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HYDRAULIC ACCUMULATORS AND HIGH PRESSURE BOTTLES IN COMPOSITE MATERIAL

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1. INTRODUCTION

MAGNAGHI MILANO S.p.A., leader in Italy in the field of the hydraulic servocontrols for aeronautic use, are developing an applied research programme financed by the "Ministry of Scientific Research and Technology" in order to design, test and manufacture high pressure hydraulic accumulators and gas bottles in advanced composite materials.

The equipment, subject of the applied research, are gas-oil accumulators for aircraft and rotorcraft hydraulic circuits, consisting of a cylindrical body with blind ends where, at least, one of them is constituted by a convex cover in only one piece, embodying a sliding piston which delimitates two chambers, one for hydraulic fluid and the other for pressurized gas.

For the manufacture of equipment and components of flying vehicles it is mandatory to guarantee maximum safety and reliability together with maximum lightness.
Accumulators function is to contain a volume of hydraulic fluid kept under pressure by a compressed gas, to supply a sufficient quantity of oil also in case of failure of the pump package or of a section of the supply circuit in such a way as to allow the operation of those equipment essential for emergency flight manoeuvres.

The reason for which such research has been promoted is because in the latest aeronautic programmes, to which Magnaghi took part, it was noted, once more, that the accumulators are the component parts which more penalize the weight of the hydraulic system.

This is due to the strict requirements of the design specifications (for inst., a factor 4 of structural safety is imposed) and to the special working stresses.
Therefore, alternative solutions have been analyzed to obtain a reduction in weight for the subject equipment, by considering two possible solutions thoroughly :

- use of special steels having very high structural resistance characteristics (ultimate tensile stress = 1800 to 2000 N/sq.mm) (solution considered as not valid as without necessary warranties as to fatigue and wear resistance in addition to cost problems).

- use of composite materials.

This second solution has been considered as valid and is the subject of a research in hand at Magnaghi Milano.
First of all, it is necessary to classify the equipment according to their use as any change in the requested characteristics and performances involves a change in the manufacturing philosophy, which utilizes composite materials.

The hydraulic accumulators can be classified as follows:

- Ripple accumulator : used for damping pressure pulses, it has, in general, reduced dimensions : it is requested not to accumulate oil but to have capacity of working among high pressure levels.

- Power accumulator : it must supply a certain oil quantity among fixed pressure levels.

If compression ratio is defined as $n = \frac{\text{useful fluid vol}}{\text{total volume}}$,

by considering as accumulator performance the quantity of oil supplied between two defined pressure levels, it is noted that "n" is directly proportional to the available pressure stage (as it can be seen on a diagram of accumulator charge-discharge) and inversely proportional to the volume.
The above stated, it is possible to select the most valid solution among those which will be illustrated.

2. SOLUTIONS IN ALTERNATIVE TO THE TRADITIONAL ONE

A) - Accumulator - bottle (fig. 1)

This system realized by M.M. and already used on the AM-X military aircraft and EAP demonstrator consists of the pairing of a standard accumulator and a bottle in composite material, series connected.
The accumulator is dimensioned to contain the fluid useful volume, a separator-piston, a minimum nitrogen quantity while the bottle contains all the nitrogen necessary to guarantee the requested performances.
As to the applications till now realized, this solution has involved reductions in weight by 50% and, with the same useful volume, it shows an increase in validity on reducing "n" as the gas container is the element which allows a reduction in weight.

B) - Steel accumulator - carbon fiber, epoxy resin (fig. 2)

This solution is based on the realization of an accumulator made of steel and composite material (carbon fiber/epoxy resin).

In this way, the thickness of the steel cylindrical wall is reduced and some of the efforts due to pressure stresses are absorbed by the fibers wound on the metallic material.
This solution is the most suitable for ripple accumulators and for accumulators having a high compression ratio.
The gain in weigth as to a traditional accumulator can be valued around 15 to 20%.
By using an accumulator of this type for "A" solution, together with the bottle, system weight can be further reduced.

