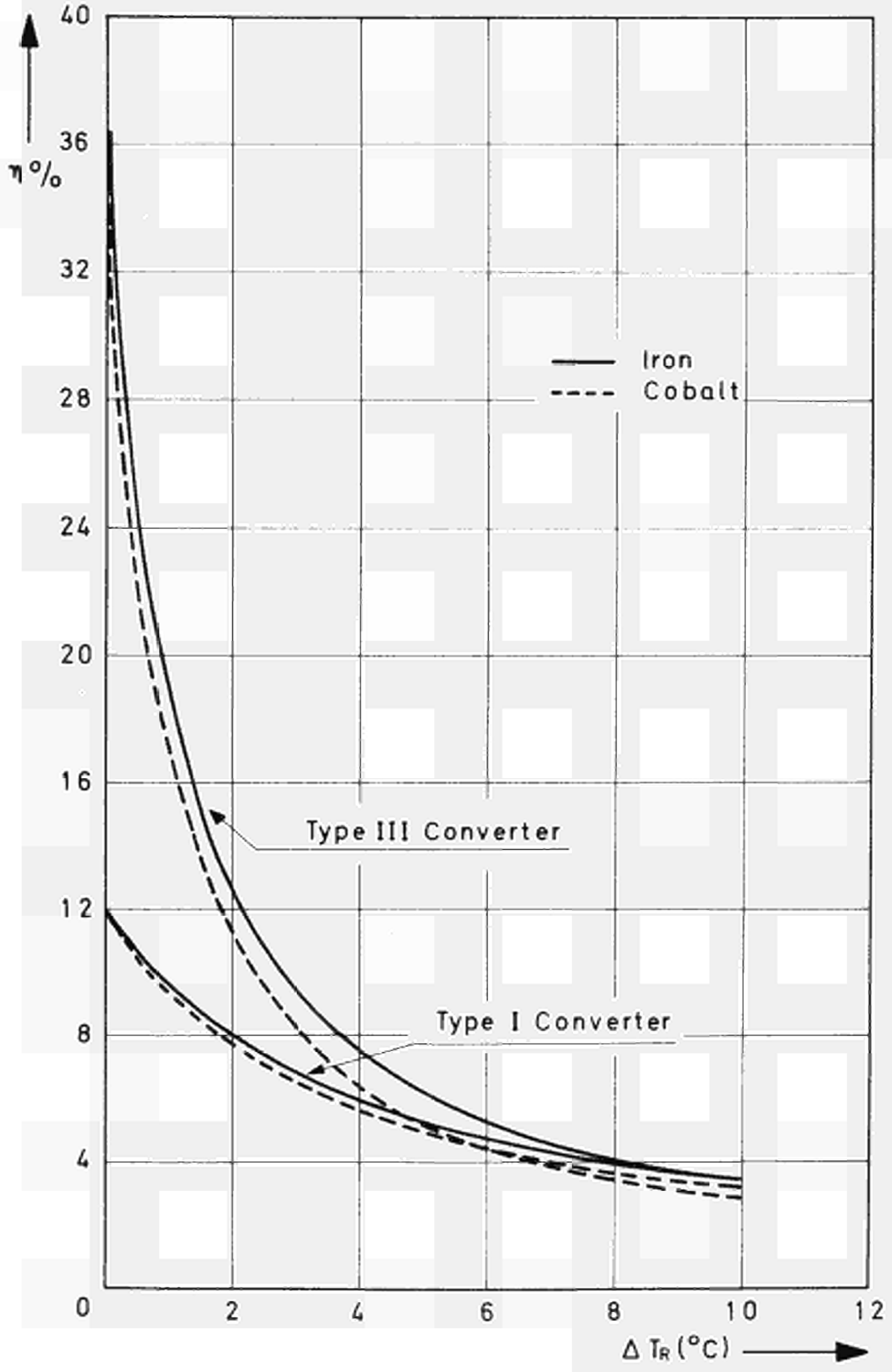
