

March 18, 1969

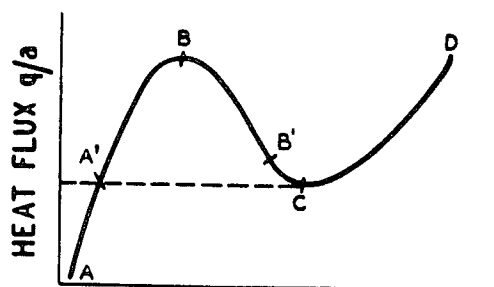
W. J. TIMSON

3,433,294

BOILING HEAT TRANSFER SYSTEM

Original Filed Dec. 6, 1963

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ΔT BETWEEN THE SURFACE OF THE SOLID
AND THAT OF THE BOILING LIQUID

Fig. 1.

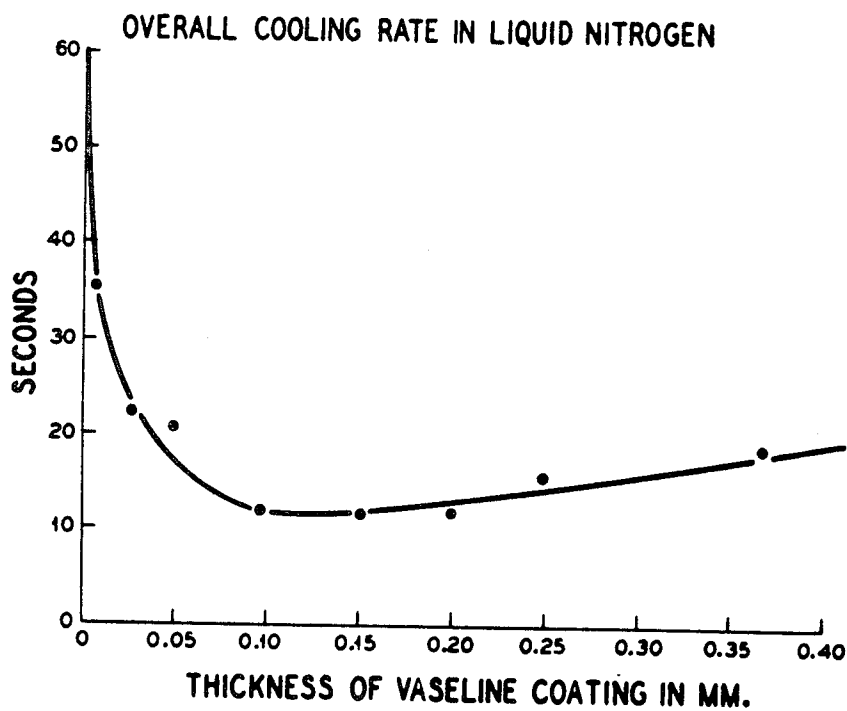


Fig. 2.

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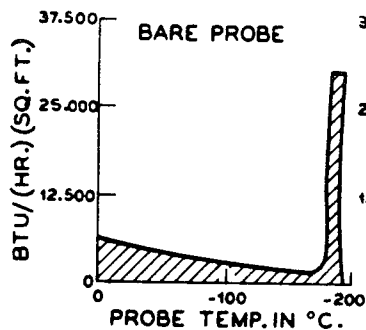


Fig. 3.a

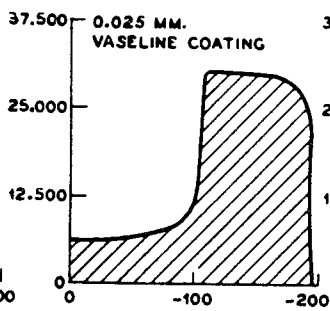


Fig. 3.b

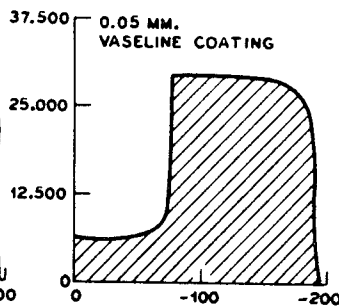


Fig. 3.c

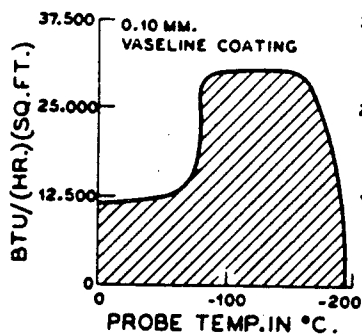


Fig. 3.d

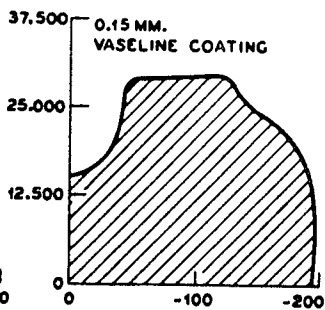


Fig. 3.e

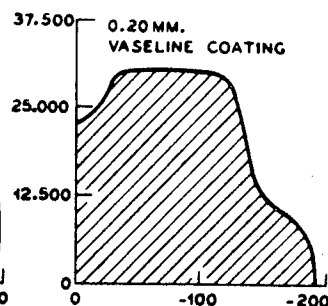


Fig. 3.f

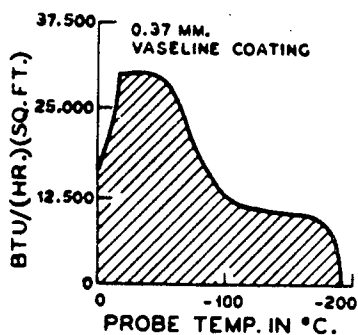
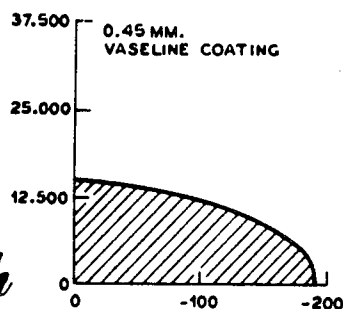


Fig. 3.g

Fig. 3.h



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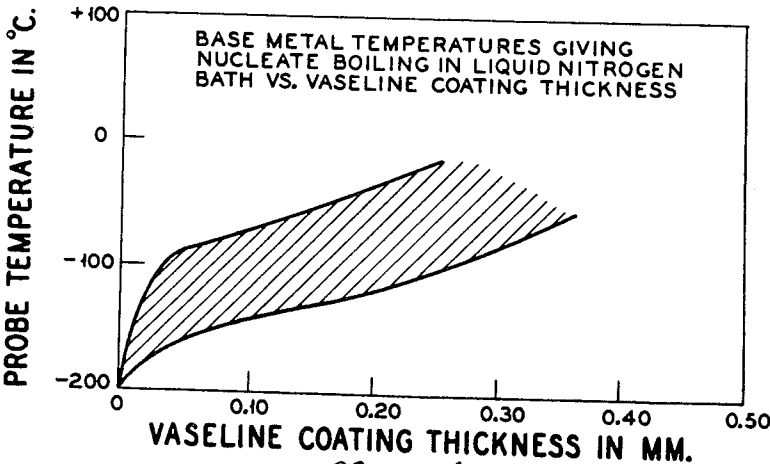


Fig. 4.

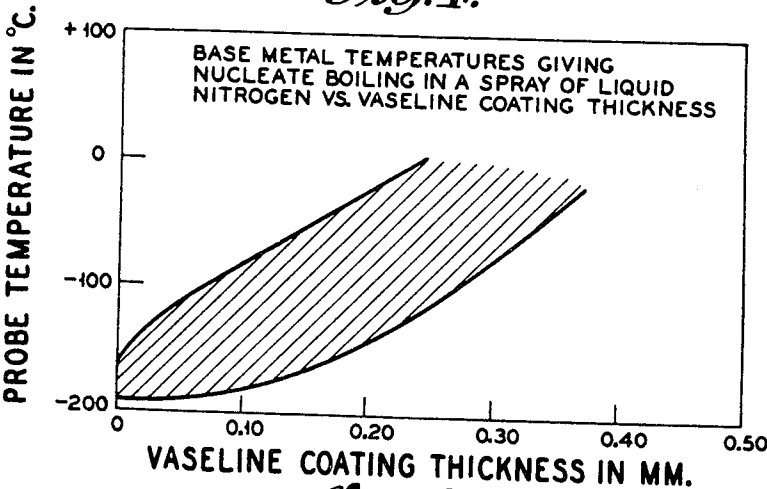


Fig. 6.

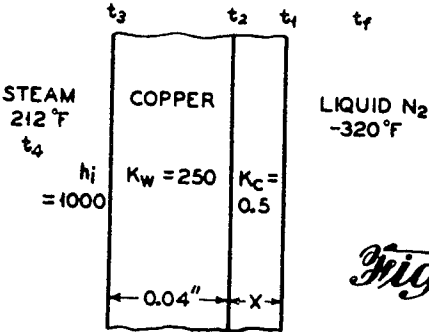


Fig. 7.

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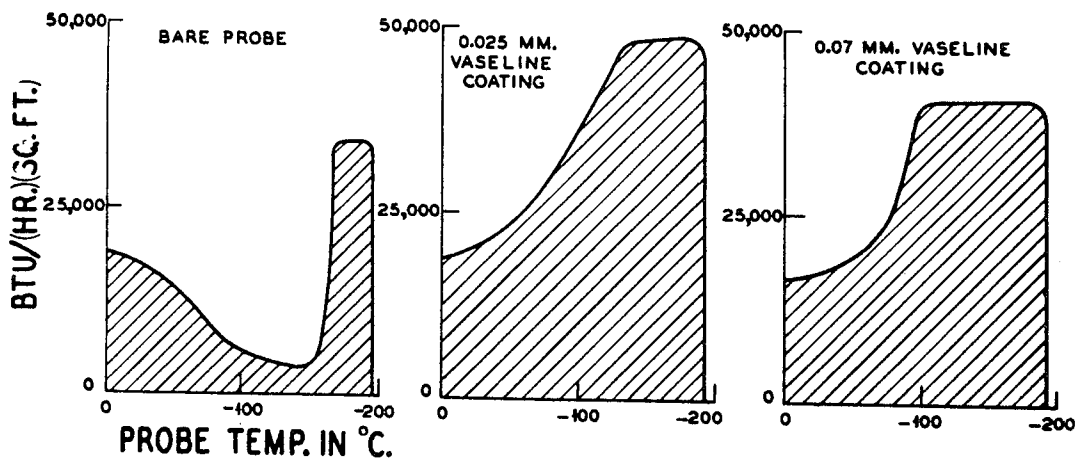