C) - Accumulator in aluminium alloy/kevlar - epoxy resin (fig. 3)

In this case, the accumulator consists of an envelope in aluminium alloy, covered with composite material, and a steel barrel where the piston moves.
Practically, this solution repeats the diagram of the steel accumulators where the traditional cylinder is replaced by the wall in aluminium alloy plus kevlar and by the piston guide-barrel.
The inside barrel works in balanced condition, so it can be of a thickness reduced to a minimum allowed by machining.
The external envelope has to withstand all pressure stresses, the external shape of the extremities must meet specific requirements to allow a correct winding of fibers, in addition to be dimensioned as to thickness, according to resistance criteria.
This solution is valid in case of high fluid volumes being supplied and a very low compression ratio.
By means of this type of accumulator it is possible to have reduction in weight to about 50% as to traditional solutions, even if not directly comparable, because the ratio between nitrogen volume and fluid is very different from the traditional accumulators.

On the ground of the characteristics of some accumulators fitted to an aircraft (AM-X), a comparative analysis, which confirmed the above reduction in weight, has been made.
In particular, on the enclosed diagram (fig. 5) it is possible to make a comparison between the validity of the different solutions under the same performances as to the standard configuration (steel accumulator) by assuming as indices weight and envelope volume.

D) - Accumulator with carbon fibers and epoxy resin without metallic liner (fig. 4)

This accumulator is in carbon fibers and epoxy resin without metallic liner and equipped with metallic inserts for the locking of the end caps.
The accumulator wall consists of an inside impermeabilization coat, where the piston slides and on which are wound the carbon fibers.
Helical winding is used to resist longitudinal stresses and circumferential for hoop stresses.

3. RESULTS

The theoretical formulation of this research has been conditioned by the special operating requirements requested to this type of product and among the others, mainly the following :

a) burst pressure equal to 3 to 4 times operating pressure with preservation of sealing up to breaking;

b) proof pressure equal to twice operating pressure without permanent sets.

c) thermal shock between -54° and +135° C.

To obtain the result of sub-para. a) two solutions have been considered :

a1) use a metallic liner in steel or light alloy to eliminate leakages due to die micro-flaws through the composite material walls;

a2) create, inside the wall, a pseudo-liner, i.e., a structural or not structural coat, which can constitute a barrier to the migration of the pressurized fluid to outside, with special patented technological solution.

As to the condition of sub-para. b) when the composite material is used with a metallic liner, it is necessary to dimension the two elements, by taking into account the differences of the modules and the ultimate tensile stresses, so that liner deformations under test pressure are kept into elastic limit and contribution to total resistance is as maximum as possible.

Means used to optimize the solution of this problem have been the following :

- netting analysis to calculate mechanic characteristics of the filament winding wall;

- the theory of lamination to calculate the elastic properties of the composite material;

- a theory on the compatibility of the elastic deformation of containers having multiple thin wall, subject to internal pressure, set up and checked during this research;

- the elasto-plastic analysis of liner deformation to determine its contribution to the accumulator resistance.

Finally, to withstand the thermal shock as per sub-para. c), it has been necessary to verify and check the expansion coefficients of the composite material in such a way as not to have breakaway between liner and composite material for different expansion because of a temperature jump of about 200° C.

Under the application aspect and in view of industrial consequences in the first part of such research has been dealt with the problem of a lightnening of the steel accumulators, by means of carbon fibers and epoxy resin by developing, in this way, an advanced configuration for an accumulator already fitted to the AM-X aircraft.

As people know, like all the cylindrical containers subject to internal pressure, the accumulators have the wall subject to a condition of biaxial stress with a circumferential stress equal to twice the longitudinal one.

For instance, on designing the cylinder with the criterium of maximum stress, the wall is proportionate according to the circumferential stress and as the material (in this case, steel) is isotropic, it appears that under the effects of longitudinal stress it is oversized so this can involve a weight (and a cost) which are not utilized.

On the contrary, on designing the same container with composite material to obtain a maximum efficiency, it is possible to realize a stratified composite capable of balancing the efforts without useless redundancies.

In conclusion, it has been achieved the result of reducing steel thickness, on the cylindrical wall, to 50% of the original thickness to withstand longitudinal stresses, by restoring it with a coat of carbon fibers-epoxy resin having specific gravity equal to 1.6 Kg/dm^3 against 7.8 Kg/dm^3 of steel with the task of containing diametrical efforts.