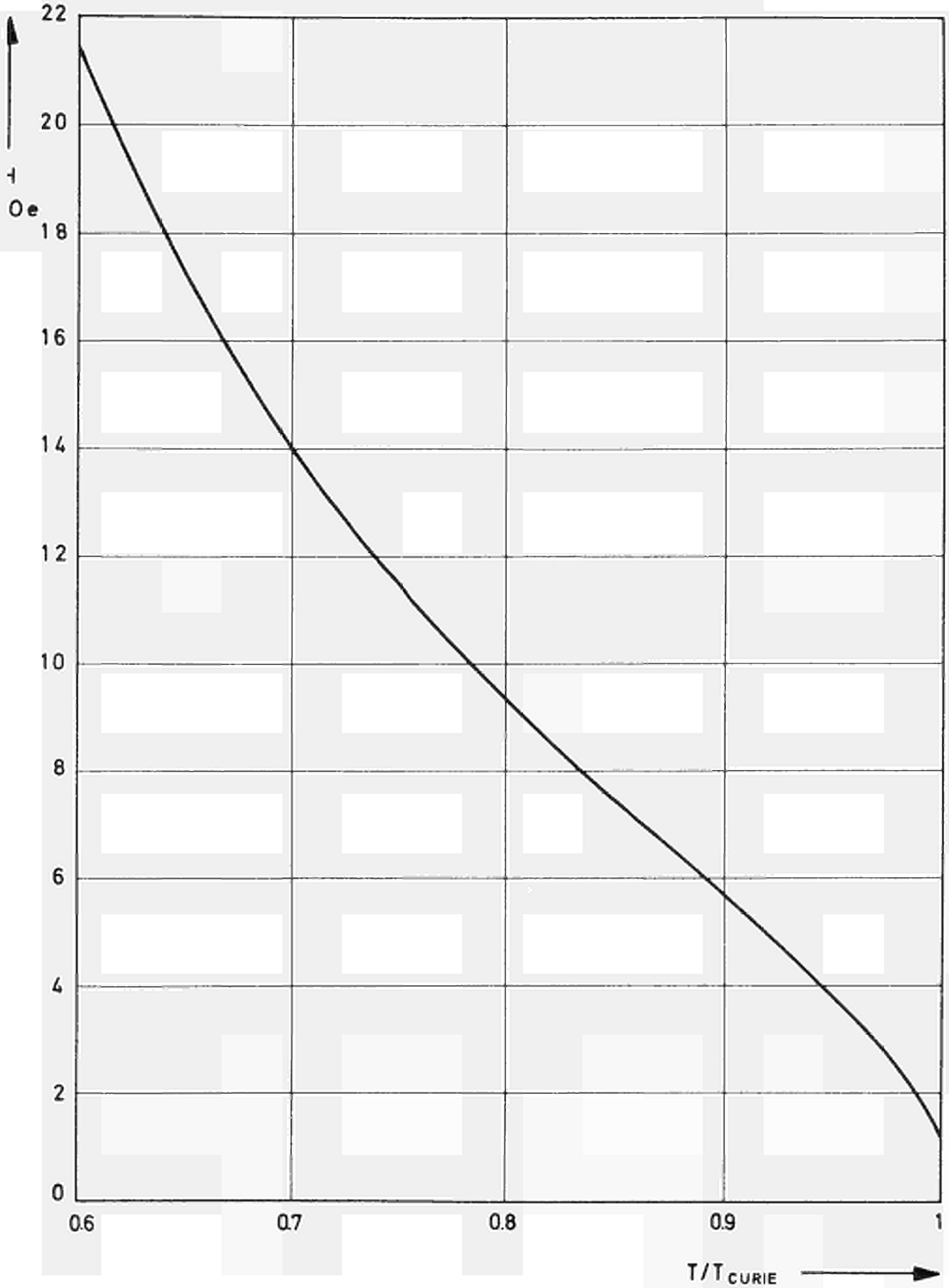


