

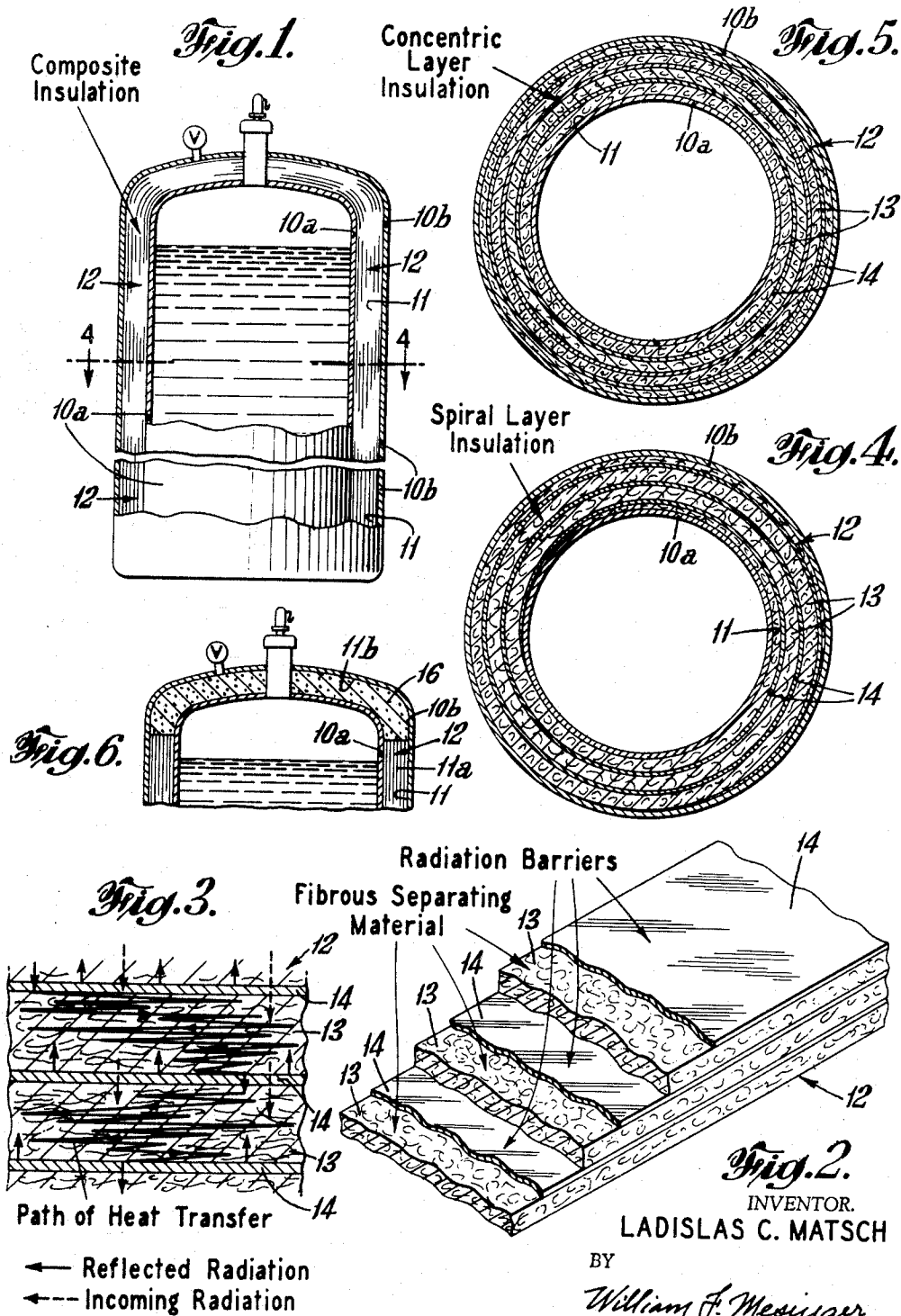
Nov. 21, 1961

L. C. MATSCH
THERMAL INSULATION

3,009,601

Filed July 2, 1959

4 Sheets-Sheet 1



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L. C. MATSCH
THERMAL INSULATION

3,009,601

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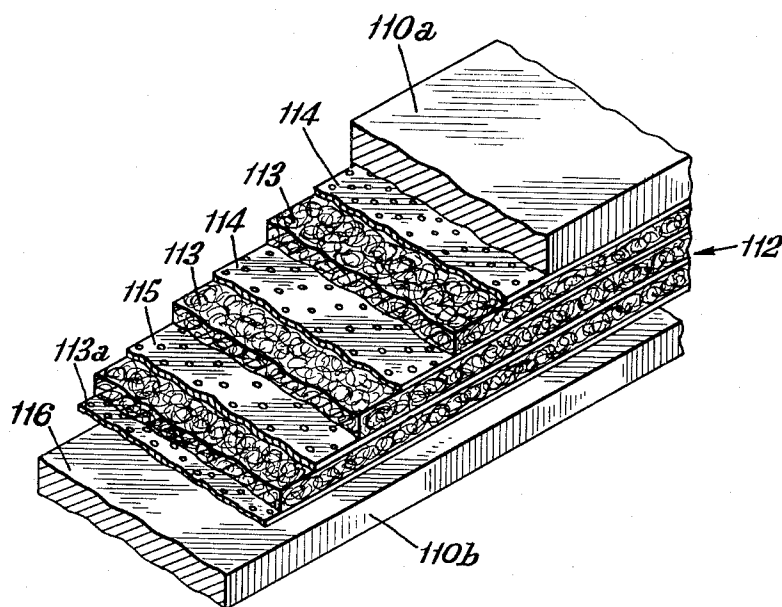


Fig. 7.