So, we obtained an accumulator dimensionally identical to the traditional configuration, but with a considerable reduction in weight, of course more important with the increase in dimensions of the equipment.
We also tried without success an additional reduction in steel thickness because of the impossibility of transferring from the metallic wall to the coat of composite material longitudinal loads due to pressure, by utilizing the only means possible for this configuration, i.e., friction and interlaminar shear, which show a low and scarcely reliable value.

The first part of this design has been devoted to evaluate the support given by the carbon fibers to the structural resistance, the carbon attitude to the changes of ambient temperature in the typical use field of those equipment (-54°C to 135°C) and the applicability of technologic procedures of standard production, cadmium plating, hydrogen embrittlement relief, painting into furnace, applicable to steel component parts.

Some structural and wear tests (endurance and fatigue tests) have been carried out to evaluate the behaviour of the composite material when stressed under efforts changeable during the time, environmental tests for different use conditions as experimental investigation of the design and to achieve a design review and a final drawing up of the procedure for winding and polymerization of the composite material.

Finally, the qualification tests on two prototypes have been completed with full compliance with the requirements of the applicable specification MIL-STD-810C.

The characteristics of the equipment are as follows:

- Operating fluid	MIL-H-5606 or MIL-H-83282B
- Temperature range	-54°C to 135°C
- Rated operating pressure	27600 KPa (4000 PSI)
- Proof pressure	55120 KPa (8000 PSI)
- Burst pressure	110240 KPa (16000 PSI)
- Gas rated volume	1260 c.c.
- Rated pressure for gas precharge	9000 KPa (1305 PSI) at 20°C
- Mass (dry)	4.2. Kg

To be qualified, the equipment has passed the following qualification tests :

- Examination of product
- Tests for quality compliance
- Magnetic inspection
- Separator under pressure
- Volumetric efficiency
- Fluid immersion / ageing
- Proof pressure (55120 KPa)
- Grounding - bonding
- Cyclic operation - endurance
- Leakages
- Seizing of component parts
- Thermal shock
- Burst pressure (110240 KPa)
- Salt fog
- Contamination
- Fragmentation
- Vibration
- Shock
- Check - final inspections

The second part of this research has been focalized to the development and manufacture of accumulators on new design, at high capacity, having concentric chambers, made of aluminium alloy and kevlar with a steel internal sliding barrel; in this case, winding is helical and circumferential type with, therefore, resistance in two directions, longitudinal and transverse.
Initially, the resistant frame was made of an aluminium alloy liner, obtained through a welding process and a reinforced winding.
Design check is based on general tests of functional testing, tensile strength, thermal shock, which have shown the problems related to the manufacture of such accumulators and the necessity of determining the composite support to the structural resistance and analyze the stresses due to changes in temperature.

So, an authomatic programme of fiber winding along geodetic directions has been set with a review of polymerization process to eliminate deformations induced by thermal effects.

The experiment has allowed to evidence problems of liner porosities and flaws close the welded points with the consequential review of the liner design which has led to its manufacture in only one piece obtained from bar (but also obtaineable from forging).

Subsequent tests have outlined the need of increasing kevlar contribution to the end opening edge moment, by oversizing the end thread in the cap side with a reinforcement by means of circumferential fibers.

On the ground of the results obtained, it has been achieved the necessary trust for carrying out the qualification tests on the prototypes manufactured as evidence of the design validity.

In the light of what above stated as subsequent development and completion of this research, in order to obtain the maximum lightening we have developed an accumulator in carbon fibers and epoxy resin, without metallic liner, equipped with metallic inserts for the locking of the end caps.
So, the accumulator wall consists of an inside impermeabilization coat, where will slide the piston on which are wound, always with the experienced technics of the filament winding, the coats of helical and circumferential winding for structural purpose.

The helical winding, responsible for resistance in longitudinal direction, is locked to suitable titanium inserts, which realize closing with caps and threaded ring nuts, by obtaining, in this way, a tube with balanced reaction walls.
The only metallic parts existing in the accumulator are the two head bushings necessary for the mechanic matings with closing. The aim of this research has immediately shown, as obstacles, the problem of the longitudinal locking of filaments and sealing of the composite wall to the ultimate elongation.
The longitudinal locking of the filaments is theoretically solved by determination of the path of the turns connected to profiles obtainable, by realization of pass lines as close as possible to geodetic curves, impossible to be exactly realized for similar shapes and under a technological aspect, by-pass of non geodetic lines with the technics of the filament winding.