Fig. 5.a

Fig. 5.b

Fig. 5.c

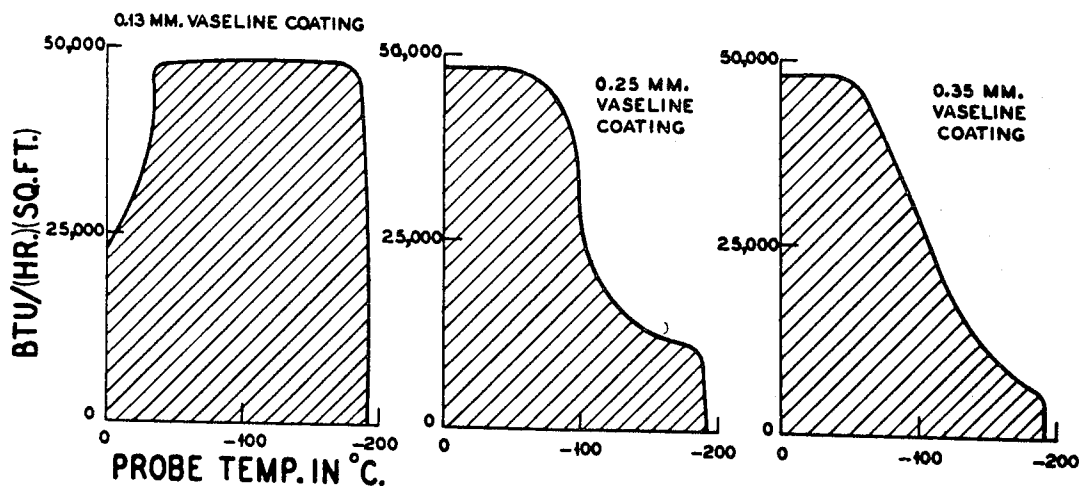


Fig. 5.d

Fig. 5.e

Fig. 5.f

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BOILING CURVES SHOWING THE EFFECT OF
COPPER POWDER ON HEAT TRANSFER

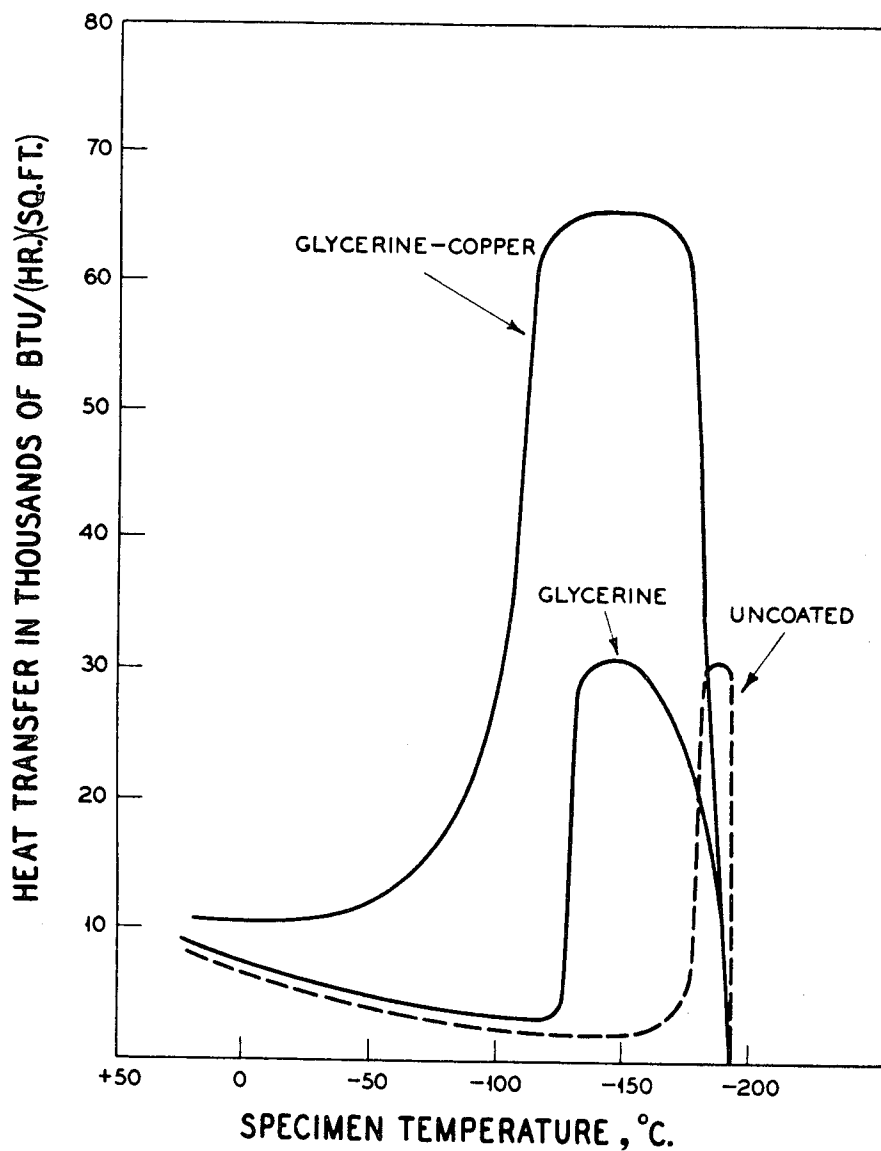


Fig. 8.

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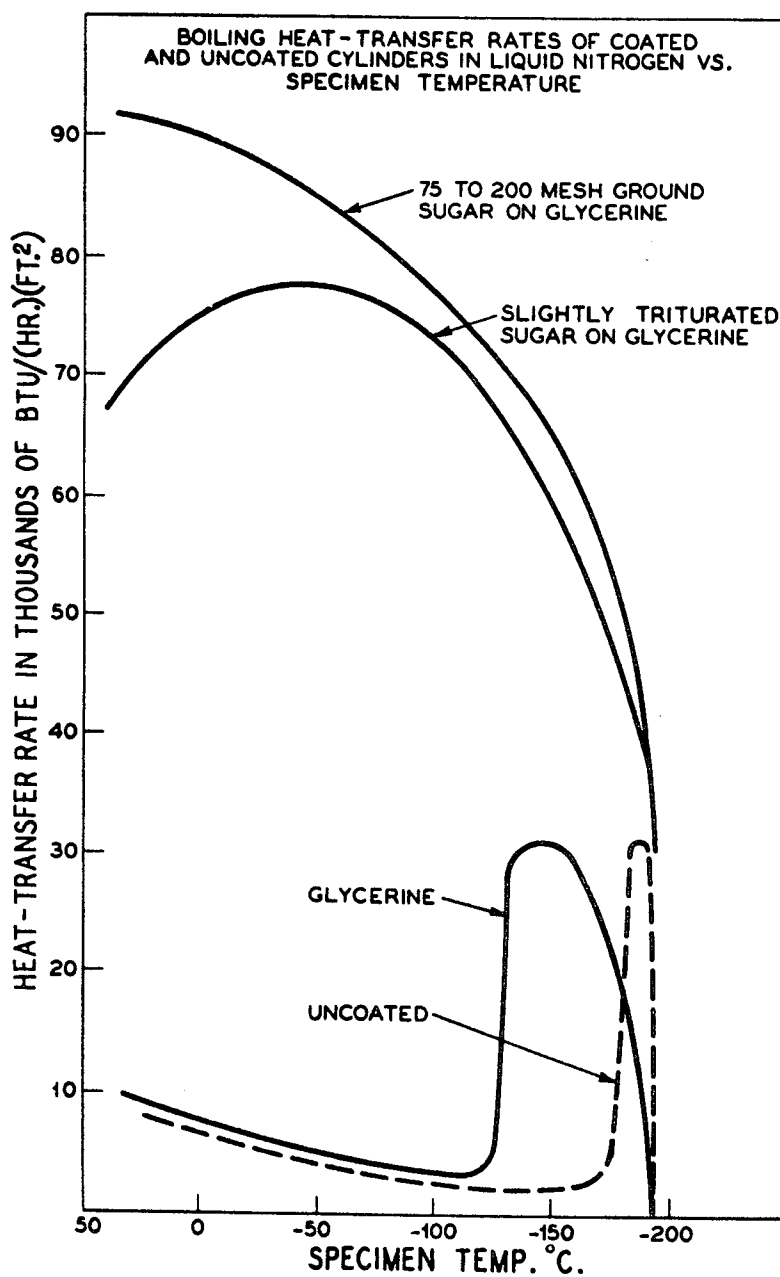


Fig. 8a

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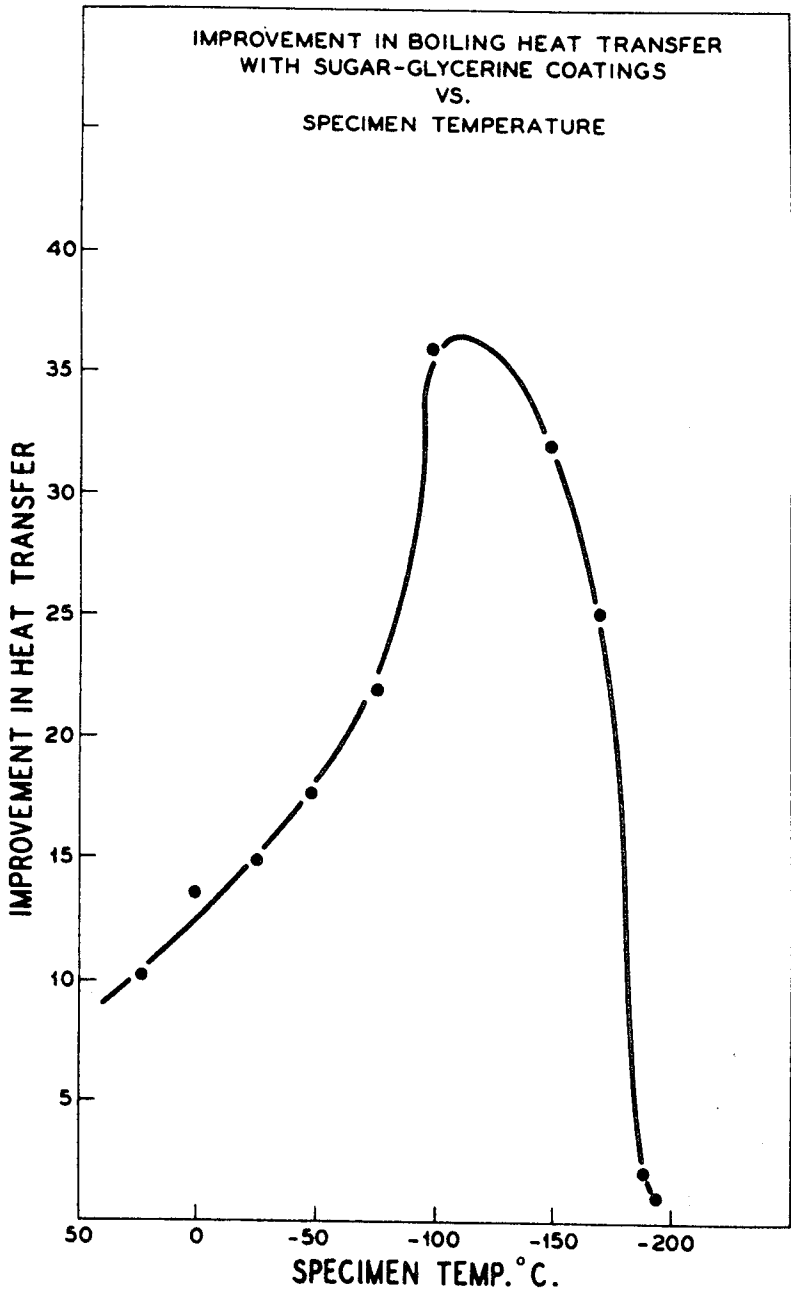


Fig. 9.

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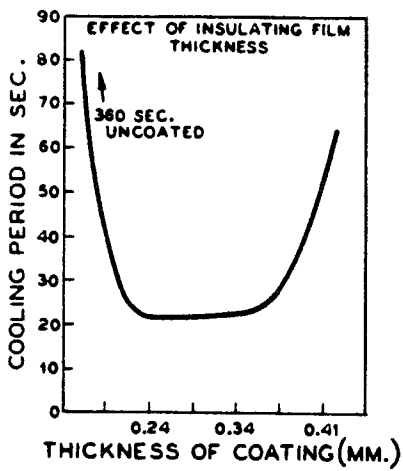