Figure 4

Isentropic Trasformation along the solenoid with a mean field of 10^5 Oe. Case of iron.



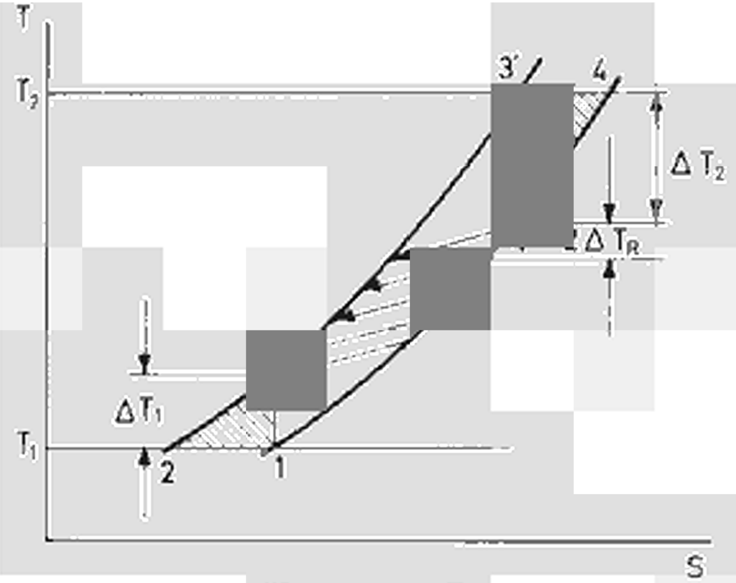
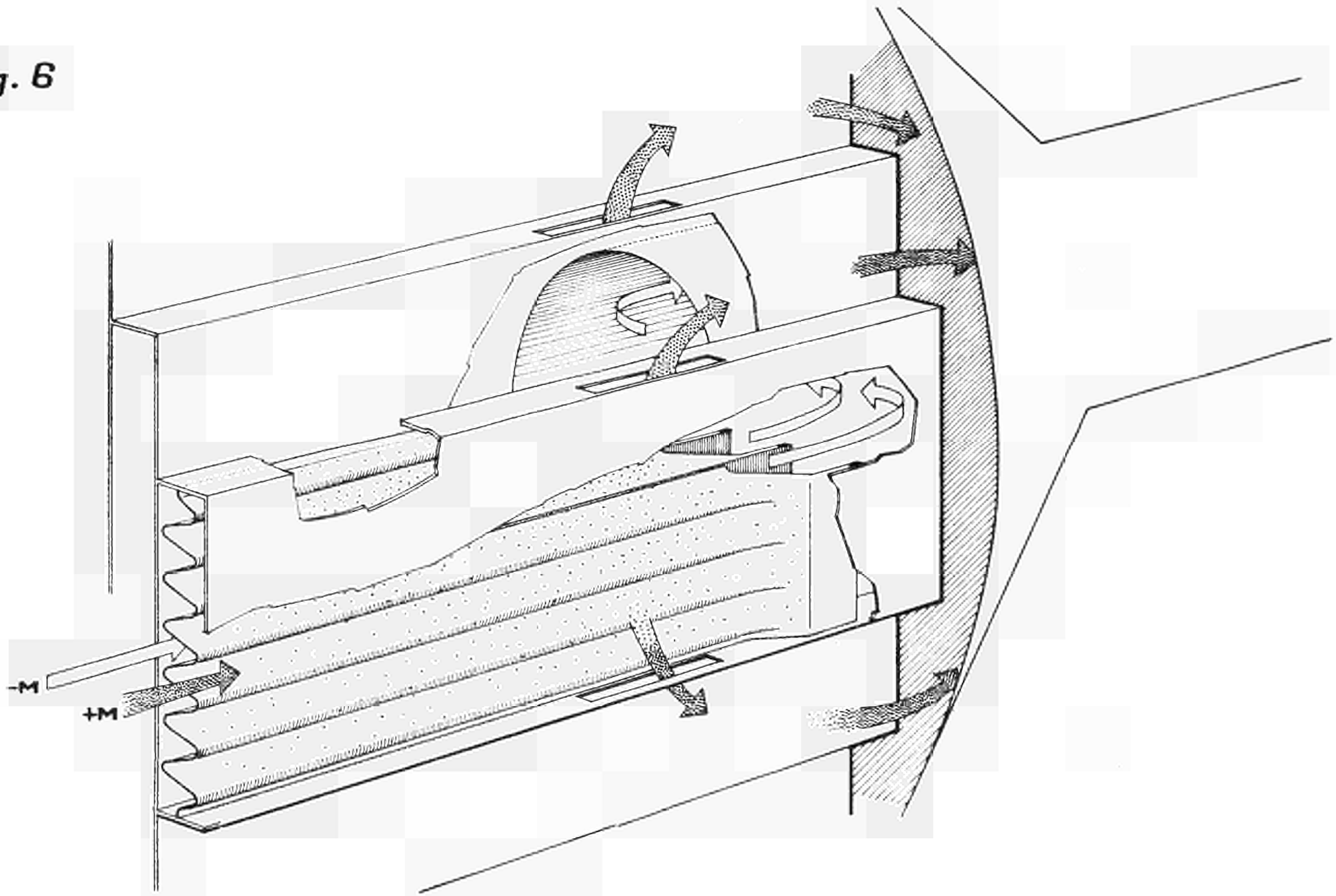