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4 Sheets-Sheet 3

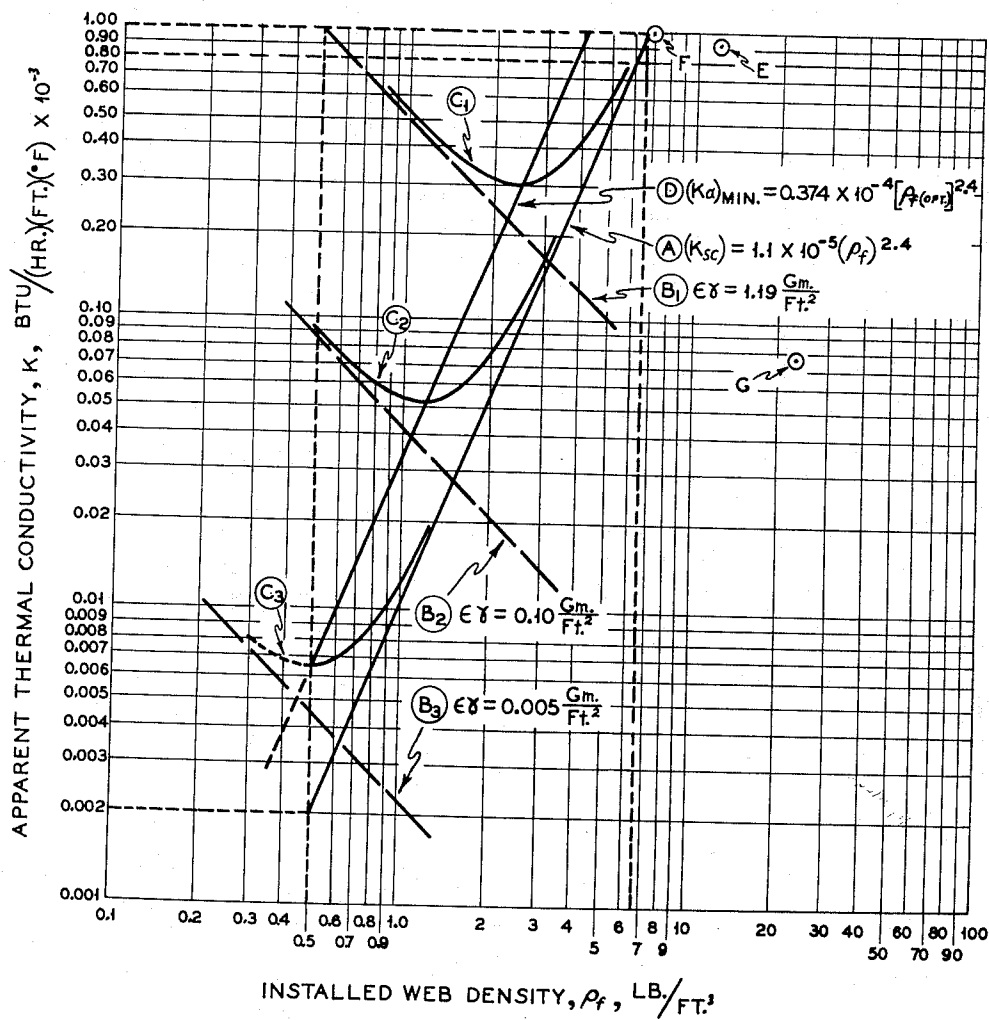


Fig. 8.

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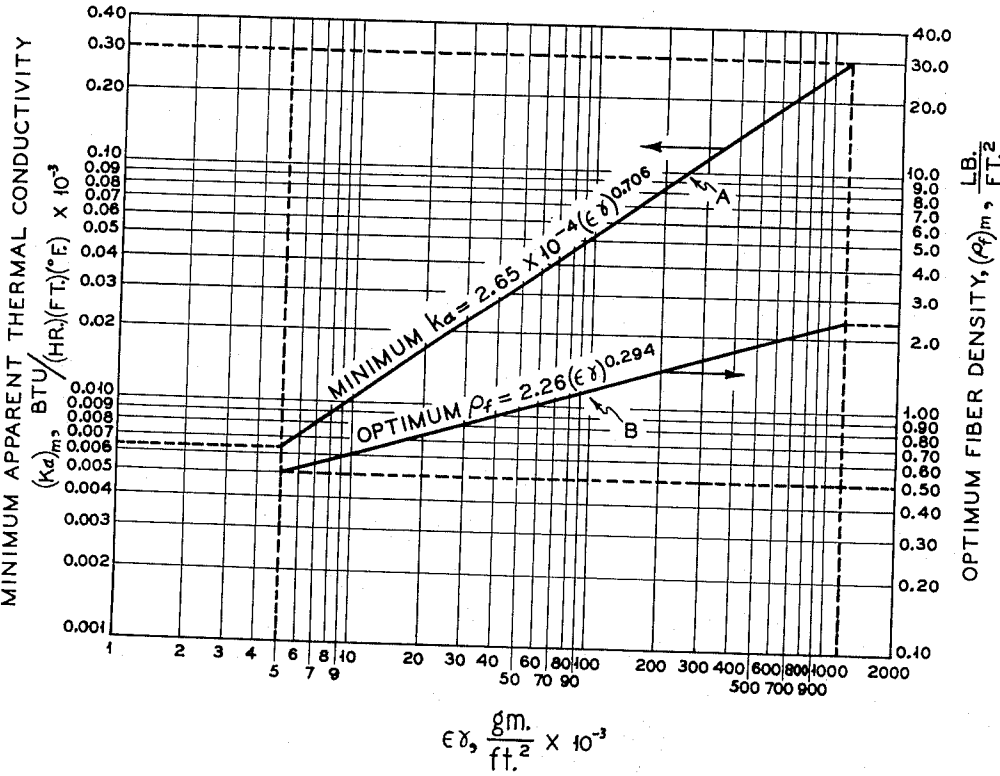
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Fig. 9.



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3,009,601

THERMAL INSULATION

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Filed July 2, 1959, Ser. No. 824,690
2 Claims. (Cl. 220-9)

This invention relates to an improved insulation having a high resistance to all modes of heat transfer, and particularly concerns a low temperature, heat insulating material adapted to improve a vacuum insulating system.

In the conservation and conveying of low temperature commercial products—for example, perishable commodities which must be held at low temperatures for substantial periods of time, and valuable volatile materials, such as liquefied gases having boiling points at atmospheric pressure below 233° K., for example, liquid oxygen or nitrogen—a major problem encountered is the control of heat leak to the material, which in the case of liquefied gases results in loss due to evaporation. In the conventional double walled liquid-oxygen container, the space between the walls is suitably insulated to limit this evaporation loss. However, up to now it has not been possible to provide an insulation system, particularly for small, portable containers having small volumes in comparison with the surface areas, which will limit the evaporation loss to satisfactorily low values.

The basic systems for insulating the conventional double walled container for the conveyance and storage of low boiling liquefied gases are: for small containers, the Dewar type high vacuum-polished metal surface system, and for large containers, the powder-in-vacuum insulation system, which uses an insulating powder in the vacuum space between the walls. This system is described in detail in U.S. Patent 2,395,459. Although powder-in-vacuum heat insulation is highly effective in reducing thermal heat loss in many systems, it is not as effective as straight vacuum-polished metal surface for containers up to two feet in diameter. While these systems have greatly affected the commercial considerations as applied to storage and conveyance of low temperature products, there, nevertheless, exists a great commercial need for more efficient insulating materials capable of meeting more rigid and exacting requirements, and which will provide even lower thermal conductivities than those afforded by either of the above-described insulations.