Fig. 10.a

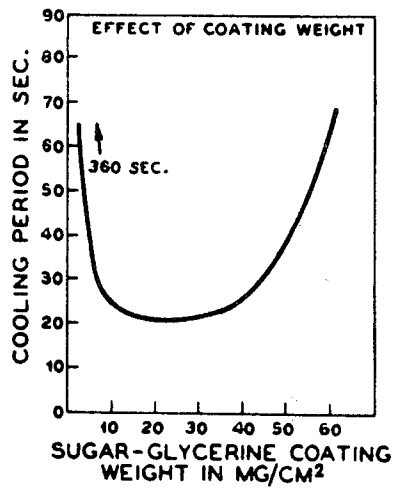


Fig. 10.b

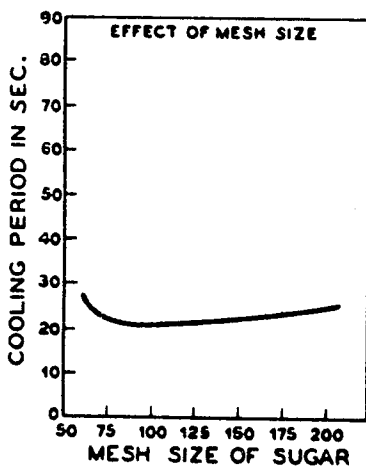


Fig. 10.c

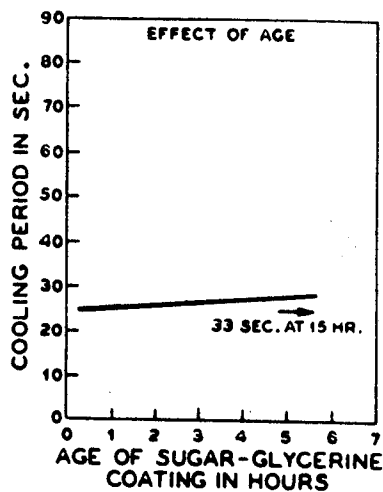


Fig. 10.d

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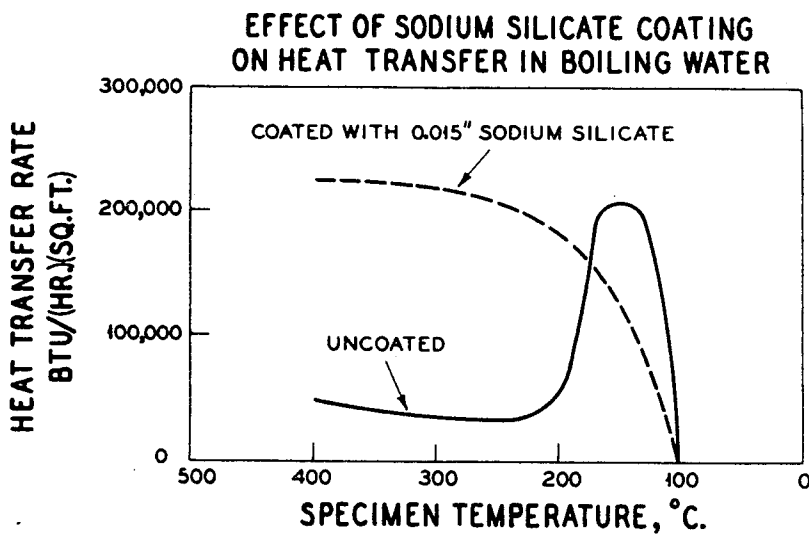


Fig.11.

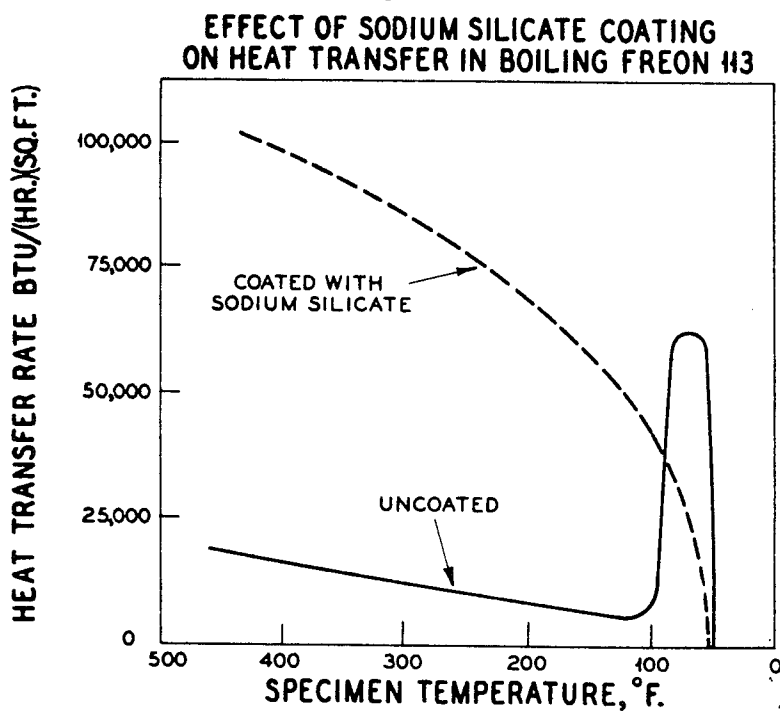


Fig.12.

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EFFECT OF GLYCERINE-SUGAR POWDER
COATING ON HEAT TRANSFER IN
BOILING FREON-22

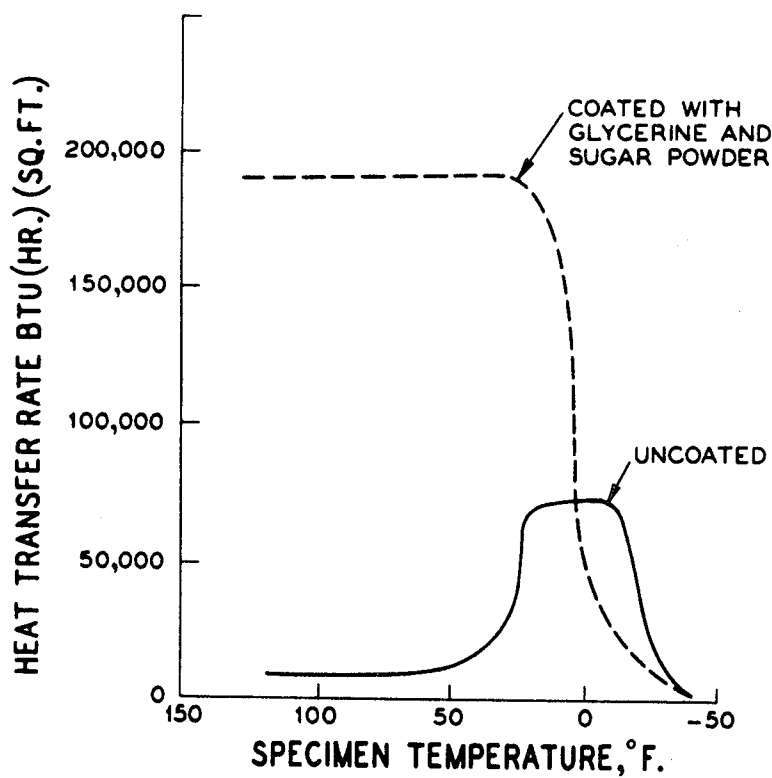


Fig. 13.

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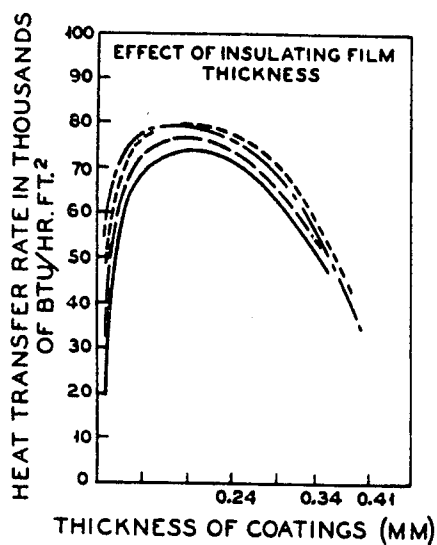


Fig. 14.a

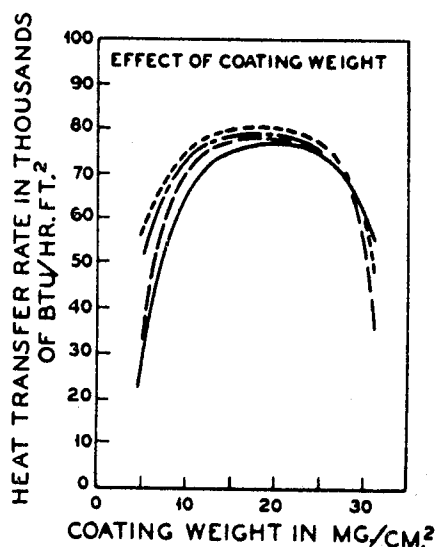


Fig. 14.b

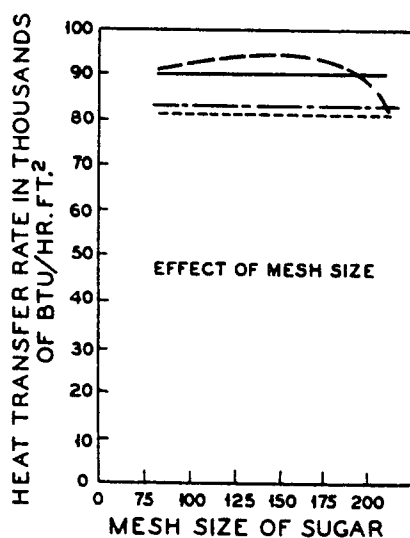


Fig. 14.c

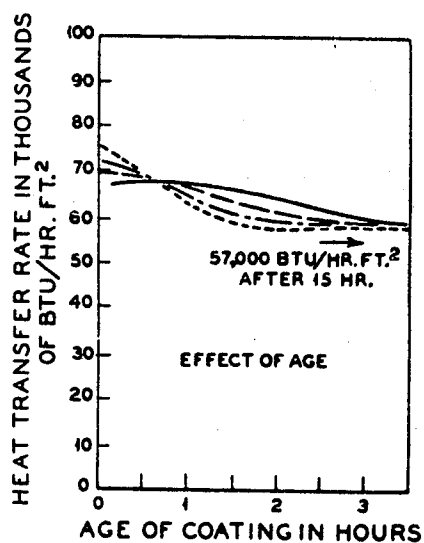


Fig. 14.d

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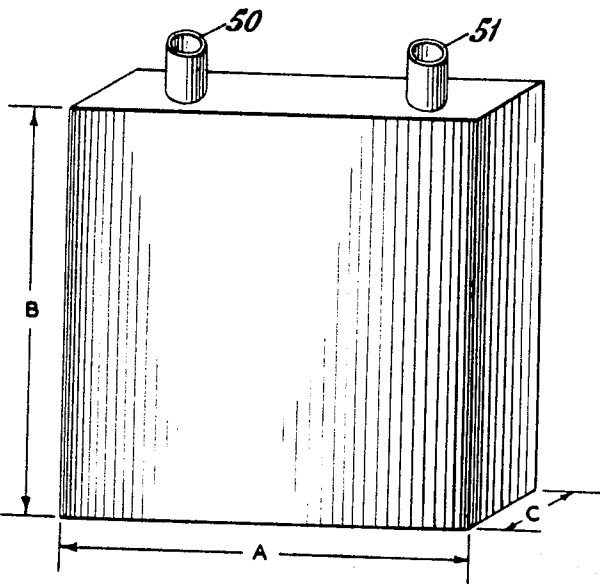


Fig. 15.

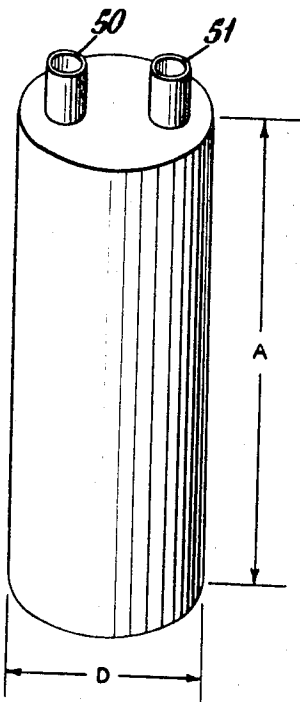


Fig. 16.

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BOILING HEAT TRANSFER SYSTEM

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Original application Dec. 6, 1963, Ser. No. 329,350, now Patent No. 3,291,198, dated Dec. 15, 1966. Divided and this application July 7, 1966, Ser. No. 586,313

U.S. Cl. 165—1

9 Claims

Int. Cl. F28c 3/00

ABSTRACT OF THE DISCLOSURE

Heat transfer between boiling liquid such as liquid nitrogen and a metal solid in thermal contact with the liquid is increased under conditions such that an insulating film of superheated vapor would normally exist, by coating the metal surface with material of lower thermal conductivity than the metal, the coating being of sufficient thickness to reduce the temperature difference between the boiling liquid and the metal surface and prevent the creation of the insulating film.

This application is a division of Ser. No. 329,350 filed Dec. 6, 1963 and now Patent No. 3,291,198, granted Dec. 13, 1966.

This invention relates to the art of heat transfer to boiling liquids. More particularly it relates to a method for controlling and improving the heat transfer from a solid to a boiling liquid under conditions such that the temperature difference between the solid and the boiling liquid is so great that film boiling, as defined hereinafter, normally occurs without the use of this invention; and to a process for freeze-preserving biological substances by controlling and improving heat transfer from a biological substance-containing container to a boiling liquid.