Figure 5

Regeneration in the Brayton cycle.

Fig. 6



Detail of the plate heat exchanger

Figure 7

Mechanical Power for $\varepsilon H = 10^4$ Oe.

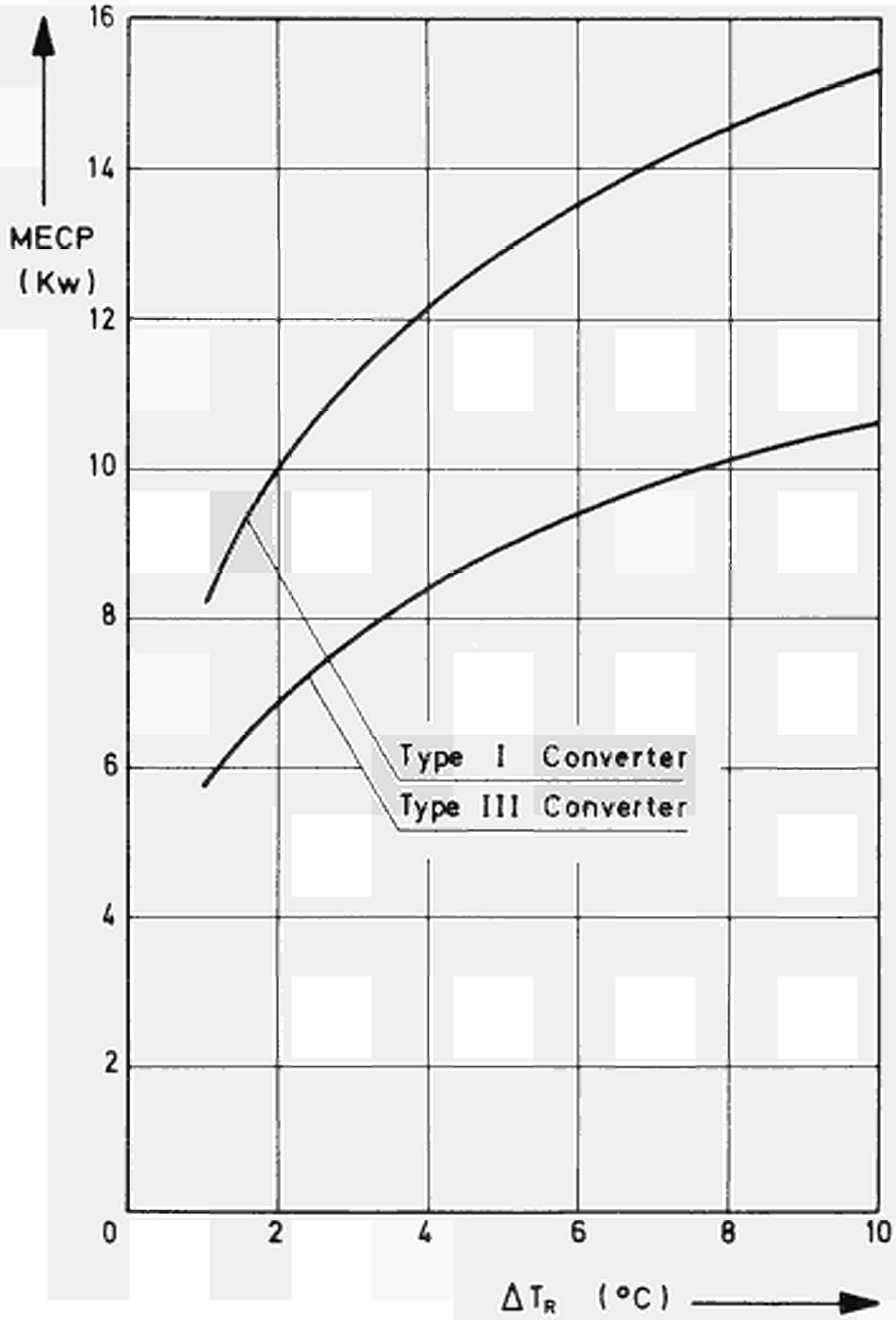


Figure 8

Converters specific weight.