As regards impermeabilization, the resins at present existing for structural filament winding show some phenomena of micro-flaw and wall sweating at elongations lower than ultimate elongations of filaments even if, individually, these resins show higher elongations.
This problem can be solved by suitably modifying the resins or by creating a pseudo-liner inside the wall without penalizing the accumulator under the structural profile.
At present, we can conclude saying that there is the possibility of reduction in weight of the hydraulic circuits of the future helicopters or aircraft, by means of accumulators and bottles designed utilizing the lightness of kevlar and carbon fibers. Accumulators and bottles so manufactured are fully in compliance with the specifications normally requested for standard accumulators and bottles mounted on the latest developed helicopter and aircraft.

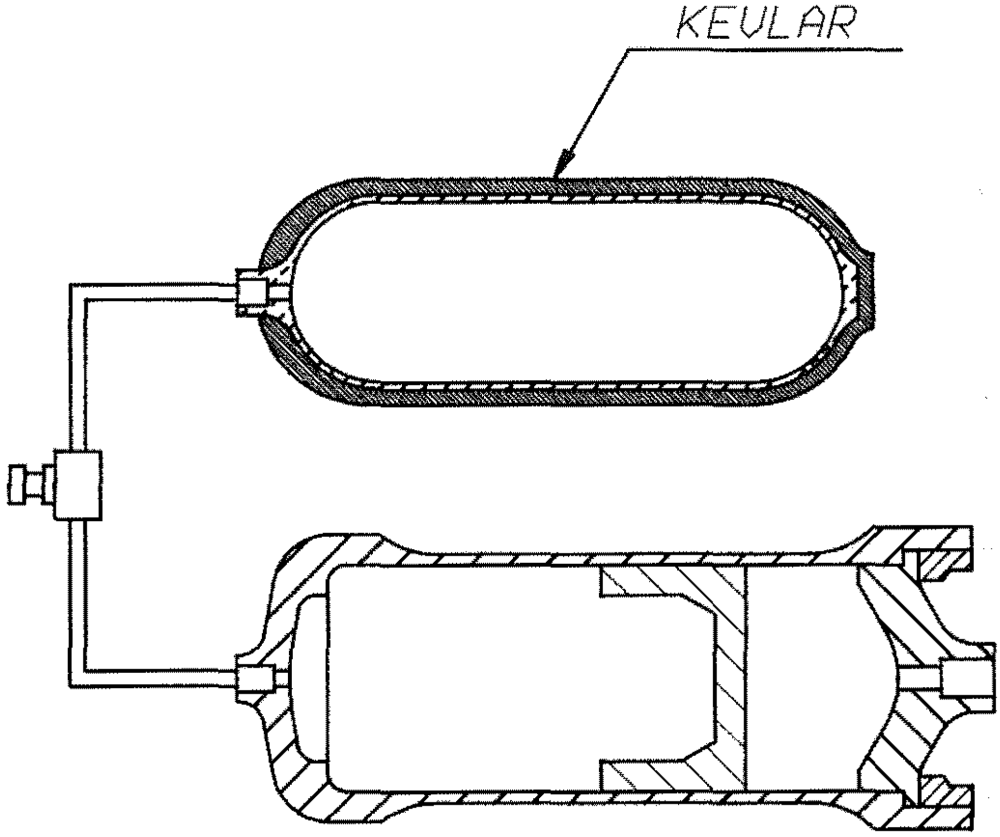

Figure 1

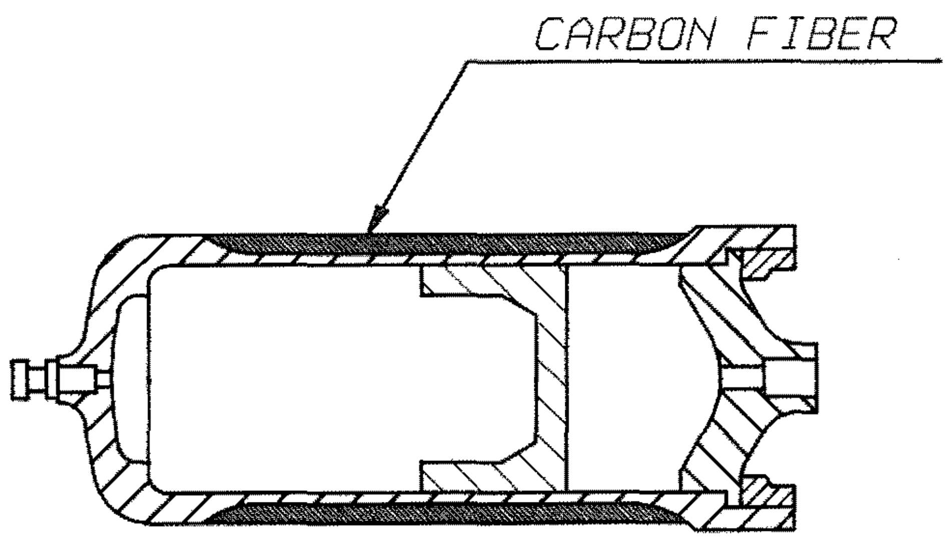

Figure 2

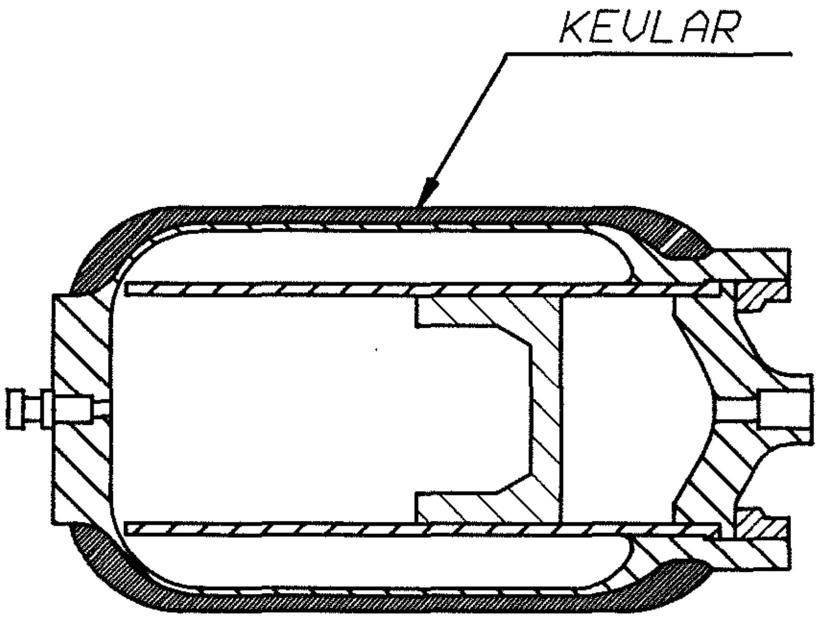

Figure 3

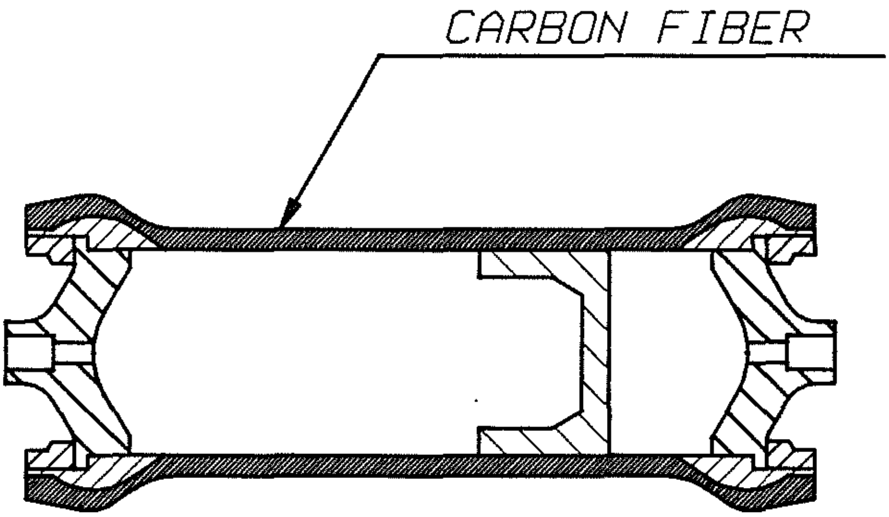

Figure 4

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ACCUMULATORS WEIGHT ANALYSIS