Heat transfer occurs either as a steady state or an unsteady state process. In all cases of heat transfer by conduction, convection or boiling, a temperature gradient must exist. In cases where the temperature remains constant with time and position, the heat transfer is a steady state process. Thus, if a steam-heated tube is submerged in a pool of boiling liquid nitrogen, the temperature of the tube will fall during the first period of immersion, but eventually becomes substantially constant and so remains under steady-state conditions as long as steam is allowed to flow through the submerged tube at a constant rate.

Unsteady state heat transfer prevails in cases where the temperature in a system varies with time and position. Thus a quenching operation involves an unsteady state heat-transfer process. The temperature at different points in the specimen will fall at various rates during the quenching operation. Since heat-transfer rates are affected by changing temperatures, these rates will also be variable.

When a liquid is boiling at a given pressure, the heat-transfer rate is dependent upon the temperature difference between the surface of the solid and that of the boiling liquid. This dependence results in specific regimes of boiling which may be described graphically. FIG. 1 shows the general shape of a boiling curve in which the heat flux, Q/A , is plotted against the difference in temperature, ΔT , between the heat transmitting surface and that of the boiling liquid. It should be noted that the coordinates are plotted on a logarithmic scale. As the surface temperature of the solid in contact with the liquid is increased above the saturation temperature of the liquid, vapor bubbles are formed at specific areas on the surface (nucleation sites). These bubbles grow to a critical size, detach themselves from the surface and rise through the liquid. Increasing the ΔT from A to B along the curve

results in a greater number of nucleation sites and an increasing frequency of bubble formation from each site. The turbulence caused by these bubbles result in greater heat transfer until point B is reached. At point B, called the point of critical heat flux, the number of nucleation points is so great that the bubbles begin to interfere with one another and a vapor film is formed over the surface. In the ΔT region from B to C, this vapor film is unstable and is constantly in the process of being dissipated and reformed at a very rapid rate. The low thermal conductivity of the vapor film reduces the heat-transfer rate in this region. At point C the vapor film becomes stable and completely blankets the solid, thus forming a relatively quiescent barrier over the hot surface. Beyond C the heat-transfer rate increases partly due to radiation effects and partly because of the increase in thermal conductivity of the vapor with temperature. In summary, the regions may be defined as follows:

ΔT range:	Boiling regime
A $\rightarrow$ B	Nucleate, pinpoint, or local.
B $\rightarrow$ C	Unstable film.
Beyond C	Stable film.

While the boiling curves for all liquids have essentially the same shape, the values associated with the curves will vary widely. For water at atmospheric pressure, point B corresponds approximately to a ΔT of 45° F. and a heat flux of 330,000 B.t.u./(hr.)(ft.²). Point C occurs at a ΔT of approximately 100° F. and a heat flux of about 100,000 B.t.u./(hr.)(ft.²). For liquid nitrogen at atmospheric pressure, point B corresponds approximately to a ΔT of 10° F. and a heat flux of about 32,000 B.t.u./(hr.)(ft.²) and point C corresponds to a ΔT of 30° F. and a heat flux of about 2,000 B.t.u./(hr.)(ft.²).

The various regions of boiling may be illustrated by considering a pan of water being heated on a stove. The water immediately next to the heat source first reaches its saturation temperature and then becomes slightly superheated. Small bubbles then begin to be formed at discrete spots on the bottom unless the surface is such that there are no nucleate spots in which event the water layer becomes superheated and unstable boiling occurs. These bubbles rise and are condensed in the cooler liquid. As heat continues to be applied to the bottom of the pan, bubbles are formed at more and more spots and the frequency of formation at each spot increases. This is the region of nucleate boiling. A point is eventually reached, however, when so many bubbles are being formed that they interfere with one another and an unstable vapor film is formed on the bottom of the pan. The explosive growth and collapse of this film is immediately apparent at the surface of the liquid as relatively large volumes of vapor are released causing a great deal of turbulence sometimes resulting in the liquid "boiling over." This is unstable film boiling. Consider now that the pan has boiled dry and a small amount of water is dropped onto the bottom. Then, the so-called "Leidenfrost" phenomenon occurs, i.e., water globules dance on the hot surface without sensible evaporation. This is because a film of superheated vapor exists below each water globule and serves as a thermal insulation between the heating surface and the water. This is stable film boiling.

The prior art has employed numerous methods for improving heat transfer to boiling liquids. The most commonly used method for improving heat transfer in boilers and the like is to clean the surface of boiler tubes by scraping scale deposits and dirt off the tubes. This decreases the ΔT across the tube and increases the ΔT between the surface of the tube and the boiling liquid, whereby heat transfer is increased. The improvement of boiling heat transfer by cleaning the tubes of scale deposits

is practical only when the temperatures in the boiler are such that the boiler operates in the nucleate boiling regime from A to B on FIG. 1. It cannot be used to increase heat transfer if the boiler operates in the unstable film or stable film boiling regimes.

Boiling heat transfer has been increased by the addition of surface active materials to the boiling liquid. The surfactants reduce the interfacial tension of the liquid. Bubbles are formed more easily whereby boiling heat transfer is improved. This method can be useful in the nucleate boiling regime from A to B on FIG. 1. It cannot be used to increase heat transfer in the unstable film or stable film boiling regimes.

Boiling heat transfer has also been increased by roughening the surface of boiler tubes, the object being to increase the number of nucleation sites at which bubble formation might occur. This reduces the degree of superheat required for the formation of bubbles resulting in improved heat transfer. Again the improvement in heat transfer is realized only in the nucleate boiling regime from A to B on FIG. 1, and in the unstable film or stable film boiling regimes the improvement in heat transfer of roughened surface boiler tubes is insignificant.

Another method commonly used to improve boiling heat transfer is to agitate the liquid. The increased turbulence on the boiling surface caused by agitation may give substantial increases in heat transfer. However, when the heat-transfer conditions are such that stable film boiling occurs, agitation is usually not effective in changing the boiling regime from stable film boiling to nucleate boiling.

It is therefore the principal object of this invention to provide a method for controlling and improving the heat transfer from a solid to a boiling liquid under conditions such that the temperature difference between the solid and the boiling liquid is so great that film boiling normally occurs without the use of such invention.

Another object is to provide a method of adjusting the temperature difference between the solid and the boiling liquid to a value such that higher rates of heat transfer may be obtained therebetween.

Still another object is to provide a method for changing a boiling regime from the relatively inefficient, stable film type to the nucleate type so as to realize higher rates of heat transfer from a solid to a boiling liquid.

A further object is to provide a method for changing a boiling regime from the relatively inefficient unstable film type to the nucleate type so as to realize higher rates of heat transfer from a solid to a boiling liquid.

It is a further object of this invention to provide novel quick-freezing processes and apparatus for biological substances.

Another object of this invention is to provide novel processes and apparatus for quick-freezing and quick thawing of blood in bulk quantities of at least 1 pint, wherein the red blood cells will have a high recovery survival rate despite such freezing and thawing.

These and other objects and advantages of this invention will be apparent from the following description and accompanying drawings in which:

FIG. 1 is a boiling curve showing a plot of heat flux against the temperature difference between the surface of a solid and that of a boiling liquid;

FIG. 2 is a liquid nitrogen cooling rate curve in which cooling time is plotted against the insulating film coating thickness;

FIGS. 3a through 3h are a series of 8 heat transfer rate curves for various thicknesses of insulating film coatings employing a boiling liquid nitrogen bath;

FIG. 4 is a curve showing base metal temperatures giving nucleate boiling in a liquid nitrogen bath for various thicknesses of insulating film coatings;

FIGS. 5a through 5f are a series of 6 heat transfer rate curves for various thicknesses of insulating film coatings employing a boiling liquid nitrogen spray;

FIG. 6 is a curve showing base metal temperatures giving nucleate boiling in a liquid nitrogen spray for various thicknesses of insulating film coatings;

FIG. 7 is a diagrammatic illustration of a steady state heat transfer system in which the present invention may be employed;

FIGS. 8 and 8a are series of boiling curves showing the effect of a powdery layer on top of an insulating film coating;

FIG. 9 is a boiling curve for a specimen having a sugar-glycerine coating;

FIGS. 10a through 10d are a series of cooling curves for sugar-glycerine coatings showing the effect of several variables over a temperature range of 25° C. to -196° C.;

FIG. 11 is a pair of curves showing the heat transfer effect of a sodium silicate coating on a specimen immersed in boiling water;

FIG. 12 is a pair of curves showing the heat transfer effect of a sodium silicate coating on a specimen immersed in boiling Freon 113;

FIG. 13 is a pair of curves showing the heat transfer effect of glycerine-sugar coatings on a specimen immersed in boiling Freon 22;

FIGS. 14a through 14d are a series of cooling curves for sugar-glycerine coatings showing the effect of several variables over a temperature range of 0 to -75° C.;

FIG. 15 is a perspective view looking downwardly on a rectangular-type container for storing biological substances according to the present invention; and

FIG. 16 is a perspective view looking downwardly on a novel cylindrical-type container for storing biological substances according to the present invention.

According to this invention, a method is provided for increasing the heat transfer between a boiling liquid and a solid in thermal contact with such liquid and having a first thermal conductivity, the thermal contact being such that an insulating film of superheated vapor exists on the surface of the solid. More specifically, a coating of thermal insulating material is applied to the solid surface, such coating having a second thermal conductivity which is lower than the first thermal conductivity of the solid. Also, the coating must be of sufficient thickness to reduce the temperature difference between the boiling liquid and the heat transmitting surface so as to essentially eliminate the film of vapor. In this manner, the temperature difference may be reduced to such a value that the boiling regime is changed from stable or unstable film boiling to nucleate boiling. As used herein, the expression "heat transmitting surface" refers to the solid surface in contiguous relation with the boiling liquid. When the solid is uncoated, the heat transmitting surface is the outer surface of such solid, and when the solid is coated in accordance with the present invention, the outer surface of the thermal insulating material constitutes the heat transmitting surface. Remarkable and completely unexpected increases in boiling heat transfer have been obtained by this method. For instance, in the case of liquid nitrogen boiling at atmospheric pressure the increase in heat transfer with certain insulating coatings is as much as 45 times greater than the obtained on uncoated surfaces and this remarkable heat transfer rate was obtained quite reproducibly with a certain type of coating.

Reference to FIG. 1 will show that the type of boiling and consequently the rate of heat transfer can be changed by an alteration of the ΔT between the boiling liquid and the surface which it contacts. Thus, a reduction of the ΔT from a point such as C to a point anywhere between C and A' will result in an increase in the heat flux from the solid to the boiling liquid. This object is accomplished by interposing between a solid and a liquid at its boiling points, a material of sufficiently low thermal conductivity to adjust the ΔT between the boiling surface and the liquid to a value which allows a greater heat transfer rate. The solid is desirably a metal and prefer-

ably a highly conductive metal so that the resistance to heat flow through the mass of a separating wall will be minimized.

The insulating material coating may be any substance which is chemically and thermally stable in the temperature range employed, and which has a lower thermal conductivity than the solid surface which it coats. This thermal insulator may have a smooth surface, an irregular surface or a powdery surface in contact with the boiling liquid. The kind of material used as the thermal insulator, the thickness of the insulator, and the size and shape of the irregularities of the surface in contact with the boiling liquid will depend on the heat-transfer conditions desired, the physical properties of the boiling liquid, and the physical properties of the solid surfaces.

To illustrate the effect of thin, insulating coatings on boiling from a solid under unsteady state conditions, aluminum cylinders $\frac{3}{8}$ inch in diameter and 1 inch long were suddenly submerged in liquid nitrogen boiling at about -196°C . (-320°F .) with and without insulating coatings. A thermocouple was placed in the center of the aluminum cylinder and attached to a temperature recorder which recorded the temperature at the axis as a function of time. The time required to cool the aluminum cylinders from 25°C . to -196°C . was recorded. The results of these determinations for an uninsulated cylinder and cylinders insulated with various thickness of petroleum paraffin base residues known commercially as "Vaseline" are shown in FIG. 2.

Other insulating film coatings were applied to the aluminum cylinders and the time required to cool from 25°C . to about -196°C . in boiling liquid nitrogen recorded. The results of these experiments are shown in Table I.

TABLE I

Time required to cool $\frac{3}{8}$ -in. diameter and 1.0-in. long aluminum cylinder from 25°C . to -196°C .