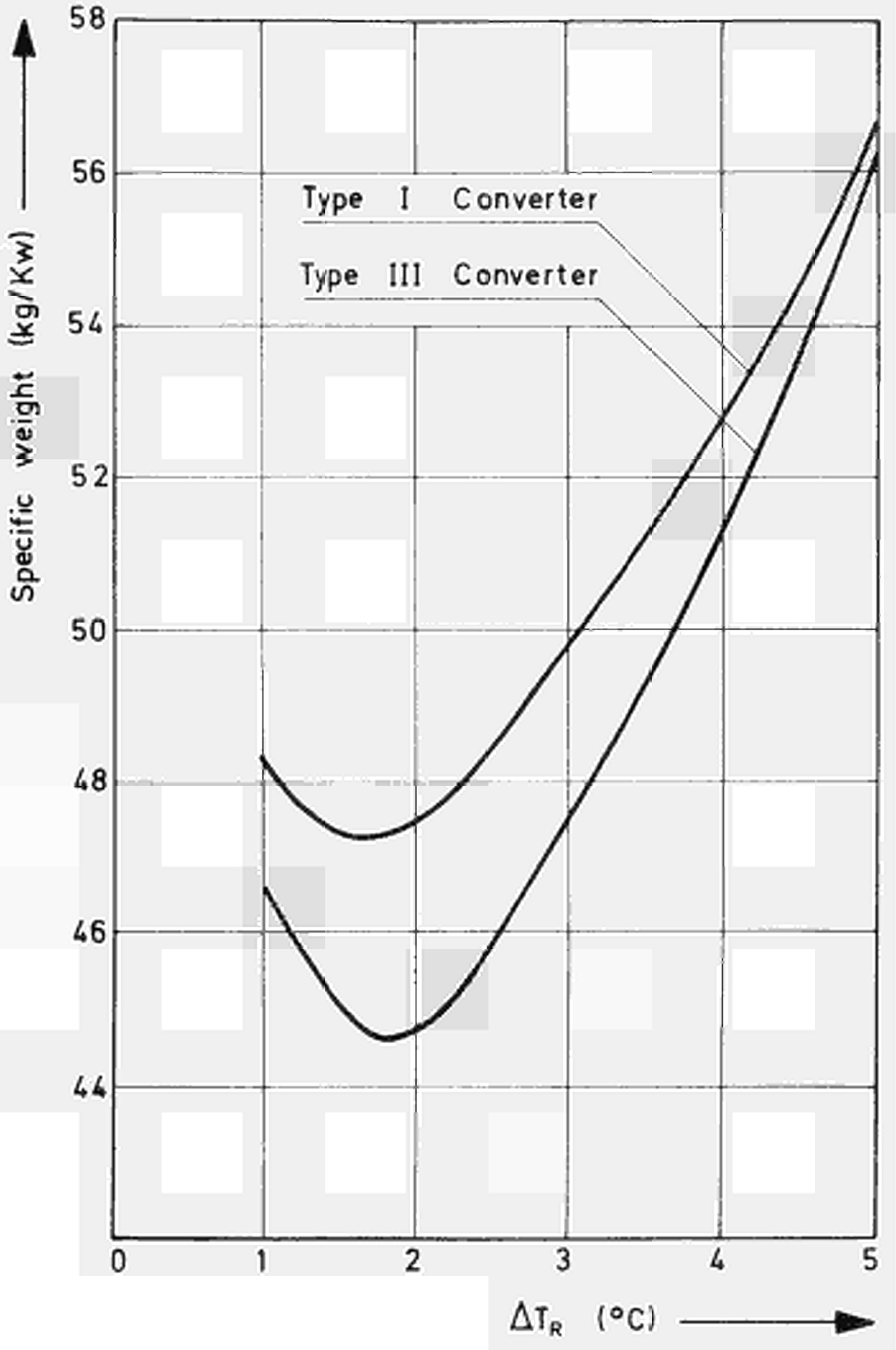