To give some insight into the problems that are presented in effecting further reductions in heat leak for small portable containers, assume for example that it is desired to insulate a double walled cylindrical container for low boiling liquefied gases such as oxygen, so that the evaporation loss due to heat leak will be less than 1% of the contained material per day. Assume further that the container will have hemispherical ends, an inner vessel diameter of 8 inches and an inner vessel total length of 48 inches. Using one of the best insulating materials of the prior art, for example, powder-in-vacuum insulation, in accordance with U.S. Patent 2,396,459, the vacuum being on the order of 0.1 micron of mercury absolute, a thermal conductivity of 9.2×10^{-4} B.t.u./(hr.) (ft.) (° F.) may be achieved. In order to more fully appreciate the significance of such a thermal conductivity, the insulating effects of the following insulation thicknesses are set forth. An insulation thickness of 1.66 inches of a powder-in-vacuum insulation will permit an evaporation loss of 7.1% per day. Such an insulation thickness results in an insulation cross sectional area equal to the useful cross sectional area of the inner storage vessel. In other words, beyond the thickness of 1.66 inches, the bulk of the insulation which must be stored and/or transported

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becomes greater than the bulk of the contained stored material.

Increasing the thickness of such an insulation to 4 inches reduces the loss rate to 3.6% per day, while simultaneously increasing the insulation volume to about 3 times that of the storage capacity of the inner vessel. It has been found that it is entirely impractical to consider insulating the vessel with a material having a conductivity as high as 9.2×10^{-4} B.t.u./(hr.) (ft.) (° F.) since calculations show the theoretical required insulation thickness to be 105 inches.

Considering a straight vacuum insulating system in which the walls of the inner vessel and outer casing forming the insulation space are polished in order to reflect radiant heat energy, there is a problem of maintaining a sufficiently low vacuum to eliminate heat conduction by residual gas. For this purpose the absolute pressure within the insulating space must be maintained at a value 10 to 100 times lower than when a powder-in-vacuum insulating system is used. The vacuum should be less than 0.01 micron of mercury absolute pressure and preferably should be on the order of 0.001 micron mercury. This may be obtainable in special laboratory equipment, but is an impractical specification for fabricated metal vessels intended for industrial service. Assuming that low vacuum conditions could be maintained so that heat transmission by conduction through the residual gas would be negligible, there still remains the problem of achieving the necessary reflectivity for the vessel walls. To obtain a maximum storage loss rate of 1% per day, surface reflectivities of at least 99.6% must be obtained. Reflectivities of this order are only obtainable, if at all, under strictly controlled laboratory conditions, which may not be duplicated or maintained either during fabrication of the container, or after the container is in service.

A lower quality reflective surface may be tolerated by interposing several concentric reflective shields within the insulation space as described in U.S. Patent 2,643,022. However, one of the limiting difficulties involved in such an arrangement is in assembling and supporting many reflective shields within a reasonable insulation thickness so that each shield is properly spaced from adjacent shields at all points. Proper spacing is an absolute necessity, for if two adjacent shields are permitted to contact in even a minute area, the insulating effect of one shield will be essentially eliminated. Moreover, the number of shields required depends on their surface reflectivity. If a very highly polished surface is provided for both vessel walls and the shields, the polished surface having a reflectivity of 95%, then at least 10 such shields must be used in order to achieve a 1% per day storage loss rate in the described vessel. At the same time, to maintain a reasonable thickness of insulation, the shields must be spaced as close together as possible. Allowing for inaccuracies in forming and assembling the shields, the spacing of at least $\frac{1}{4}$ inch would appear to be reasonable. Ten shields between the container walls would provide 11 spaces, and taking the thickness of the shields into consideration, would account for an overall thickness of at least 3 inches. Under these circumstances the fabrication of vessels having a storage loss rate of less than 1% per day would be costly and time-consuming.

In view of these obstacles, it has heretofore been impossible to approach, much less achieve, heat leaks of such small quantities for systems involving extended periods of storage of low boiling liquefied gases in portable storage containers.

It is, therefore, an important object of the present invention to provide a greatly improved insulation system for reducing heat transmission by all modes of heat trans-

fer to values well below that of any previously known insulating system.

Another object of the present invention is to provide a novel insulating material in an insulation system where radiation would otherwise be an important mode of heat transfer.

Another object of the invention is to provide in a low heat conductive material wherein radiation is the predominant remaining mode of heat transfer, a multiplicity of parallel radiant heat barriers interposed in said low conductive material for substantially reducing the passage of radiant heat therethrough.

Yet another object of the invention is to provide in a low heat conductive insulation, a series of spaced, heat reflecting barriers so constructed and arranged as to impede the passage of radiant heat through said insulation without affecting the thermal conductivity thereof.

Another object of the present invention is to provide in a restricted gas-evacuated insulating space, a plurality of radiation barriers, said barriers being disposed in spaced relation to each other, and maintained in such spaced position by a low heat conductive spacing material.

Still another object of the present invention is to provide in a vacuum-solid insulating space for small portable containers, a multiplicity of radiation barriers comprising spaced and parallel foils of heat reflective material for reducing the transfer of heat by radiation, and a spacing material between said radiation barriers, comprising a low-conductive, heat insulating material for reducing the transfer of heat by conduction between said barriers.

A further object of the invention is to provide a multi-layer composite insulation system in which gas molecules can move transversely through the layers, so as to facilitate easier evacuation of such system.

A still further object of the invention is to provide a vacuum, multi-layer composite insulation system which is superior to heretofore proposed vacuum insulating systems in impeding heat transfer without requiring the extremely high vacuums associated with straight vacuum systems.

A further object of the present invention is to provide an improved method of fabricating and applying a heat insulation for cylindrical containers wherein the heat insulation comprises a low-conductive, heat insulating material for reducing the transfer of heat by conduction, and incorporates therein a multiplicity of radiant heat barriers for reducing the transfer of heat by radiation.

A further object of the present invention is to provide in an enclosed volume defining a gas evacuated insulating space, a novel insulating structure adapted to fill the insulating space and effect contact with the wall surfaces defining the insulating space, said insulating space being characterized by the absence of gross voids, and having a low rate of heat transfer by conduction and radiation.

Other objects, features and advantages of the present invention will be apparent from the following detailed description.

In the drawings:

FIG. 1 is a front elevational view, partly in section, of a double-walled liquid gas container embodying the principles of the invention;

FIG. 2 is an isometric view of the composite insulating material of the invention shown in a flattened position with parts broken away to expose underlying layers;

FIG. 3 is a greatly enlarged detail section view showing the irregular path of heat transfer through the composite insulating material of the invention;

FIG. 4 is a sectional view taken along line 4-4 of FIG. 1, illustrating the spiral wrapping of insulating material of the invention;

FIG. 5 is a section view similar to FIG. 4, but showing a concentric layered modification thereof;

FIG. 6 is a fragmentary elevational view, in section, of a modified double-walled liquid gas container embodying the principles of the invention;

FIG. 7 is an isometric view similar to FIG. 2, but modified to show a composite insulating material with perforated foil;

FIG. 8 is a graph showing the effect of web density on the performance of the present insulating material; and
FIG. 9 is a graph for selecting an optimum insulating material of the invention for a given system.