	Cooling period sec.
(1) Bare cylinder -----	55
(2) Knurled cylinder, no coating -----	40
(3) "Poxalloy" adhesive, 0.04 mm. -----	40
(4) "Poxalloy" adhesive, 0.23 mm. -----	28
(5) "Poxalloy" adhesive, 0.75 mm. -----	25
(6) Clear varnish, 0.04 mm. -----	29
(7) Clear varnish, 0.10 mm. -----	20
(8) Vulcanized rubber, 0.04 mm. -----	26
(9) Vulcanized rubber, 0.23 mm. -----	15
(10) House paraffin, 0.025 mm. -----	36
(11) House paraffin, 0.27 mm. -----	23
(12) House paraffin, 0.34 mm. -----	26
(13) Rubber paraffin, 0.028 mm. -----	38
(14) Rubber paraffin, 0.28 mm. -----	17
(15) Rubber paraffin, 0.39 in. -----	19
(16) Paper masking tape, 0.30 mm. -----	19
(17) Paper masking tape, 0.60 mm. -----	32
(18) Paper masking tape, 0.90 mm. -----	38
(19) Rubber electrician's tape, 0.16 mm. -----	18
(20) Rubber electrician's tape, 0.33 mm. -----	26
(21) Rubber electrician's tape, 0.50 mm. -----	32
(22) Vaseline, 0.01 mm. -----	36
(23) Vaseline, 0.025 mm. -----	24
(24) Vaseline, 0.05 mm. -----	21
(25) Vaseline, 0.10 mm. -----	14
(26) Vaseline, 0.15 mm. -----	13.5
(27) Vaseline, 0.20 mm. -----	14
(28) Vaseline, 0.25 mm. -----	16
(29) Vaseline, 0.37 mm. -----	17
(30) Vaseline, 0.45 mm. -----	20
(31) Asbestos, 0.25 mm. -----	42
(32) Asbestos, 0.95 mm. -----	64
(33) Sodium silicate, 0.11 mm. -----	33
(34) Sodium silicate, 0.17 mm. -----	30
(35) Kaolin, 0.11 mm. -----	38
(36) Plaster of Paris, 0.19 mm. -----	10

Table I shows that the improvement in heat transfer is nonspecific with respect to the chemical nature of the coating but is affected by the thermal properties of the coatings.

FIGS. 3a through 3h are a series of boiling curves of liquid nitrogen boiling at atmospheric pressure on $\frac{3}{8}$ -in. diameter and 1-in. long aluminum cylinders, coated with various thicknesses of Vaseline. This series of curves shows the effect of insulating coatings on boiling heat-transfer rate as a function of the temperature at the center of the cylinder. An examination of the boiling curve of liquid nitrogen boiling on a bare metal cylinder will show that the heat-transfer rate at a cylinder temperature of 0°C . is about 6,000 B.t.u./hr. ft.². As the cylinder cools, the heat-transfer rate decreases gradually until it becomes only about 2,000 B.t.u./hr. ft.² at a cylinder temperature of -180°C . At -190°C . the heat-transfer rate increases, it passes rapidly through a nucleate boiling heat-transfer peak at about 32,000 B.t.u./hr. ft.². Nucleate boiling ceases when the cylinder cools down to -196°C . which is the temperature of the liquid nitrogen.

A comparison of the boiling curves of liquid nitrogen boiling on a bare aluminum cylinder and on Vaseline-coated aluminum cylinders shows that increasing thicknesses of Vaseline coatings broaden the nucleate boiling heat-transfer peak with respect to cylinder temperature. Further, the nucleate boiling heat-transfer peak is shifted to higher cylinder temperatures as the thickness of the insulating coating of Vaseline is increased. FIG. 4 shows the range of cylinder temperatures at which rapid nucleate boiling, heat-transfer rates are obtained in a liquid nitrogen bath as the thickness of the insulating coating of Vaseline is increased.

FIGS. 5a through 5f show a series of boiling curves of a spray of liquid nitrogen boiling at atmospheric pressure on $\frac{3}{8}$ -in. diameter and 1-in. long aluminum cylinders coated with various thicknesses of Vaseline. Comparison of FIG. 5 and FIG. 3 shows that the heat-transfer rates obtained in the liquid nitrogen spray were about twice as great as those obtained in a stationary pool of boiling liquid nitrogen. FIG. 6 shows the range of cylinder temperatures at which rapid nucleate boiling heat-transfer rates are obtained on the cylinder as a function of the Vaseline coating thickness when a spray of liquid nitrogen is used. A comparison of FIG. 6 and 4 shows that the liquid nitrogen spray gives rapid, nucleate boiling, heat-transfer rates over wider cylinder temperatures than in the case of non-agitated pool boiling. Thus, turbulence in the boiling liquid adds to the improvement in the heat-transfer rate above and beyond the improvement obtained with the insulating coating alone.

Under steady state heat-transfer conditions the thickness of the insulating coating required can be calculated using heat-transfer formulas. This is best illustrated by means of the following numerical example in which liquid nitrogen is to be evaporated by atmospheric steam across a 0.04 in. or 0.0033 ft. thick copper wall using an insulating coating, the system being illustrated in FIG. 7.

Q/A =heat flux (B.t.u./hr. ft.²)

K_w =thermal conductivity of copper wall (B.t.u./hr. ft. ° F.)=250

K_c =thermal conductivity of coating (B.t.u./hr. ft. ° F.)=0.5

h_1 =heat-transfer coefficient between steam and copper wall=1,000 B.t.u./hr. ft.² ° F.

x =thickness of coating

t_f =temperature of liquid N_2 = -320°F .

t_1 =temperature of outer layer of coating (° F.)

t_2 =temperature of coating-copper interface (° F.)

t_3 =temperature of steam-copper interface (° F.)

t_4 =temperature of steam= 212°F .

To obtain maximum heat transfer across this system, it is necessary to consult a boiling curve of liquid nitrogen from which it can be determined that a maximum

heat flux of 32,000 B.t.u./hr. (sq. ft.) exists at a temperature difference ($t_2 - t_1$) of 10° F. Thus, $t_1 = 310^\circ$ F.

$$Q/A = h_1[t_4 - t_3], [t_4 - t_3] = \frac{32,000}{1,000} = 32^\circ \text{ F.}$$

so that $t_3 = 180^\circ$ F.

$$Q/A = \frac{K_w}{0.0033}[t_3 - t_2] = \frac{(32,000)(0.0033)}{(250)} = 0.4$$

so that $t_2 = 179.6^\circ$ F.

Therefore, $t_2 - t_1 = 179.6 + 310 = 489.6$

$$Q/A = \frac{K_c}{x}[t_2 - t_1], x = \frac{K_c}{Q/A}[t_2 - t_1] = \frac{(0.5)(489.6)}{(32,000)} = 0.076 \text{ ft.}$$

$$= 0.092 \text{ in.}$$

$$= 2.3 \text{ mm.}$$

These equations become rather complicated when exact values are to be calculated because the thermal conductivity of materials usually changes with temperature. Geometric factors may further complicate the calculations. However, certain simplifying assumptions may be made. For instance the temperature drop across the wall can be ignored in view of the great differences in the thermal conductivities of copper and Vaseline. As a first approximation all the temperature drop can be assumed to the place in the coating. Under these conditions

$$x = \frac{k(T_1)}{Q/A_1}, x = \frac{(0.5)(532)}{32,000} = 0.0083 \text{ ft.} = 2.5 \text{ mm.}$$

Under unsteady state conditions of heat transfer the situation is more complicated and not as amenable to mathematical computations as in the steady state case. Considering the boiling curve FIG. 1 for the heat-transfer fluid under consideration, for liquid nitrogen the maximum heat flux is about 32,000 B.t.u./hr. (ft.²) and occurs at a ΔT of 10° F., which is point B. Also, the minimum Q/A at point C occurs with a ΔT of about 400° F. It may be assumed that a piece of material having cylindrical geometry is plunged into liquid nitrogen at -320° F. At the instant of its immersion the ΔT between the surface of the cylinder and the liquid nitrogen will be about 400° F. This would correspond to point C on the FIG. 1 curve and a heat flux of about 6,000 B.t.u./hr. ft.². As time progressed the surface temperature of the cylinder would be lowered as the heat flux would move to the left along the curve, eventually reaching the peak at point B. This would correspond to a surface temperature of about -310° F. and a heat flux of about 32,000 B.t.u./hr. ft.². From this point in time and thereafter the heat flux would begin to decrease until point A is reached at a ΔT of about 1 or 2° F. Then boiling would cease and subsequent heat transfer would take place by convection. Now assume that the material being quenched has a high thermal conductivity such as aluminum, copper, silver and the like. Under these conditions an insulating coating could be applied to the surface of the cylinder with the characteristic that its surface temperature would drop to -310° F. and it would then sustain a ΔT of $70 - (-310) = 380^\circ$ F. at a heat flux of 32,000 B.t.u./hr. ft.². If one selected a coating material with a thermal conductivity of, for example, 0.1 B.t.u./hr. ft. ° F., then the required thickness would be

$$x = \frac{K}{Q/A} \Delta T = \frac{(0.1)(380)}{(32,000)} = 0.0012 \text{ ft.}$$

$$0.36 \text{ mm.}$$

Such a coating, however, would have the effect of pushing the effective ΔT to point B almost immediately after the cylinder was immersed in the liquid nitrogen. From then on the heat flux would begin to decrease at a rapid rate as the ΔT went from B to A'. This, then, may

not be the optimum coating thickness if one is interested in obtaining a minimum quenching time for the cylinder over the whole range from room temperature to -320° F. The maximum average heat-transfer rate will result if we start at a point to the right of B, say B', such that the area under BB' is equal to the area under Ba'A.

For instance, if we take the boiling curve for liquid nitrogen and plot the point B', it occurs at a ΔT of about 14° F. and a heat flux of about 29,000 B.t.u./hr. (ft.²). For a Vaseline coating (with a thermal conductivity of 0.1 B.t.u./hr. ft. ° F.) the thickness may be determined to be

$$x = \frac{K}{Q/A} \Delta T = \frac{0.1(376^\circ)}{29,000} = 0.013 \text{ ft.} = 0.4 \text{ mm.}$$

The ΔT of 376° F. used in this formula is arrived at by the requirement that the surface of the coating be 14° F. higher than the liquid nitrogen while the interior of the cylinder is at 70° F.

If the aluminum probes referred to in Table I and FIG. 2 are used, the calculated time to cool, using a Vaseline thickness of 0.4 mm., would be 16 sec. Referring to Table I the experimental time for a coating of 0.37 mm. was 17 sec. while the minimum time to cool was 14 sec. obtained with a measured coating thickness of 0.10 mm. Considering the assumptions involved in the theory and the inherent errors involved in the experiments, this is considered excellent agreement. Thus a mathematical approach to the determination of the optimum coating thickness under unsteady state conditions is established.

The above discussion has been concerned with establishing an optimum coating thickness when it is desired to cool (or warm) the material over the whole temperature range. In some cases this may not be important. For instance, when blood is frozen in metallic containers, it is desirable to freeze and cool the blood as rapidly as possible through the 32° F. to -58° F. (0° C. to -50° C.) temperature zone. The problem of computing the coating thickness under these conditions is considerably more complicated. Among other things, the internal resistance of the system begins to play an appreciable role. The only satisfactory solution is to experiment with different coating thicknesses to determine the optimum. However, as a first approximation it is possible to consider the boiling curve as being symmetrical about its peak. Then assume that optimum conditions will prevail if the maximum Q/A is reached as the surface temperature of the specimen reaches the half-way mark (-13° F.) on its cooling path from 32° F. to -58° F. under these conditions, the surface temperature of the coating must be at -310° F. resulting in a gradient of $-13 - (-310) = 300^\circ$ across it. The heat flux will then be $Q/A = 32,000$ B.t.u./hr. (ft.²). Then

$$x = \frac{(0.1)(297)}{(32,000)} = 0.00093 \text{ ft.} = 0.29 \text{ mm.}$$

It has been found that the heat transfer rate between a boiling liquid and a solid in thermal contact with such liquid under conditions where stable film boiling occurs may be even further improved by applying a layer of powdery substance to the thin insulating film coating. The powder layer provides an irregular surface for the promotion of bubble formation and the exposed portions of the powder particles cool down rapidly. This increases the nucleation rate of the boiling liquid, and consequently the speed at which boiling is established. This effect is shown in FIG. 8 which shows boiling curves of liquid nitrogen boiling at atmospheric pressure on a smooth copper cylinder 1½ in. in diameter and 2 in. long, the same cylinder coated with a thin film of glycerine, and the cylinder coated with the same film thickness of glycerine and on which was sprinkled copper powder that passed a 100-mesh screen. The insulating film of glycerine shifted the boiling curve to higher base metal temperature as expected from the previous discussion of smooth insulating

coatings. The peak boiling heat-transfer rate of the uncoated copper cylinder and the glycerine-coated cylinder are both about 32,000 B.t.u./hr. ft.². The glycerine-coated and the glycerine-copper powder-coated cylinders give boiling curves that are approximately similar with respect to the temperature range of the base metal at which nucleate boiling occurs because the thermal resistances of the two coatings are approximately identical. However, the glycerine-copper powder coating gives a peak boiling heat-transfer rate of about 68,000 B.t.u./hr. (ft.²) as compared to about 32,000 B.t.u./hr. (ft.²) for glycerine coated and uncoated copper cylinders. The two-fold increase in the value of the peak boiling heat-transfer rate is therefore shown to result from the increase in the number of nucleation sites.