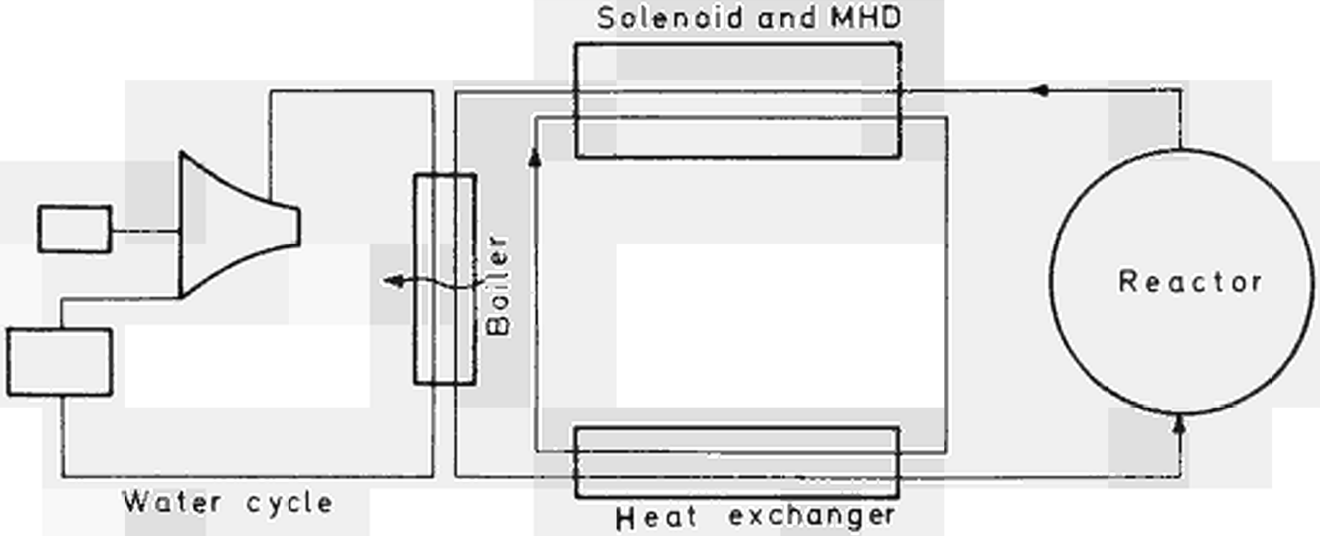