In the past, radiation shields used in vacuum spaces have been constructed for the most part to be supportingly suspended in spaced relation to each other. Numerous small diameter supports were employed in the vacuum space to support the insulated vessel and to maintain proper shield spacing. A minimum number of these supports were employed to restrict the passage of heat leak by conduction. The remaining space was left unfilled to avoid creating additional pathways for thermal conduction. Furthermore, it was believed that the reflective characteristics of the shields would be seriously impaired by contact with an insulating filler.

It has been discovered that the insulating qualities of an evacuated insulating space may be substantially enhanced to a degree never before attained with a novel insulating structure, which may occupy part of or the entire insulating space. Yet the insulating structure does not require numerous brace bars or other supports, does not provide gross voids within the insulating structure, and can also be employed as a novel means for elastically supporting the insulated inner container.

More specifically, it has been discovered that the transmission of heat across a solid-in-vacuum type insulation may be substantially reduced to a degree greater than has heretofore been possible by the use of a low heat conductive material which incorporates therein a multiplicity of radiation impervious shields to substantially eliminate heat leak by radiation.

Furthermore, it has been discovered that the placing of reflective shields in direct contact with an insulating material does not substantially impair the radiation barrier qualities of the shields.

The term "vacuum" as used hereinafter is intended to apply to sub-atmospheric absolute pressure conditions not substantially greater than 10 microns of mercury, and preferably below 5 microns of mercury. For superior quality results, the pressure should preferably be below 1 micron of mercury.

According to the invention, a vacuum insulated space is provided with a low heat conductive material having incorporated therein a multiplicity of radiation barriers disposed substantially transversely to the direction of heat flow in spaced relation to each other. The radiation-barriers or shields of the invention may comprise one or more sheets of heat absorbing material, or preferably thin sheets or layers of a material possessing high reflecting characteristics when exposed to infra-red radiation, such as aluminum or tin foil. The low conductive material also acts as a supporting and spacing material for retaining the radiation barrier sheets in uniformly spaced relation to each other independently of the thickness and stiffness of the barriers. In this manner it is possible for a large number of thin foils to be supportably mounted and maintained in position in an insulation space of limited thickness. A clearance of a few thousandths of an inch between foils is enough to effectively interrupt and reflect the radiant heat. In this way it is possible to provide a large number of shields in a very limited space, ranging up to several hundred shields per inch of composite insulation thickness.

Shown in FIG. 1 is a double walled heat insulating container having parallel inner vessel and outer casing walls 10a and 10b and an evacuated insulating space 11 therebetween. Disposed within the insulation space 11 is a composite insulation material 12 embodying the principles of the invention, and comprising essentially a low heat conductive material 13 having incorporated therein multiple reflective shields or radiation barriers

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14 in contiguous relation for diminishing the transfer of heat by radiation across the insulating space 11. The insulation appears as a series of spaced reflectors 14 disposed substantially transversely to direction of heat flow and supportably carried by the low-conductive insulating material. The insulating material uniformly contacts and supports the surface of each radiation shield in superposed relation and, in addition to its primary purpose of serving as an insulating material, constitutes a carrier and spacing material for maintaining a separation space between adjacent shields. No other supports are required to maintain the insulation in operative assembled relation.

The radiation shield material 14 to be used in the insulation material 12 of the invention may comprise either a metal or a metal coated material, such as aluminum coated plastic film, or other radiation reflective material. Radiation reflective materials comprising thin metallic foils are admirably suited in the practice of the present invention. The foils should have sufficient thickness to resist tearing or other damage during installation. For high-quality insulations, the foil should be as thin as practical consistent with strength requirements. Thinness is beneficial because it facilitates folding and forming the insulation to fit the contour of the insulation space. It also minimizes the weight of the container. In cryogenic vessels, low density is additionally important because it reduces the time and the quantity of expensive refrigeration needed to cool down the inner vessel and establish a stable temperature gradient through the insulation. Foil thicknesses between 0.2 mm. and 0.002 mm. are suitable, and when aluminum foil is employed, thickness between 0.02 mm. and 0.005 mm. are preferred.

A preferred reflective shield is $\frac{1}{4}$ mil (0.00025 in. or 0.0062 mm. thick) plain, annealed aluminum foil without lacquer or other coating. Also, any film of oil resulting from the rolling operation should be removed as by washing. Other radiation reflective materials which are susceptible of use in the practice of the invention are tin, silver, gold, copper, cadmium or other metals. The emissivity of the reflective shield material should be between about 0.005 and 0.2, and preferably between 0.015 and 0.06. Emissivities of 0.015 to 0.06 (98.5% to 94.2% reflectivity) are obtainable with aluminum and are preferred in the practice of this invention, while with more expensive materials such as polished silver, copper or gold, emissivities as low as .005 may be obtained. The above ranges represent an optimum balance between the high performance and high cost of low emissivity materials.

In a preferred embodiment, the reflective shields are perforated so as to permit gas in the insulation space to move radially through the insulation layers, rather than only parallel to the foil layers. This permits the gas molecules to migrate more freely towards the evacuation connection or towards a gas trapping means such as an adsorbent or getter.

The base or separating material of the invention is a low heat conductive material such as fiber insulation which is provided in an uncompacted, elastically compressible, resilient and fluffy state, preferably in the form of sheets. The present low conductive material is preferably sufficiently compressible so that the installed density of such material as an element of the composite insulation is at least twice that of the uninstalled material. The physical properties of this material, known as "webs" to those skilled in the art, must be closely controlled to obtain the highly efficient composite insulating material of the present invention. It has been found that compressible sheets of very fine, low conductive fibers which are matted but unbonded together are satisfactory. Resin bonding is frequently employed in the manufacture of fibrous materials but such bonding cannot be tolerated in the insulation of the present invention because of the resulting excessive solid conductive path.