It can thus be seen that one embodiment of this invention provides an insulating undercoating with a sufficiently low thermal conductivity to thickness ratio to shift the boiling to an optimum region as previously discussed, in combination with another powdery coating to provide nucleation sites and thus increase the heat flux in the nucleate boiling region.

The powder characteristics that appear important from the standpoint of heat transfer efficiency are particle size and distribution of particle size. When the physical characteristics of the powders employed are similar and the particle size is varied, a somewhat thicker insulating film is required as the particle size of the powder is reduced. A silica aerogel powder having a particle size of 0.04 micron gave best results with a 5 mil glycerine undercoat while powdery crystalline molecular sieve metal aluminosilicate zeolites having a particle size of 2 to 4 microns showed an optimum heat transfer rate when applied to a glycerine film of about 4 mils thickness.

The choice of particle material will depend to a large extent upon the heat-transfer operations involved. For example, in the low-temperature processing of blood and other biological materials, it is important that the coating does not impede heat transfer during the thawing process. According to this invention, a solution to this problem is to provide a coating system which is dissolved off the container surface immediately after the cold container is plunged into warm water during the thawing operation. One such system admirably suited for blood preservation is a glycerine insulating coating and a sugar outer layer. It was found that peak heat transfer rates of about 90,000 B.t.u./hr. ft.² could be obtained when the specimen was first sprayed with a thin coat of glycerine and then sprinkled with an excess of powdered sugar.

Since, as has already been discussed, the particle size should be important, a series of experiments were run using sugar graded to different mesh sizes. A copper cylinder 1½ in. diameter and 4 in. long was provided with thermocouples at the center and the surface. The glycerol was applied by dipping the cylinder in a solution of 22% glycerol in methanol. After withdrawal from this solution the methanol was allowed to evaporate and then the sugar was sprinkled over the cylinder. The cylinder was then immersed in liquid nitrogen and time-temperature curves recorded for the center and the surface. The experimental results show that, as the particle size is decreased, heat transfer is improved up to a mesh size of 60-140. Beyond this size, heat transfer decreases. Because of the interrelationship of powder particle size and undercoating film thickness, some degree of uniformity of powder particle sizes is necessary. In general, finer size powders are preferred, and they are generally more uniform than coarser powders. When the powder is a relatively poor thermal conductor, such as the nonmetallic substances exemplified by the silica aerogel and zeolite powders mentioned above, the insulating properties aid in establishing a surface to boiling liquid temperature relationship essential to nucleate boiling and a relatively thinner insulating undercoat is required than when a good thermal conductor such as powdery metals are employed.

In addition to finely divided silica such as silica aerogel having agglomerate particle size of less than about 0.1 micron and crystalline zeolitic molecular sieves A and X, both in agglomerate particle sizes of 2-4 microns, sugar powders have been used. Silica aerogel, known commercially as "Santocel," is preferred over sugar because it is more readily available in the ultra-fine sizes and uniformity which are desired for best reproducibility in actual practice while sugar must be ground down to the correct mesh sizes in order to obtain an optimum coating. Zeolite A is described and claimed in U.S. Patent No. 2,882,243 and zeolite X is described and claimed in U.S. Patent 2,882,244, both having issued Apr. 14, 1959 to R. M. Milton.

Any powdery material which is chemically stable to the boiling liquid contacting it and the coating adhering it to the solid surface throughout temperatures employed in the particular system would be suitable. For best results the powdered material should be sufficiently large in size so as to insure that it will project beyond the insulating film coating. This is for the reason that when a powder that is completely submerged within a film is employed it will serve only to modify the thermal conductivity of the film without yielding the improvement associated with the projections. When powders of particle size less than the film thickness are employed the mode of application should be such that the projections will be obtained. For example, the powder can be applied onto a film into which it does not sink. Metal powders such as copper, iron, iron alloys such as ferrosilicon; refractory materials such as boron nitride, boron carbide, magnesium carbide, silicon carbide, quartz, and other metal oxides; minerals such as sand, cristobalite, clinoptilolite, diatomite and erionite; and the synthetic zeolites as exemplified by those listed, are all suitable as the powdery material of this invention.

It should be recognized that when a powder layer is to be employed, there is an additional requirement for suitable film coatings. That is, the undercoating must be formed of materials which will receive and hold the powder. Both glycerine and polyvinylpyrrolidone have been successfully used. Glycerine has been employed alone and also diluted with methanol. Other suitable undercoating materials include oils in general, polymerizable plastic liquids such as epoxy resins, and the silicone fluids. As previously discussed, a water soluble undercoating is preferred in the blood preservation process, so that it will wash off during the thawing step. Each of the above-mentioned materials is either water soluble or may be obtained in a water soluble form. For example, many detergent oils are available. The solvent or diluent such as the methanol mentioned above can also be varied. For example ethanol, water or any substance that will not impair the water stripping of the film may be employed. The function of the diluent is to adjust the properties of the insulating film (a) to produce a good adherent uniform film according to whether it is applied by spraying, dipping or otherwise, (b) to keep it fluid at least until the powder addition is made, and (c) in some instances, to act as a plasticizer and help prevent drying out and flaking off during the cooling step.

A smooth insulating coating may be formed by applying a molten insulator or a solution of the insulator, for example, by spraying or dipping onto the solid surface which, upon cooling or evaporation of the solvent, produces the desired insulating coating on the surface. In the dipping technique, the thickness of the insulating film may for example be controlled by adjusting the concentration of the solution and the number of dippings.

For example, a glycerol-methanol solution may be prepared containing at least 20% glycerol. The solid is then dipped into this solution, withdrawn and allowed to stand in the air for about 30 seconds. The latter "aging" step allows the film to become stabilized before the powdery layer is applied. At least part of the solvent is evaporated and the resultant film becomes more uniform, prob-

ably due to an increase in viscosity. Some film compositions could conceivably suffer from too long an aging in that too great a loss of solvent would result in poor adherence either before or during the freezing step. The aging is preferably done before the powder addition to the film, although it may be done after such addition.

Experiments have shown that an optimum heat transfer coefficient is obtained when a 50% glycerol-methanol solution is used as opposed to solutions above or below this value, the powder being finely divided silica aerogel. When a sugar coating is used, a 22% glycerol in methanol solution is preferred. The 50% glycerol solution results in a film thickness of about 0.005 inch as compared to 0.0015 inch for the 22% glycerol solution. As previously mentioned, the preferred silica particle size is less than 0.1 micron, while the preferred particle size of sugar is 60 to 140 mesh.

Composite coatings consisting of a base insulator coat and a powdery top layer may be applied onto a solid surface in any convenient manner as for example spraying a base insulator coat onto the solid surface and thereafter hand sprinkling the powder onto the base coat. Alternatively, the powdery material may be applied after impregnation with a suitable adhesive material.

Another method for interposing an insulator between a solid body and a boiling liquid is to coat the solid body with the insulator and then clad the insulator with a durable material which may or may not be a good thermal conductor. For example, the solid body can be placed between two metal conduits, one having a smaller outer diameter than the inner diameter of the second conduit. Such a configuration will protect the insulator coating against physical abuse and will still provide the desired temperature drop to bring the temperature of the surface on which boiling occurs into the nucleate boiling range. The heat-transfer rate of this conduit configuration can, of course, be increased further by coating it with a powder layer of a thermal conductor or thermal insulator which may be an integral rough or porous surface.

Another series of tests were conducted which clearly illustrate the additional heat transfer improvement attainable by employing a powdery layer on the thin insulating film undercoating. In these tests, a thin coat of glycerine was sprayed on a 1½ in. diameter by 2-in. long copper cylinder after which an excess of powdered sugar was added thereto. The heat transfer rate obtained with the sugar coating was on the average 16 times greater than that obtained with the uncoated container. It took 350 seconds to cool the uncoated cylinder from 25° C. to -196° C. in liquid nitrogen. The same cylinder cooled in 22 seconds when it was coated with the glycerine-sugar coatings. FIG. 8a shows the heat transfer rates obtained with such a coating as a function of the temperature of the specimen. FIG. 9 shows the improvement in heat transfer at various specimen temperatures. The improvement in heat transfer can be as high as 35-fold at a specimen temperature of -100° C. At this temperature the heat transfer rate of the uncoated specimen is very low, about 2,000 B.t.u./(hr.) (ft.²). It is apparent from FIGS. 8a and 9 that superior freezing rates can be obtained with glycerine-sugar coatings.

Experiments were performed to determine whether the heat transfer properties of the glycerine-sugar powder coatings are reproducible. This involved an investigation of the following variables:

- (1) The thickness of the glycerine-sugar coating.
- (2) The weight of the glycerine-sugar powder coating.
- (3) The mesh size of the sugar powder used for the coating.
- (4) The age of the glycerine-sugar powder coating.

FIGS. 10a through 10d show the time required to cool the aforementioned copper cylinder from 25° C. to -196° C. as a function of the four variables mentioned above. The four curves have wide flat surfaces over which

the cooling periods are constant, suggesting that the heat transfer characteristics of the coatings are easily reproducible within the flat regions of the curves.

However, in blood freezing operations the heat transfer rate down to about -50° C. is of greater importance than the overall heat transfer rate. FIGURE 14 shows the heat transfer rates in the range of 0° C. to -75° C. as a function of the same four variables mentioned above. Again, the curves have relatively wide, flat sections or are flat, indicating that the heat transfer rates are reproducible over relatively wide ranges of the coating conditions.

It is to be understood that the present method for improving heat transfer to boiling liquids with insulating coatings is generally applicable to all boiling liquids ranging from extremely low temperatures to the exceedingly high temperatures of molten metals. A series of quenching experiments were performed in water (B.P. 100° C.), Freon 113 (B.P. 47.6° C.), and Freon 22 (B.P. -40.8° C.). A sodium silicate coating provided high heat transfer rates in water and the Freons. An aqueous solution of sodium silicate was sprayed directly on a copper specimen at 400° C. to 700° C. When the spray hit the hot specimen, the water flashed off instantly, leaving a coating of sodium silicate polymer on the specimen, which had considerable resistance to the solvent action of water. The heat transfer rates of the uncoated and silicate coated specimens in boiling water and Freon 113 are shown in FIGS. 11 and 12, respectively. These curves also show that the sodium silicate coating shifts the boiling curves to higher specimen temperatures.

A similar experiment was performed employing Freon 22 at the boiling liquid. A copper specimen at about 150° F. was sprayed with glycerine, after which powdered cane sugar was added to the glycerine undercoating. The coated cylinder was then immersed in boiling Freon 22, and FIG. 13 shows the remarkable heat transfer rates obtained.

The thickness of an insulation coating-powdery layer combination to provide a desired temperature drop across such combination may be calculated in a manner similar to that used for smooth insulating coatings cited previously. However, exact mathematical solutions of the equations are complicated because the thermal conductivity of the materials usually change with temperature and the geometric factors of the powder coatings are variable. If the exact size and shape of a combination coating and the thermal properties of the coating submerged in a boiling liquid are known, the temperature differential can be calculated by those proficient in the art of heat transfer by the foregoing method. However, it is usually much easier to determine the coating requirements experimentally by performing a series of tests with likely powder coating materials.