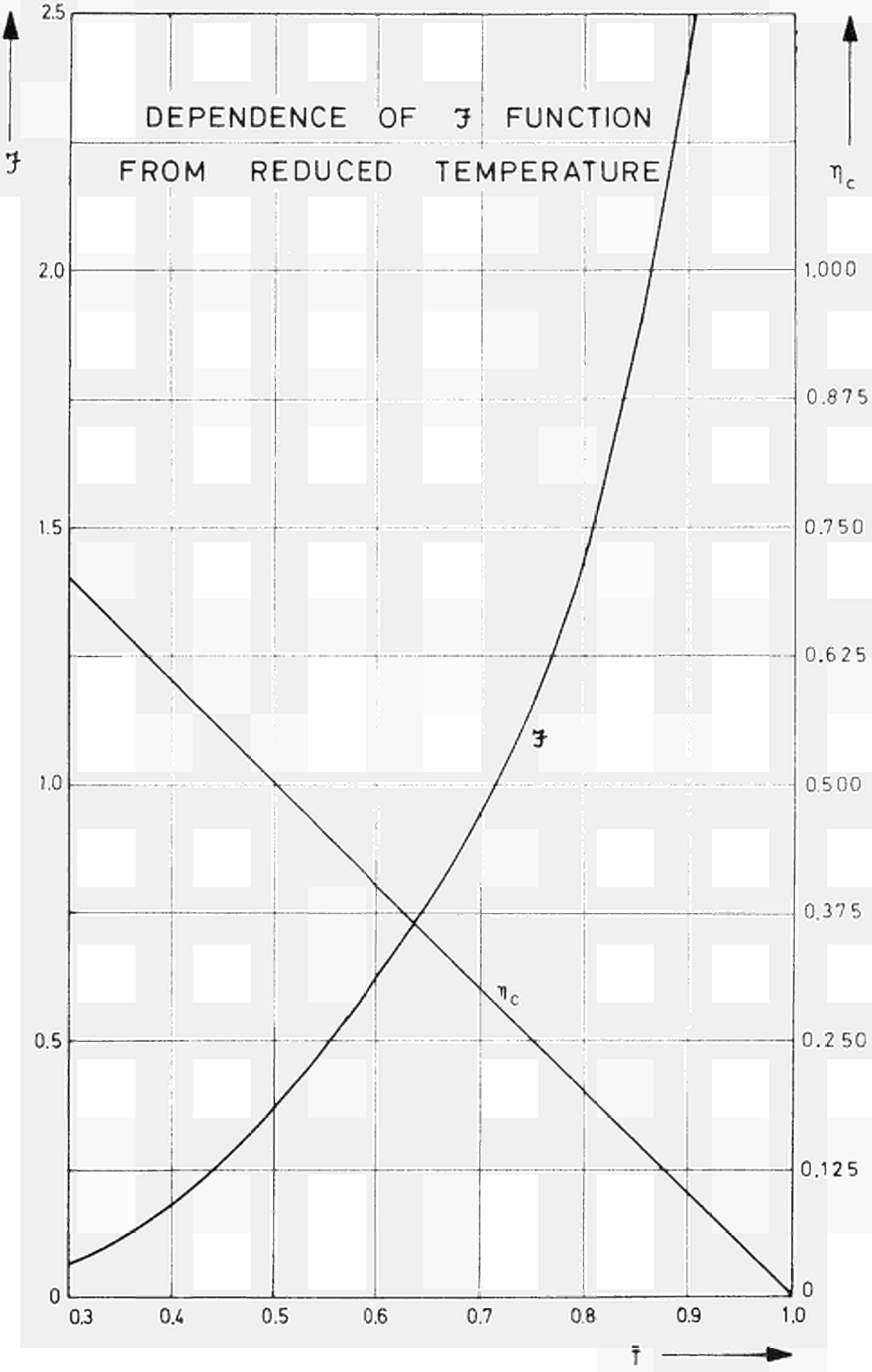