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Suitable fibers include clean glass filaments having diameters between 0.2 and 5 microns such as those produced by the so-called flame attenuation process. A fiber diameter range of 0.5 to 3.8 microns is preferred in the practice of this invention. The above ranges represent preferred balances between increasing fragileness and cost of relatively small diameter fibers, and increased conductance and gas pressure sensitivity of relatively large diameter fibers, as will be discussed later in detail. Furthermore, the low conductive separating material of this invention preferably comprises fibers which are substantially randomly disposed within the plane in the installed condition, and the individual fibers are also preferably oriented in a direction substantially perpendicular to the flow of heat. It will be understood that as a practical matter, the fibers will not be individually confined to a single plane, but rather, in a finite thickness of fibrous material, the fibers will be generally disposed in thin parallel strata with, of course, some indiscriminate cross weaving of fibers between adjacent strata. Compressible fibers having diameters in the range of 0.75 to 1.5 microns such as those commercially designated as 108 or "AA" fiber, and fibers designated as 112 or "B" fiber having diameters in the range of 2.5 to 3.8 microns are normally prepared as webs, and are suitable for practicing this invention.

It is to be understood that the compressible, low conductive material which constitutes a preferred element of the present invention does not include "paper" type materials which are relatively smooth, non-compressible, and permanently compacted when provided in the sheet form. In many systems, the present compressible materials are superior to paper materials because in several respects, one being that they minimize the number and size of gross voids in the composite insulation when assembled in the compressed state. This means that the pressure sensitivity of the insulation is minimized; that is, the thermal conductivity does not increase at a rapid rate as the pressure in the vacuum space increases.

The reflective shield separating layer must be "low conductive" in the sense that it presents a high resistance to the flow of heat through the solid material of which it is composed. While we do not wish to be bound by any particular theory, it is believed the principal reasons for the far superior insulating effects achieved by the previously described fiber orientation are the relatively few fibers traversing the thickness of the insulating layer and the very large number of point contacts established between crossing fibers. These point contacts represent the points of bearing between adjacent fibers in the direction of heat flow, and as such, constitute an extremely high resistance to the flow of heat by conduction. In a given thickness of low conductive material, it is clear that more point contact resistances will be present in fine compressible fibers than in coarse fibers. Alternatively, for a given number of point contact resistances, fine fibers will permit a thinner separating layer than will coarse fibers. This is one important reason why extremely fine compressible fibers are preferred in this invention.

Another reason for using extremely fine compressible fibers is to reduce gaseous conduction through the insulation and to obtain an insulation which is relatively insensitive to moderate changes in residual gas pressure. The larger the particle size (e.g. fiber diameter) of the low conductive material, the larger will be the voids between the particles and the greater will be the heat transfer by solid conductance. Heat is transferred across the voids by molecules of the residual gas in the insulation space. However, the path of greatest resistance to heat flow is through the individual particles and across the point contacts between the particles. Gas conduction across the voids may, therefore, be viewed as a "short circuit" around the principal resistance. The rate of heat transfer by gaseous conduction is dependent upon the number of molecules present and upon the mean-free-path of molecular motion. Reducing the absolute pressure

reduces the number of molecules present to transfer heat, and for this reason, a good vacuum is important. However, reducing the absolute pressure will increase the mean-free-path of the molecules and tend to increase gaseous conduction. If the voids are large so that their average dimension is comparable to or exceed the mean-free-molecular path, then the adverse effect of increasing the mean-free-path essentially cancels out the beneficial effect of fewer molecules. For this reason, reducing the absolute pressure will not reduce gaseous conduction until the mean-free-path has lengthened to the point that molecular motion is restricted by the dimensions of the void spaces. This is why extremely low absolute pressures (e.g., 10^{-6} mm. Hg.) are required in straight vacuum systems or in coarse particle fillers where the dimensions across the void spaces are relatively long. In such systems, a slight increase in absolute pressure not only increases the number of molecules present but also reduces their mean-free-path so that the voids no longer restrict molecular motion. The gas then attains its maximum heat carrying capacity, and the full effect of the "short circuit" by gaseous conduction develops rapidly. In commercial vessels constructed of metal and subject to rough treatment, it is usually impractical to maintain extremely low absolute pressures such as 10^{-6} mm. Hg. in the insulation at all times. A very fine particle compressible material between the shields relaxes the vacuum requirement for the insulation and results in a dependable high-quality insulation system. Accordingly, for the aforementioned reasons it has been found that fiber diameters of between about 0.5 and 3.8 microns provide far superior quality insulation than fibers with larger diameters, and this constitutes the preferred range of the low-conductive material of the present invention.

The sequence of modes of heat transfer which might occur in a typical multi-layer insulation of aluminum foils which are proximately spaced from each other by layers of glass fiber having a fiber orientation substantially parallel to the aluminum foils and transverse to the direction of heat flow, might be as follows:

Referring to FIG. 4, radiant heat striking the first sheet of aluminum foil will for the most part be reflected, and the remaining part absorbed. Part of this absorbed radiation will tend to travel toward the next barrier by reradiation, where again it will be mostly reflected, part will travel by solid conduction, and a minor part by conduction through the residual gas. According to the solid conduction method of heat transfer, the heat leak proceeds along the fiber webs in what might be considered an irregular path, crossing relatively small areas of point contact between crossing fibers until it reaches the second sheet of aluminum foil, where the heat reflecting and absorbing process described above is repeated. Because of the particular orientation of the individual fibers in the webs, the path of solid conduction from the first sheet of aluminum foil to the second is greatly lengthened, and encompasses an indefinitely large number of point contact resistances between contacting fibers. By analogy it will be seen that a multi-layer insulation having a series of heat reflecting sheets and a compressible fiber oriented web layer of low conductive insulating material therebetween may be particularly efficient in preventing or diminishing heat losses by radiation as well as by conduction.

In the practice of the present invention, the radiation shield spacing may be between about 5 per inch using relatively thick webs for separation, and about 50 shields per inch using very thin webs having only a few fibers per unit area of the low conductive layer. A preferred range is between 10 and 30 shields per inch. These ranges represent preferred balances between the conductive and radiative modes of heat transfer as will now be explained in detail. With a given compressible web, the thickness of the layers may be varied considerably by applying more or less compression on the layer material during installation. However, it has been unexpectedly discovered that

the fine fiber materials of this invention are extremely sensitive to compression, and that a rather narrow optimum range exists for the number of radiation shields installed per unit thickness of composite insulation as previously defined. This optimum range is related to the emissivity of the radiation shields, and to the weight per unit area of the web layer used to separate the shields.

If the insulation is compressed excessively so as to install more than the optimum number of layers per unit thickness, then heat conductance increases sharply due to additional solid material being present to transfer the heat. The fibers are thereby crushed and matted to such a degree that numerous fiber-to-fiber contacts result in excess of the number needed for web strength and for radiation shield support purposes. On the other hand, if the composite insulation is relaxed excessively by installing fewer than the optimum number of layers per unit thickness, the heat transmission increases rapidly due to the decrease in the number of radiation shields per unit thickness and due to the increase in gaseous conductance. Gaseous conduction increases because the voids become larger, thus permitting greater freedom of molecular motion.