A - Steel standard configuration
B - Carbon fiber reinforced configuration
C - Kevlar-Al.alloy configuration
D - Steel standard configuration - pressure bottle
E - Carbon fiber reinforced configuration - pressure bottle

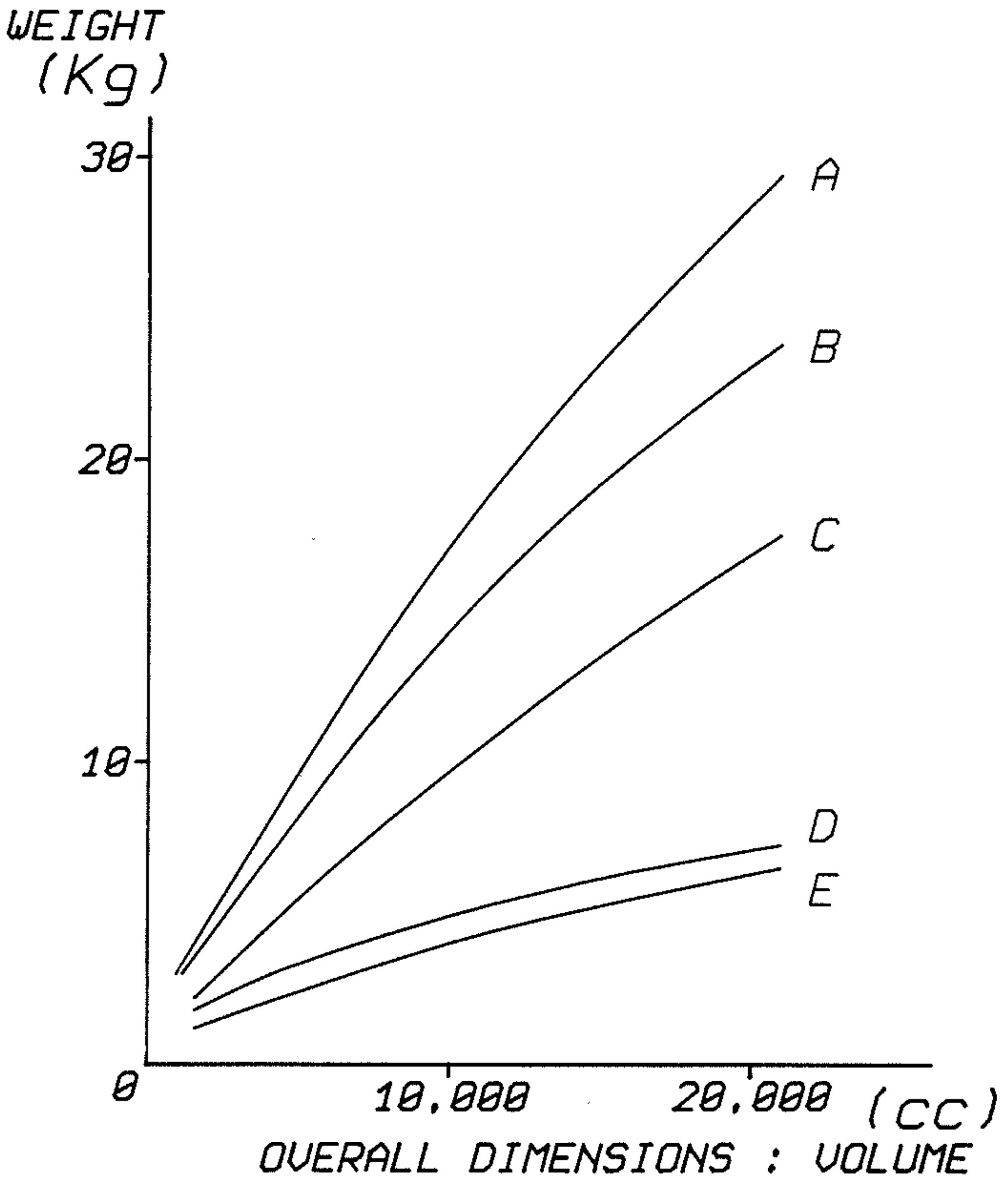

Figure 5