The present method of improving boiling heat transfer has many significant industrial applications. For example, it may be employed to increase heat transfer through metal container walls to at least 14,000 B.t.u./(hr.) (sq. ft. of container surface). Thus, a biological substance such as blood may be placed on a container and the outer walls of the latter coated with a thin insulating layer and preferably a powdery substance, in accordance with the present invention. The blood-storing, coated container is then contacted with a boiling liquid refrigerant such as nitrogen. In this manner the blood may be quickly cooled through the critical temperature range of 0° to -50° C. so as to preserve its biological integrity, and frozen. Without the present coatings, a substantial percentage of the red blood cells would be permanently damaged due to the long duration of time in such critical temperature range.

In the case of blood, the primary viable constituents are the erythrocytes or red blood cells. Hence, the problem of preserving whole blood basically relates to the preservation of the red blood cells. The red blood cells

are globular in form and contain a special kind of cytoplasm enclosed in a semi-permeable membrane. This membrane preserves the integrity of the enclosed protein and the electrolyte content of the contained cytoplasm. The membrane is ductile, but essentially non-elastic and thus has a critical maximum volume beyond which its integrity is damaged. This damage of the membrane results in the release of the oxygen-carrying element of the erythrocytes, i.e. hemoglobin, into the blood plasma where it cannot function to carry oxygen and carbon dioxide. The amount of hemoglobin released from a given number of cells provides a measure of the efficiency of various blood preservation processes. The lower the amount of hemoglobin released, the greater the efficiency of the process and/or apparatus for preserving the cells.

Normally i.e. in the circulatory system of the body, the red blood cells have a life span of between about 100 days and 120 days. However, outside the body, the red blood cell deteriorates much more rapidly. One of the changes affecting blood outside of the body is the phenomenon of clotting. It is important for purposes of storing blood that clotting be avoided. To this end, the addition of citrate, oxalate or fluoride ions is effective. These ions inhibit the chemical changes, such as the interaction of calcium ions with certain components, which ordinarily result in clotting. However, clotting is not the only problem affecting stored blood.

The red blood cell has its own supporting metabolism and outside the body it carries on its metabolic processes until the blood sugar is depleted and converted to lactic acid. As this occurs, the substances and processes which are essential to the maintenance of the cell structure are exhausted. In addition the pH of the plasma is lowered to an unsatisfactory level by the accumulation of lactic acid. The osmotic balance between the intracellular material and the extracellular material is soon destroyed in drawn blood and water from the plasma diffuses into the cell causing abnormal swelling and eventual membrane rupture. These changes occur rapidly at room temperature and at ordinary citrate and glucose concentrations.

It has been discovered that if biological substances such as whole blood are frozen and supercooled sufficiently rapidly, and, after any desired storage period, are thawed at sufficiently high rates, the biological integrity of the substance may be maintained without substantial damage. Unfortunately, the extremely high freezing and thawing rates necessary to avoid biological damage cannot be obtained by methods heretofore employed by the art, as for example, immersing a blood storage container in a liquid nitrogen bath. In this prior art method, the rate of heat transfer between the liquid nitrogen and the container is on the order of 5,000 B.t.u./(hr.) (sq. ft. of container surface) until the temperature of the container inner wall is reduced to about -175°C. , at which point the heat transfer rate increases sharply. However, the initial heat transfer rate is too low for rapid freezing without, for example, substantial reduction of red cell recovery percentage. It has been found that if the rate of heat transfer is at least 14,000 B.t.u./(hr.) (sq. ft.) and preferably at least 24,000 B.t.u./(hr.) (sq. ft.) during the entire freezing step, the freezing may be effected in a sufficiently short period for high red cell recoveries on the order of at least 85%. The present invention affords a novel method of obtaining this remarkably high rate of heat transfer, wherein a biological substance-storing container is coated with a thin insulating film having sufficient insulating power to adjust the temperature difference between the heat rejecting surface of the coated solid and a boiling refrigerating medium to a value where more efficient heat transfer will result. The heat transfer rate may be further improved by applying a layer of powdery material on the previously mentioned thin insulating film, which then serves as an undercoating. Glycerine for example is admirably suited as

a material for forming the thin insulating film, and finely divided silica for example has been found particularly effective in providing the powdery material layer.

Glycerine is water soluble, and the invention also contemplates a highly efficient method of thawing the frozen biological substance by contacting the container walls with water at a temperature preferably below about 55°C. The insulating film and powdery layer are preferably removed by such contact. To achieve the necessary quick thaw, the container is preferably constructed from material having a K/L value of at least 2,500, wherein $KB = \text{B.t.u.}/(\text{hr.}) (\text{sq. ft.}) (^{\circ}\text{F.}/\text{ft.})$ and $L = \text{wall thickness in feet.}$

The container is preferably shaken during both the quick freezing and thawing steps so as to facilitate a uniform flow of heat through the biological substance within the container.

Although the invention will be specifically described in terms of preserving blood, it is to be understood that it is well suited for preserving other biological substances such as bone marrow, serum which is blood with the cells and fibrinogen removed, blood plasma fractions and spinal column fluids. Also, micro-organisms such as bacteria may be preserved as for example *Azotobacter vinelandi*, *Escherichia coli*, *Micrococcus pyrogenes*, *Aspergillus niger* (a fungus) and *Saccharomyces* sp. (yeast).

The specific steps for the preservation of bulk quantities of blood will now be discussed in detail:

Anti-coagulant medium

The blood obtained from a donor is collected in a suitable anti-coagulant medium. Particularly suitable as such mediums are standard citrate-dextrose solutions or heparin solutions. This is a customary procedure presently in use for the preservation of whole human blood by refrigeration at about 4 to 6°C.

Protective additives

The blood is collected into a mixture of the anti-coagulant and the protective additive in the container. Alternatively, the blood may be collected in a suitable anti-coagulant and the protective additive mixed therewith. Freezing and thawing of human red cells usually result in liberation of the hemoglobin (hemolysis), and loss of the biological integrity of a considerable portion of cells. The degree of destruction depends upon the composition of the blood used and the physical conditions of cooling and warming. Thus, rapid cooling to very low temperatures and rapid warming to the liquid state from the frozen state favors high percentage recovery of red cells, as previously discussed. The presence of certain solutes, referred to herein as protective additives, in combination with other features of this invention, permits freezing and thawing to be performed with high percentage recovery of the cells.

Freezing and thawing of human red cells have been successfully carried out according to the present invention in the presence of several protective additives including sugars and soluble polymers.

Various additives differ markedly in the rate at which they enter into or are taken up by cells; some compounds, because of size or structure, do not enter the cell. For example, red cells are permeable to glucose but are impermeable to lactose and sucrose. For those which enter the cell, entrance may be by simple diffusion or "active uptake." The latter depending upon enzyme systems or carrier substances in the cell membrane. Glycerol enters very rapidly; glucose enters more slowly. Because of molecular size and the absence of suitable transport systems, the di- and trisaccharides do not enter. Such differences in permeability can be easily demonstrated by exposing red cells to solutions of various substances and directly analyzing cellular concentrations or measuring total increased intracellular concentration by osmotic procedures.

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In summary, protective additives may be divided into four classes:

(a) *Five and six carbon sugars*.—These are characterized in that they are known to permeate through the membrane of the red cells. This class is exemplified by xylose, arabinose, ribose, glucose, fructose, galactose and mannitol. Effective concentration for the class fall in the range of 0.3 to 0.75 M.

(b) *Di- and trisaccharides*.—These are characterized in that they do not enter the red cell. Examples are maltose, sucrose, lactose and raffinose. Effective concentrations fall in the range of 0.075 to 0.3 M.

(c) *High molecular weight, water-soluble polymers*.—These are also characterized, as (b) above, in that they do not enter the red cells. Examples are dextran and polyvinyl-pyrrolidone. Effective concentrations fall in the range of 6 to 10 wt. percent. These are more conveniently expressed in wt. percent than in molarity because their molecular weights are so high.

(d) *Mixtures of at least one each from classes (a) and (b) above*.—Lactose and glucose are an example of such a mixture. Such mixtures are expected to be more effective than either of the individual additives when used at about the minimal concentrations. This conclusion is supported by the data in Table I.

TABLE II.—FREEZE-THAW PROTECTIVE ACTIVITY OF VARIOUS SUGARS

Concentration of Sugar, moles/liter	Percent Red Cell Recovery			
	Freezing Bath Temperature, ° C.			
	-20	-40	-77	-120
Lactose 0.1.....	7	17	62	45
Lactose 0.2.....	9	43	72	69
Lactose 0.3.....	18	49	83	83
Glucose 0.1.....	2	11	35	45
Glucose 0.2.....	3	17	51	59
Glucose 0.3.....	9	29	61	71
Lactose 0.1, Glucose 0.2.....	13	30	65	69
Lactose 0.1, Glucose 0.4.....	25	47	76	82
Lactose 0.1, Glucose 0.6.....	38	42	84	82
Lactose 0.3, Glucose 0.1.....	44	66	87	85
Lactose 0.3, Glucose 0.2.....	47	64	86	86
Lactose 0.3, Glucose 0.3.....	44	73	88	84

The procedure for the experiments of Table I was as follows: Samples consisting of 4 volumes of blood were mixed with a 0.9% NaCl solution and the test sugar to give the indicated sugar concentrations. Five ml. samples were then frozen in thin-walled aluminum tubes of elliptic cross section 4 x 29 mm. by immersion in suitable baths of dry ice-methanol (-20, -40, -77° C.) or isopentane cooled by liquid nitrogen (-120° C.). Thawing was done by immersion in water at 40° C.

Table II also indicates the red cell recovery percent increases when samples are frozen in baths of decreasing temperatures.

The insulating material may be any substance which is chemically and thermally stable in the temperature range employed, and which has a lower thermal conductivity than the blood mixture storing container material. The thermal conductivity of the insulating material is preferably below about 0.15 B.t.u./(hr.)(ft.)(° F.) The insulating material should be of sufficient thickness to adjust the ΔT between the boiling surface and the saturation temperature of the liquid refrigerant to a point where more efficient heat transfer will occur. The thickness of the insulating film necessary to adjust the ΔT between the boiling surface and the liquid refrigerant to the most efficient value is a function of its thermal conductivity and thickness and conductivity of the container wall, and the boiling characteristics of the liquid refrigerant.

Experiments have shown conclusively that the use of thin insulating film coatings such as the previously discussed "Vaseline" on blood-storing containers allow much faster cooling times and result in increased red blood cell survival after the blood has been thawed. For instance, human blood containing 0.3 mole lactose as a protective additive was frozen in the previously described

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aluminum containers by immersion in a pool of liquid nitrogen at -196° C. Increasing thicknesses of "Vaseline" were put on the containers and the red blood cell recovery was determined after thawing. Table III illustrates the results obtained.

TABLE III

Vaseline coating Thickness (mm.)	Red blood cell recovery percent
0.....	65
0.001.....	69
0.023.....	73
0.16.....	78
0.24.....	82
0.26.....	82

The coating materials are nontoxic, inexpensive and readily available. The coating will not interfere with the collection or transfusion of blood if the container is coated after the collection of the blood. The glycerine-sugar coating dissolves readily in water during the thawing step and will therefore not interfere with the administration of the blood to a patient.

Refrigerant for freezing biologicals

A refrigerant suitable for use in the present invention must of course be cold enough to freeze the biological matter. In the case of blood, this means that the refrigerant must have a temperature of below about -120° C. to insure adequate recovery of the red blood cells.

Liquid nitrogen is the preferred refrigerant, since it has the advantages of being relatively inert, safe to handle, and relatively inexpensive. It also has an exceedingly low boiling point, namely -196° C. at atmospheric pressure. The liquid nitrogen employed can for example be obtained by the well-known rectification of air. However, other refrigerants may also be employed. Among those liquids which may be used are liquid air (containing normal amounts of nitrogen), helium, neon, argon and krypton.

Liquid nitrogen and the other low-boiling refrigerants are saturated fluids at atmospheric pressure, and boil violently when a warm object such as the blood-storing container is plunged therein. The heat transfer is dependent upon the temperature difference ΔT between the fluid and the warm object, as previously discussed. At very high values of ΔT , a vapor film is formed around the warm container resulting in very poor heat transfer. This vapor film becomes less and less stable as the ΔT is decreased and the heat transfer improves. At a ΔT of about 3° C. (for liquid nitrogen), maximum heat transfer is attained and drops off as the ΔT is reduced to zero. In view of this heat transfer rate- ΔT pattern, it would appear that a prohibitively low heat transfer rate would be attained when a blood storing container at 25° C. is suddenly plunged into liquid nitrogen at -196° C. However, the application of the aforescribed coatings on the container outer walls allow the surface in contact with the liquid nitrogen to be cooled very rapidly and provide a ΔT value closer to 3° C.