FIG. 8 illustrates the very pronounced effect of varying the density of the web materials by applying different degrees of compression during installation. Curve A correlates installed web density ρ_t with the portion k_{sc} of the heat transmission due solely to solid conduction through the fibers, and is represented by the following empirical equation:

$$k_{sc} = 1.1 \times 10^{-5} (\rho_t)^{2.4} \quad (1)$$

which may be written in the alternative form

$$\rho_t = \left(\frac{k_{sc}}{1.1 \times 10^{-5}} \right)^{.416} \quad (2)$$

The steep slope of the curve indicates the sensitivity of the web to compression, and illustrates the detrimental effect of crowding too many layers in a given space or of requiring the composite insulation to support a large sustained load in service as discussed later in detail. Curves B₁, B₂ and B₃ show the change in radiant heat transmission which normally accompanies a change in web density. As the insulation is compressed, the separating web-layers become thinner and more shields can be installed in a unit thickness of composite insulation with the result that heat transfer by radiation is decreased. The "B" curves are determined by the general formula:

$$k_r = 4.2 \times 10^{-4} \frac{\epsilon \gamma}{\rho_t} \quad (3)$$

where k_r is the component of the total heat transmission due to radiation, ϵ is the effective emissivity of the foil surface in the assembled condition, γ is weight per unit area of the web layer in grams/sq. ft., and ρ_t is the installed web density in lbs./cu. ft. Thus, each of the "B" curves is typical for a given foil emissivity ϵ and a given weight per unit area of the web layer. For example, curve B₂ is suitable for a web layer of 4.7 grams per sq. ft. used with a foil emissivity of .021 for which the product $\epsilon \gamma$ is $.021 \times 4.7 = 0.10$. If for example an installed web density ρ_t of 3.0 lbs./cu. ft. is employed, curve B₂ indicates that the contribution of radiation to the total heat transmission is 0.014×10^{-3} B.t.u./ (hr.) (ft.) (° F.). The number of layers of foil and web materials which must be installed per inch of composite insulation thickness in the above examples is ρ_t or $(3.0/4.7) (453.6/12) = 24$ layers/inch.

It should be emphasized that " γ " is defined as the weight per unit area of the total web layer used to separate adjacent foils. Thus web material available in sheets weighing 2 gms./sq. ft. will have a value " γ " of 2.0 if used singly between foils, and a value of 4.0 if used in a double thickness between foils.

Curves C_1 , C_2 and C_3 are the sums of heat transmission by solid conduction and by radiation, e.g., C_1 is the sum of A and B_1 . Assuming that heat transmission by gaseous conduction is negligible, the "C" curves therefore represent total heat conduction K_a for the insulation. It is entirely proper to assume that gaseous conduction will be negligible for the high quality insulations of this invention wherein heat transfer by all modes is minimized. In order to justify the installation of a large number of radiation shields, it is first necessary to essentially eliminate gaseous conduction by employing a suitable vacuum and small fiber diameter web material so that, without shields, radiation becomes a major contributor to total heat transmission.

The "C" curves exhibit definite minimums with extensions which approach the radiation curve B on the left and the solid conductance curve A on the right. It is apparent that unless the compression sensitivity of the web materials is recognized and properly used in accordance with the present invention, the composite insulating quality may be only a fraction of that which may be obtained by operating in the minimum area of the "C" curves. The "C" curves also illustrate the highly detrimental effect of using the composite insulation to withstand sustained physical loads in service. The occasional practice of requiring the insulation to support the weight of the inner vessel is precluded for the present insulation since the latter would be compressed excessively beneath the vessel and would be too loose above the vessel. The common practice of allowing the insulation to support or brace the walls of the vacuum space against sustained atmospheric pressure force is also to be avoided, that is, the composite multi-layered insulation of the present invention is external load-free.

Optimum web density may be obtained by differentiating the sum of Equations 1 and 2 with respect to density ρ_t , and the following equation is obtained:

$$\rho_t(\text{Opt.}) = 2.26(\epsilon\gamma)^{0.294} \quad (4)$$

Additional algebraic manipulation leads to an expression for K_a minimum as follows:

$$K_a(\text{min.}) = 2.65 \times 10^{-4}(\epsilon\gamma)^{0.706} \quad (5)$$

Solution of Equations 3 and 4 to eliminate $\epsilon\gamma$ provides the expression for curve "D" of FIG. 8 as follows:

$$K_a(\text{min.}) = 0.374 \times 10^{-4}(\rho_t \text{Opt.})^{2.4} \quad (6)$$

Returning to the illustrative example using insulation materials corresponding to curves B_2 and C_2 , it will be seen that the selected density ρ_t of 3.0 lb./ft.³ is by no means optimum for the installed composite insulation. A density of 3.0 results in an overall heat transfer coefficient of about 0.17×10^{-3} B.t.u./(hr.)(ft.)(°F.), whereas the materials are capable of providing a coefficient of 0.05×10^{-3} B.t.u./(hr.)(ft.)(°F.) if installed with an optimum density of 1.2 lb./ft.³.

FIG. 9 is a graph of Equations 4 and 5 which permits the designer to select materials and to install them properly so that he may obtain a required K_a value in the most economical manner. Assuming any desired overall heat transfer coefficient K_a , the necessary emissivity-to-web weight relationship can be determined from curve A of FIG. 9. Also, the proper installed density for the web material can be determined from curve B. Once the web weight is selected, the number of layers per unit thickness (N) may be calculated using the optimum installed density:

$$N = (\rho_t/\gamma)(453.6/12) \quad (7)$$

For preferred practice of the invention, a practical limitation is imposed by the physical characteristics of the materials. From FIG. 8, one might infer that ultimately, best performance would be obtained at extremely low densities below those included on the curves, pro-

vided that materials can be found of suitably low emissivity and web weight. However, the insulation must be compressed sufficiently to prevent sagging and excessive wrinkling, and to maintain contact between the webs and the shields. Sagging and wrinkling produces large gross voids within the insulation which take up space in the insulation compartment and contribute little to the insulating effect. Since K_a "ratings" for insulations are based on their effectiveness per unit thickness, it will be apparent that sagging or excessive wrinkling will seriously reduce the K_a value. Contact is desirable to produce sufficient friction between the low conductive layers and reflective shields so that the composite insulation may be handled easily and without damage during assembly of equipment such as insulated containers. In order to avoid difficulty, it has been found that the installed density of the web material should be not less than 0.5 lb. per cu. ft. The heavy vertical dashed line on FIG. 8 at $\rho_t=0.5$ defines this preferred boundary.