Figure 9



TOPPING DEVICE FLOW SHEET

Figure 10


DEPENDENCE OF 𝔉 FUNCTION
FROM REDUCED TEMPERATURE
𝔉
η_c
2.5
2.0
1.5
1.0
0.5
0
1,000
0.875
0.750
0.625
0.500
0,375
0.250
0,125
0
0,3
0,4
0.5
0.6
0.7
0.8
0.9
1.0
$\bar{T}$

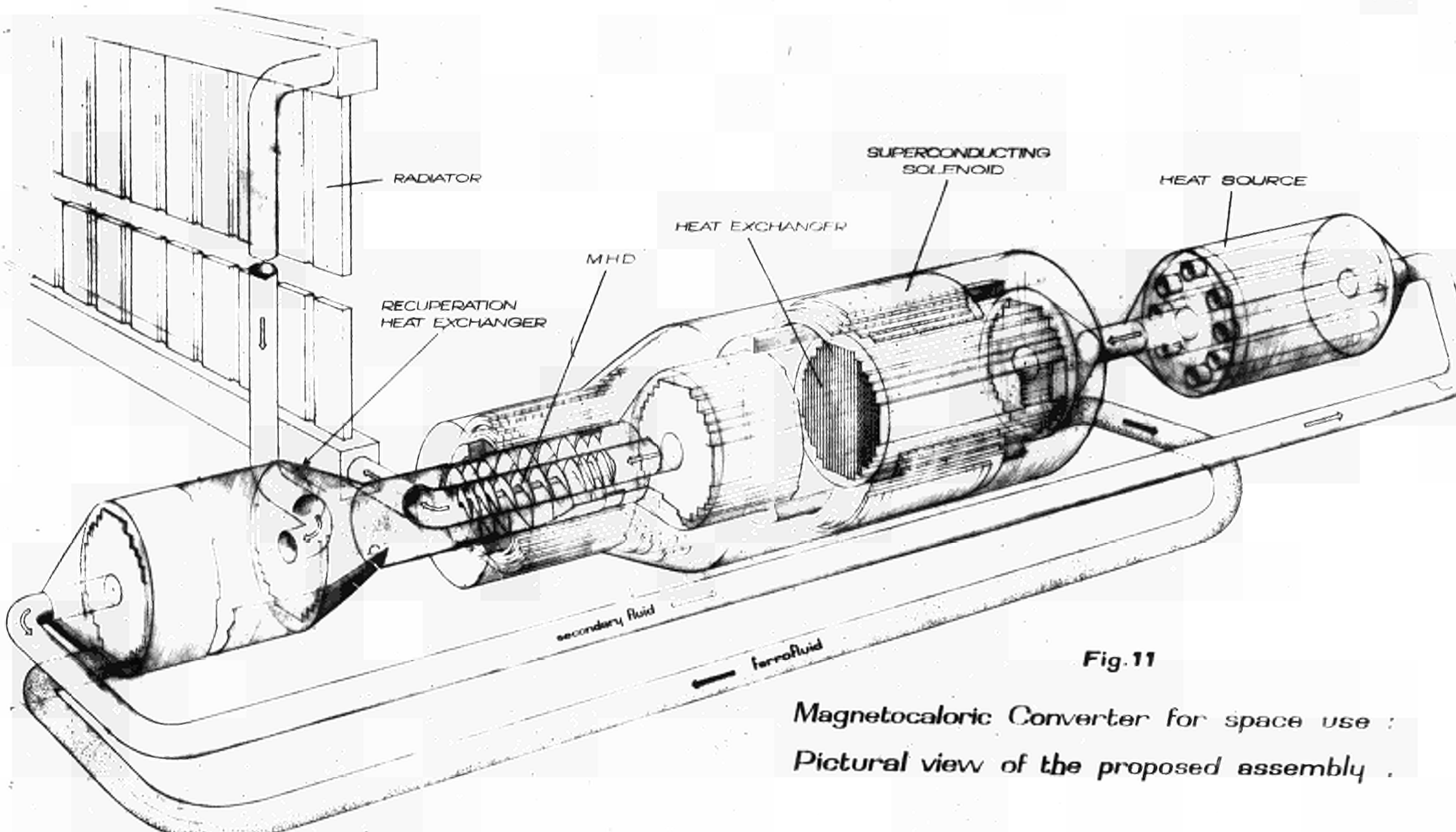


Fig. 11

Magnetocaloric Converter for space use :
Pictural view of the proposed assembly .

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To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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