In order to thaw a container of frozen blood, it is necessary to again pass through the critical temperature region from -50° C. to melting as rapidly as possible. Unfortunately there is an added limitation in that blood is rapidly and irreversibly damaged at temperatures higher than 50° C. Thus the temperature of the fluid used to perform the thawing function should not be substantially higher than this value. Water is the preferred thawing medium, but other methods such as thawing by means of radio frequency energy are also feasible.

The exact cause for damage to the cells in the critical temperature region is not known, but it may be due to either or both (1) the continued enlargement of ice crystals, and (2) the increase in electrolyte or salt concentration as water is frozen out of solution. This being the case, it should not be necessary to consider the time re-

quired to move the heat of fusion for all of the blood, but only the last increment thereof. Experiments were made to correlate the time spent by the blood in the temperature range from -10°C. to -50°C. with the red cell recovery. This was done by inserting a thermocouple in the center of the blood mass in tests in which the container was shaken both during freezing and thawing. The results indicate that with a 0.3 M lactose (10.7%) protective additive, it is necessary to pass the blood through this temperature zone both during the freezing and thawing steps in less than 15 seconds in order to obtain 85% or greater red cell recovery. If this time is reduced to 10 seconds or less, 90% recovery is attainable. With a protective additive of 5% glucose and 7½% lactose, a cumulative time of less than 40 seconds should give 85% recovery and 25 seconds should give 90% red cell recovery.

Any practical method of contacting the heat exchanging fluids with the blood-storing container walls may be employed, although in the previously described tests contact was obtained by simply immersing the container in a fluid bath. An alternate method is a fluid circulating system wherein the refrigerant and/or the thawing fluid may be forced across the container walls, one possible advantage being a higher rate of heat transfer than afforded by the immersion system. As a further alternative, the heat exchanging fluids may be sprayed against the container surfaces, and experiments with liquid nitrogen have shown considerable heat transfer advantages over simple immersion. This probably results from the scrubbing action of the spray which inhibits formation of a continuous vapor film.

Containers

It has been found that substantial improvements in red cell recovery percentages are attainable under certain circumstances, when the blood-storing container is shaken during the freezing and thawing steps. This is probably due to the fact that the heat transfer efficiency is improved by virtue of circulating the melting and freezing blood as compared to a stationary container in which heat must be transferred to and from the center portion of the stored blood, through the surrounding blood in contact with the container walls.

The reasons for this phenomena may be best understood by examining the freezing and thawing mechanisms. As soon as the cold container is contacted with warm water, a layer of thawed blood is formed next to the container wall. This layer has one-third the thermal conductivity of the ice and much lower conductivity than the container wall so that it immediately slows down the transfer of heat from the container. By agitating the liquid layer, improved heat transfer is afforded between itself and the iced surface on the remaining frozen blood. Thus, if the container is shaken during the thawing step there will be relative motion between the liquid and the ice which improves the heat transfer across the liquid film. Experiments have shown that shaking the container during thawing gives no substantial advantage if the blood mass thickness is 6 mm. or less; however, if it is of the order of 10 mm. or greater, then shaking has a definite advantage during the thawing process. Experiments have also shown that where the blood mass thickness is 17 mm. or greater, shaking during freezing results in an improvement. Thus, with a 17 mm. container, shaking during freezing may result in an improvement in red cell recovery of 1 or 2%. In a 33 mm. container, this improvement may be of the order of 20 to 25%.

A series of tests were conducted which illustrate the effect of the ratio of blood volume to container volume. In these tests a glycerine-sugar coating was applied to 35 cc. containers, and the blood samples were introduced therein with 0.15 M lactose as a protective additive. The freezing medium was liquid nitrogen at -196°C. , and the thawing medium was water at 45°C. , the

shaking amplitude during thaw being 4 inches for 30 seconds. The results of these tests are as follows:

TABLE IV

Container Material	Blood Sample Volume, cc.	Percent Container Capacity	Freeze Time, sec.	Percent Red Cell Recovery
Aluminum	15	43	52	82.5, 86
	30	86	54	75.5, 76.5
Magnesium	15	43	48	82, 80
	30	86	49	82, 72
Stainless steel	15	43	71	80, 78
	26	74	69	75.5, 70

It is apparent from an inspection of the data in Table IV that if the sample takes up too much of the available volume, the degree of internal turbulence at any amplitude of shaking will be reduced and result in lower blood cell recovery percentages. This trend, however, is opposed by space and portability considerations, and a blood mixture volume comprising about 60% of the container capacity is preferred as an optimum balance between the two extremes for practicing the present invention.

With regard to construction materials for the blood-storing container, it has been found that suitable materials must provide a K/L value of at least 2,500, where K is the thermal conductivity in B.t.u./ (hr.) (ft.) ($^{\circ}\text{F.}$) and L is the material thickness expressed in feet. If the K/L value is less than 2,500, heat cannot be introduced through the preferably uncoated container walls at a sufficiently fast rate during the thawing step to avoid substantial damage to the red blood cells. Among the materials which have been found suitable for construction of the containers are aluminum, magnesium and stainless steel. A reexamination of the data reported in Table IV will reveal that 35 cc. containers were constructed from each of these materials, and there was very little difference between their performances under identical tests.

Several container shapes have been tested and found suitable for employment in the present invention. There are basically two available shapes: a flat geometry and a cylindrical geometry or combinations of the two. Inherently the cylindrical geometry is more efficient than the flat geometry since for a given blood mass thickness it provides twice the area-to-volume ratio that the flat geometry affords. From the practical viewpoint, however, the flat geometry offers certain advantages. For example, it can be built in a smaller physical size for the same volume than the cylindrical geometry. Also, it is probably less expensive to build. For example, a flat rectangular-type container as illustrated in FIG. 16, with inlet and outlet tubes 50 and 51 is particularly suitable as it can be stored with the highest packing factor (lowest void space) of various possible configurations. This leads to economy in the storage system, and such a configuration lends itself to inexpensive fabrication. The practicability of the FIG. 16 container is a function of the thickness dimension C . A full size container for use in the present invention must be capable of holding about 500 cc. of blood in addition to the protective additive. If the protective additive is assumed to fill 10% of the volume of the blood, and 10% free space is provided to allow for expansion of the ice during freezing, the total capacity must be 600–650 cc. It of course is desirable to make the container as small as possible which means that the thickness dimension C must be as large as possible, consistent with acceptable red blood cell recovery values.

If freezing is carried out by simple immersion in liquid nitrogen using glycerine-sugar coatings and thawing is by immersion in warm water, the thickness C can probably be no greater than about 6 mm. (0.236 in.). This is due to the fact that with greater thicknesses the internal resistance to heat transfer is too great for sufficiently rapid cooling and warming. Such a value for thickness C leads to dimensions for the width A and height B of about 16 in. However, it is preferred to shake the container during both freezing and thawing, as previously discussed. Under

these conditions the container is preferably larger than 10 mm. (0.394 in.) thick. Also, it is preferred that only about 60% of the container capacity be used by the blood containing mixture. This requires a container capacity of about 900 cc.

It has been found that satisfactory red blood cell recovery values may be attained with a rectangular container having a thickness of 19 mm. (0.75 in.). It may be possible to employ rectangular containers having even larger thicknesses.

A cylindrical container as illustrated in FIG. 17 would also be suitable as the blood storage means of the present invention. Again for the preferred method in which the container is shaken during the freezing and thawing steps, the container diameter D should be greater than about 10 mm. (0.394 in.) and less than about 33 mm. (1.3 in.). A total capacity of 900 cc. would be required.

The overall process and advantages of the present invention are illustrated in Table V, which lists data obtained from a series of tests incorporating the various features of the invention.

TABLE V
I. CYLINDRICAL GEOMETRY
[0.035 inch aluminum wall]

Blood Mass Thickness mm.	Additive ¹	Dilution ²	Coating	Cooling Conditions ³		Water Temp., ° C.	Warming Conditions ³		Percent Red Cell Recovery
				Amplitude Time			Amplitude Time		
				Inches	Secs.		Inches	Secs.	
6	7% PVP ⁴	4:5	PVP-methanol	0	⁵ 1-2	45	Rotation	⁵ 1-2	95
33	0.3 m. lactose	4:5		1¼	50	45			93
33	do.	4:5		0		45	4	30	94
33		4:5		2½		45	4	45	89

II. FLAT GEOMETRY
[0.34 inch aluminum wall]

4	7% PVP.....	1:2	PVP methanol.....	0	⁵ 1-2	45	0	⁵ 1-2	94
14	0.3 m. lactose.....	4:5	Silica-glycerol.....	2 1/2	45	45	2 1/2	30	93
4-5	12 1/2 glucose.....	1:2	[Combination of Flat and Cylindrical (0.035 inch aluminum wall) PVP-methanol.....]	0		45	0	⁵ 1-2	92

¹ Additive: Molarity shown is that in the diluted blood solution.

² Dilution: Volume of blood to total volume of final preparation.

³ Cooling and Warming Conditions: The time given under cooling and warming are the total time that the sample was

subjected to the cooling or warming conditions. It is not indicative of the time interval for travel through a given temperature range.

⁴ PVP: Refers to polyvinylpyrrolidone.

⁵ Minutes.

This application is a continuation-in-part of copending application Ser. Nos. 851,711 and 9,023 filed Nov. 9, 1959 and Feb. 16, 1960, respectively.

Although preferred embodiments of the invention have been described in detail, it is contemplated that modifications of the method and apparatus may be made and that some features may be employed without others, all within the spirit and scope of the invention.

What is claimed is:

1. A method for increasing the heat transfer between boiling liquid nitrogen and a metal solid in thermal contact with such liquid and under conditions such that an insulating film or superheated vapor of said liquid would ordinarily exist on the surface of said solid, which method comprises the steps of applying a coating of material on the metal solid surface, said material having a thermal conductivity which is lower than the thermal conductivity of said solid, and the coating being of sufficient thickness to reduce the temperature difference between said boiling liquid nitrogen and the heat transmitting surface to less than 30° F. so as to essentially prevent the creation of said insulating film, and thereafter contacting the coated metal surface with liquid nitrogen.

2. A method according to claim 1 in which said temperature differential between said heat transmitting surface and the boiling liquid is reduced sufficiently to establish heat transfer in the region of nucleate boiling.

3. A method according to claim 1 in which said boiling liquid is sprayed on said solid surface to obtain said thermal contact.

4. A method according to claim 1 in which said solid surface is immersed in said boiling liquid to obtain said thermal contact.

5. A method according to claim 1 in which said coating is glycerine.

6. A method according to claim 1 in which said coating is water soluble.

7. A method according to claim 1 in which said coating is in the form of a film, and a layer of powdery substance is applied on top of said coating.

8. A method according to claim 7 in which said powdery substance is a member selected from the group consisting of sugar, silica and crystalline zeolitic molecular sieve.

9. A method for increasing the heat transfer between boiling liquid and a metal solid in thermal contact with such liquid and under conditions such that an insulating film of superheated vapor of said liquid would ordinarily

exist on the surface of said solid, which method comprises the steps of applying a film coating on the metal solid surface of material having lower thermal conductivity than said metal solid surface and said film coating being of sufficient thickness to reduce the temperature difference between said boiling liquid and said metal solid surface so as to essentially prevent the creation of said insulating film, applying a layer of powdery substance on top of said film coating and having powder particles of sufficient size to project beyond the top of said film coating, and thereafter contacting the powder-film coated metal surface with said boiling liquid.

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165-133, 186

**UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION**

Patent No. 3,433,294

March 18, 1969

William J. Timson

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

Column 19, line 61, "or" should read -- of --. Column 20, line 52, "suffifficient" should read -- sufficient --.

Signed and sealed this 14th day of April 1970.

(SEAL)

Attest:

Edward M. Fletcher, Jr.

Attesting Officer

WILLIAM E. SCHUYLER, JR.

Commissioner of Patents