The horizontal dashed line on FIG. 8 representing $K_a=0.8 \times 10^{-3}$ approaches the best practical insulation of the prior art, i.e., powder-in-vacuum insulation and represents the upper limit of applicability of this invention. Powders are normally available in finer particle size than webs, and for systems permitting K_a values above about 0.8×10^{-3} , powders are preferable in order to utilize their lower gas pressure sensitivity.

The superiority of the web-type alternate layer insulations of this invention is shown clearly by comparison with points E, F, and G on FIG. 8. Point E represents typical performance of fine perlite powder-in-vacuum, while point F represents performance of a sub-micron particle size silica aerogel in vacuum. Point G is the performance of a clean glass cloth woven of 5-6 micron diameter fibers and having a weight of about 2.6 grams per sq. ft. This cloth was tested in alternate layers with aluminum foil in the same manner as the web-type materials. In woven materials, the fibers are not randomly oriented in the plane of the sheet, but instead bundles of fibers in close longitudinal contact pass alternately from side to side through the sheet. This results in a very high density material which exhibits very high heat conductance through the fibers. Due to the openness of the weave, cloth materials are also very gas pressure sensitive.

It is to be understood that employment of reflective shields with the prior art powder materials under a vacuum would not provide a workable insulating system. This is primarily due to the fluid and settling characteristics of powders, which are magnified by the movement and vibration associated with portable systems. Also, foam-type materials and coarse, non-oriented or bonded fibers exhibit such high solid conductance that even used with radiation shields, would produce thermal conductivities well above the range of this invention. Similarly, non-vacuum insulating systems of all types are characterized by extremely high thermal conductivities due to the overwhelming contribution of gaseous conduction.

As may be concluded from the previous discussion an important advantage of the insulation of this invention is the very low coefficients of heat transmission which may be obtained. For example, using an insulation consisting of alternate layers of aluminum foil having an effective emissivity of 0.058 and a 4.7 gm./sq. ft. web of oriented, unbonded type "B" compressible glass fiber, a thermal conductivity coefficient of 0.118×10^{-3} B.t.u./(hr.)(ft.)(°F.) has been obtained at a near-optimum web density of 1.6 lbs./cu. ft. If the illustrative double-walled container described above were insulated with this material, an insulation thickness of only 1.31 inches would be required for an evaporation rate of 1% per day or contained liquid oxygen. In order to further demonstrate the effectiveness of this insulation, Table I compares its thermal conductivity with that of the prior art insula-

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Table I

Type of Insulation	Absolute Pressure in Vacuum Space Microns Mercury	Thermal Conductivity B.t.u./ (hr.) (ft.) ($^{\circ}$ F.)
Powder-in-vacuum insulating systems in accordance with U.S. Patent 2,396,459...	0.1	9.2×10^{-4}
High vacuum-polished metal surface system with radiation shields in accordance with U.S. Patent 2,643,022	0.01	1.9×10^{-4}
Insulation illustrative of this invention: "B" fiber web 4.7 gms./sq. ft. alternating with 94.2% reflective aluminum foil compressed to a fiber density of 1.6 lbs./cu. ft.	0.1	1.18×10^{-4}

It is thus seen that the quality of the present insulation is over eight times that of the powder-in-vacuum type. Compared with the high vacuum-polished surface type, this invention reduces the conductivity more than 60% and simultaneously permits use of a practical vacuum. By using foils of higher reflectivity and webs of lighter weight, still lower coefficients of thermal conductivity are obtainable.

Another advantage of the web-type alternate layer insulation is its low weight per unit heat flow resistance. This is an important characteristic for two reasons: first, it achieves minimum tare weight in portable containers, and thus facilitates handling and reduces transportation costs; second, by minimizing the insulation weight one also reduces the amount of expensive refrigeration needed for cooling the inner vessel to operating temperature and for establishing a stable temperature gradient through the insulation thickness. An insulation's "weight per unit heat flow resistance" is measured by the factor $(k)(\rho)$, where k is the coefficient of heat transmission (reciprocal of heat resistivity) and ρ is the total density of the material including shields. For example the alternate-layer insulation described above with a coefficient of 0.118×10^{-3} B.t.u./ (hr.) (ft.) ($^{\circ}$ F.) was found to have a total density ρ of 2.5 lbs./cu. ft. Thus its $(k)(\rho)$ factor is 0.29×10^{-3} , but the present invention contemplates factors as high as 1×10^{-3} . By contrast the $(k)(\rho)$ factor for perlite-in-vacuum is about 9.6×10^{-3} and that for sub-micron size silica aerogel in vacuum is about 6.0×10^{-3} . An alternate layer insulation using aluminum foil with a woven glass cloth was found to have a $(k)(\rho)$ factor of 2.75×10^{-3} , still about 10 fold greater than the illustrative web and foil insulation of this invention.

As k values are reduced, low total density becomes increasingly important in order to obtain a reasonable cool-down time for the insulation when placed in service. Reference to point G located on FIG. 8 shows that while woven glass cloth with foils achieves a significant improvement in k -factor over the prior art, it unfortunately has an extremely high density (22.7 lbs./ft.³ density of fiber alone). If a warm container insulated with a 3-inch thickness of such insulation were filled with liquid nitrogen, about 1200 hours time is required to approach within 10% of a steady temperature gradient. On the other hand if 3 inches of a low density web and foil insulation is used, only 600 hours time is required to reach an equivalent gradient in spite of the fact that the k value is approximately $\frac{1}{3}$ that of the glass cloth and foil insulation. A thickness of 9 inches of the glass cloth and foil insulation would be required to achieve a heat flow resistance equal to 3 inches of web and foil, but such a bulky insulation would take over 10,000 hours to approach a stable gradient.

Another of the many important advantages in the thermal insulation of the present invention is that the flexibility of the layers of aluminum foil and fiber glass web allows the insulation thickness as a whole to be plially bent so as to conform to irregularities and changes in the surface conditions of the container to be insulated. The composite material of the invention is adapted to be

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applied to contoured surfaces, and is particularly well suited for insulating either flat or cylindrical surfaces.

Obviously the multiple foil insulation of the invention may be mounted in the insulation space in any one of a variety of ways. For example, in FIG. 5, the insulation 12 may be mounted concentrically with respect to the inner container 10a, or it may be, as in FIG. 4, spirally wrapped around the inner vessel with one end of the insulation wrapping in contact with the inner vessel 10a, and the other end nearest the outer casing 10b or in actual contact therewith, the latter form of mounting being preferred and illustrated herein. Referring to FIG. 4, the metal foil may be loosely spirally wrapped around the inner vessel 10a, the tightness and number of turns being selected preferably to obtain optimum performance as discussed above.

It will be recognized that because of the difficulty involved in conformably applying the composite insulation material 12 of the invention to surfaces other than flat or cylindrical surfaces without sacrificing insulating qualities, for maximum benefit it may be advantageous in some instances to employ a supplementary low heat conductive material in combination with the insulation 12.

In the modification shown in FIG. 6 the composite insulation material 12 of the invention may be employed in the cylindrical portion 11a of the insulation space 11, and the end portions 11b of the insulation space, including the flat bottom portion and the upper spherical portion, provided with a supplemental low heat conductive material 16. The supplemental low heat conductive materials which may be used in the terminal sections 11b may comprise a finely divided powder of the type disclosed in U.S. Patent No. 2,396,459, or a thermal insulation such as disclosed in the co-pending application to L. C. Matsch et al., Serial No. 580,897, filed April 26, 1956, now Patent No. 2,967,152, or any other suitably low conductive material.

Coupled with the composite insulation 12, the supplemental insulation 16 provides the means for producing low thermal heat transfers in containers of a wide variety of shapes. The cooperative relationship between the supplemental insulation 16 and the composite insulation 12 meets the requirements of the most critical present day insulation standards, and has extended the usefulness and capabilities of the present invention.

A very significant advantage of the present invention arises from the elastic properties of the insulation, particularly when a fibrous insulation is employed in the annular insulating space of a double walled container. The ability of the insulation to "give" and resist movement of the inner container, and to restore or expand itself when the forces exerted upon it are relaxed, enables it to operate along the lines of a shock mount. Obvious advantages to using the insulation as an elastic support are that the inner vessel is maintained in substantially centered position, and the need for lateral braces or other centering devices is obviated, thus further reducing the heat leak into the container. It is to be understood, however, that the present invention does not provide vertical support for the inner vessel, and that specific means for vertical support must be provided.

In the preferred modification shown in FIG. 7, means are provided for facilitating the evacuation of the insulating space between walls 110a and 110b after the composite insulation of the invention has been installed therein. For this purpose, the aluminum foil 114 is provided with passages or perforations 115 preferably arranged in helical or spiral rows, the perforations in any one layer of foil being out of registry with the perforations in the adjacent foil layers. This arrangement affords means for providing a suitable number of perforations in the foil 114 without noticeably reducing the shielding properties thereof. Suitable perforations are $\frac{1}{16}$ in. diameter holes pricked or punched on $1\frac{1}{2}$ in. centers.

The function of the perforations is to permit gas in

the insulation space to move radially through the insulation layers, rather than only parallel to the foil layers. This permits the gas molecules to migrate more freely towards the evacuation connection or toward a gas trapping means such as an adsorbent or getter. Also, the perforations permit the migration of condensable gases to the cold outer wall 110a of the inner vessel, where they form deposits having negligible vapor pressure. Perforations are especially beneficial in systems where the insulation does not fill the entire space but is omitted from one or more free flow channels running from the evacuation connection to remote points within the insulation space. For example in FIG. 7, space 116 between the outer-most foil layer 113a and the outer wall 110b of the vacuum space comprises an open channel leading to an evacuation connection (not shown). Gas molecules trapped near cold wall 110a are free to migrate through the holes 115 in foils 114 and through webs 113 until they reach low flow resistance channel 116.

From the above description it will, therefore, be seen that the present invention provides in a solid-in-vacuum type insulation, a compressible low heat conductive material having incorporated therein multiple radiation shields for impeding radiative heat transmission through the insulation, while minimizing the flow of heat by conduction therethrough. The low conductive material uniformly supports and maintains the radiation shields in spaced relation. A low conductive material which is admirably suited for use in the practice of the invention is one having a fibrous structure oriented in a direction perpendicular to the direction of heat flow. Possessed of a relatively small percentage of solid material per unit volume, the low conductive insulating material provides a very small, solid conduction heat path between radiation foils, and is remarkably efficient in minimizing the transmission of heat leak by conduction.

Insulating systems of the invention, using a fine diameter, low conductive, compressible fiber-type insulating material, have been found to be superior to any known insulating system. Employing coarser, low-conductive insulating fibers, the present insulation achieves low thermal conductivities, which are comparable or superior to those obtained with either high quality straight vacuums or the best powder-in-vacuum systems known, yet is considerably less expensive than either of these forms of insulation, and does not require as low absolute pressures as straight vacuum-polished metal insulating systems.

It will be understood that variations and modifications may be effected without departing from the novel concepts of the present invention. For example, independent support means such as high strength plastic spacers, may be provided in the insulation space to support the walls defining such space from the load of atmospheric pressure.

This is a continuation-in-part application of my application Serial No. 597,947, filed July 16, 1956.

What is claimed is:

1. In an apparatus provided with a vacuum insulating space, a composite multi-layered, external load-free insulation in said space comprising low conductive fibrous sheet material layers composed of fibers for reducing

heat transfer by gaseous conduction and thin, flexible radiant heat reflecting shields, said radiant heat reflecting shields being supportably carried in superposed relation by said fibrous sheet layers to provide a large number of radiant heat reflecting shields in a limited space for reducing the transmission of radiant heat across said space without perceptively increasing the heat transmission by solid conduction thereacross, each radiant heat reflecting shield being disposed in contiguous relation on opposite sides with a layer of the fibrous sheet material, the fibers of said fibrous sheet material being oriented substantially perpendicular to the direction of heat inleak across the insulating space, said fibrous sheet material being an elastically compressible web composed of fibers having diameters between about 0.2 and 5 microns, said radiant heat reflecting shields having a thickness less than about 0.2 mm. and being perforated to provide flow paths through the shields, and said multi-layered composite insulation being generally spirally wound in the insulation space to provide more than 5 radiant heat reflecting shields per inch of said composite insulation.

2. In an apparatus provided with a vacuum insulating space, a composite multi-layered, external load-free insulation in said space comprising low conductive fibrous sheet material layers composed of fibers for reducing heat transfer by gaseous conduction and thin, flexible radiant heat reflecting shields, said radiant heat reflecting shields being supportably carried in superposed relation by said fibrous sheet layers to provide a large number of radiant heat reflecting shields in a limited space for reducing the transmission of radiant heat across said space without perceptively increasing the heat transmission by solid conduction thereacross, each radiant heat reflecting shield being disposed in contiguous relation on opposite sides with a layer of the fibrous sheet material, the fibers of said fibrous sheet material being oriented substantially perpendicular to the direction of heat inleak across the insulating space, said fibrous sheet material being an elastically compressible web composed of fibers having diameters between about 0.2 and 5 microns, said radiant heat reflecting shields having a thickness less than about 0.2 mm. and being perforated to provide flow paths through the shields, and said multi-layered composite insulation being disposed in the insulation space to provide more than 5 radiant heat reflecting shields per inch of said composite insulation.

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