ENGINEERING ASPECTS OF CONTROLLED HYPOTHERMIA

Shiu Kee Leung, B.Sc., A.R.C.S.T.

Thesis presented for the Degree of Master of Science of the University of Glasgow

August 1965

A B S T R A C T

The investigation presented concerned applications of experimental and clinical hypothermia. The techniques and apparatus commonly utilized for its production have been reviewed and are described, both as regards to surface and extra-corporeal cooling. The heat transfer phenomenon has been examined both from the physiological and engineering standpoint.

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The analytical techniques of Forrester and Brown were extended to evaluate the specific heat of the perfused and intact animal and to assess the heat extraction pattern with and without meta:bolic heat generation of the experimental animal.

The predictive results of the after-fall of the oesophageal temperature in all the experiments carried out showed an average error of less than 1% with dogs of body weights ranging from 8.7-37 kg and of various breed.

Muscle temperature gradients have been studied in eleven dogs subjected to hypothermia. After the active cooling process, during the period of stabilization, negative temperature grad:ients were experienced in six animals.

The random variations of the heat transfer coefficient from skin to air suggested no consistency in the pattern. However, the very consistently gradual decrease of the thermal conducti:vity of the muscle with oesophageal temperature indicated the necessity for less and less heat extraction from the dog to maintain heat balance as hypothermia progressed.

The above work is presented in the thesis in Sections I-VI, treating respectively a review of hypothermic techniques; the heat transfer phenomenon in vivo; the experimental programme, the description of apparatus; pilot tests and the experimental procedures. The theoretical and experimental findings are dis:cussed in Section VII followed by a summary re-statement of the conclusion in Section VIII. The thesis terminates with a bibliography and appendices, the latter presenting certain an:cillary and calculations in detail.

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NOTATION

t	temperature in general
t_a	effective ambient temperature °C
t_n	instantaneous temperature at a radius r from the axis of the nth element
t_{an}	arterial blood temperature entering the capillary beds of the nth element
t_d	rise in temperature of cold air °C
t_{de}	rise in temperature of air (cabinet empty) °C
t_s	surface temperature of subject °C
t_i	inner temperature of subject °C
θ	$(= t - t_a)$ temperature difference
r	distance from the axis of the nth element
a_n	radius of nth element
r_s	outer radius of cylinder m
r_i	inner radius of cylinder m
s	time
ds	finite increment of time intervals
S	product of specific heat and density of blood
C_d	mean specific heat of dog (perfused) or subject (C)
C_p	specific heat of coolant
ρ	mean density of dog or subject
V	volumetric flow rate of blood in capillary beds
q	rate of heat flow per unit area kcal/m^2/hr
$\hat{q}_m$	rate of metabolic heat production in the nth element

h	thermal conductance or surface heat transfer coefficient $kcal/m^2/hr/°C$
k	thermal conductivity of muscles kcal/m/hr/°C
M	rate of flow of coolant
W	body weight of subject kg
A_m	effective mean surface area m^2
A_s	actual surface area ($= 0.112 \times W^{2/3}$, Benedict 1938) m^2
K	hypothermic cabinet coefficient, for calibration at 5-minute intervals
d	instantaneous temperature depression of dog °C
D	total temperature depression of dog °C
Q	heat extraction rate of animal ($= HW$) kcal/hr
H	heat extraction rate of animal per unit weight kcal/hr/kg
H_p	metabolic heat production rate of animal (modified from Keller) kcal/hr/kg
H_o	heat extraction of dog with metabolic heat production rate ceased kcal/hr/kg

Air Flow Measurements

h	water gauge column in
V	mean velocity of air ft/sec
σ	relative density of air
ρ	density of air $lb\text{-}sec^2/ft^4$
P_1	atmospheric pressure mm Hg
T_1	atmospheric temperature absolute
P_o	pressure at S.T.P. (= 760) mm Hg
T_o	temperature at S.T.P. (273+15.3) absolute
n	number of apertures
b	width of each aperture (= 2r) in
L	length of each aperture in
a	area of each aperture in^2
A	total area of all apertures ft^2
M	mass flow of air kg/sec
C_p	specific heat of air at constant pressure (= 0.2397 at -10°C)
Q	volume flow rate of air ft^3/sec
k	conversion factor of flow-meter of pitot-static tube (= 0.05)

I N T R O D U C T I O N

Hypothermia, although its definition varies, is perhaps best defined as the deliberate reduction below normal of body temperature. It is accomplished by a refrigeration technique of surface cooling, blood-stream cooling and cooling of body cavities.

It is used to reduce the oxygen requirements of the tissues, in particular the brain. This facilitates the performance of certain surgical procedures during which the circulation may be interrupted for a limited length of time (Forrester, 1963).

The first recorded therapeutic use of hypothermia was by the Liverpool physician James Currie in 1798 who studied the effects of cold and warm water on febrile patients. In 1940 Smith and Fay used hypothermia in patients suffering from carcinomata in an attempt to induce regression of the tumours.

The advantages of using hypothermia in cardiac surgery were demonstrated experimentally by Bigelow and his associates (1950a) and the clinical application of the method was rapid and widespread.

C L A S S I F I C A T I O N O F H Y P O T H E R M I A

The body is a heat exchange mechanism with a sensitive regulating control. Cooling or heating can occur only when this control is adequately depressed. The problem of cooling is essentially twofold: (1) creating an external cold environment to increase loss of heat and (2) disrupting the mechanism which tends to maintain normal body temperature. The carrier of heat is blood. It is the same whether the blood remains within the body or is brought to the outside and passed through some artificial device. The warm blood must be cooled before hypothermia can be achieved. The great variety of techniques are essentially governed by this single factor.

In attempting to classify various methods, somewhat arbitrary definitions of different types of hypothermia have been employed. Whole body hypothermia, in which the primary aim of the procedure has been a simultaneous reduction in the temperature of all the body tissues, has been differentiated from local or regional hypothermia in which the primary aim of the procedure is to lower the temperature of a specific region or organ system(s) even though secondaily there may have been a reduction in the temperatures of other regions of the body.

GENERAL HYPOTHERMIA

The reduction of body temperature to about 30°C is termed moderate hypothermia. This temperature is usually measured in the rectum or the oesophagus, the patient is cooled by surface cooling or blood-stream cooling. The heart itself acts as the perfusing pump and the reduction of the total body temperature results from perfusion of the viscera by blood which has been cooled by passing through capillaries of the skin. Many parameters have been studied with the final conclusion that moderate hypothermia would permit safe circulatory arrest for about 6-10 minutes (Forrester, 1963). Below this temperature, cardiac output is greatly reduced, and ventricular fibrillation is apt to occur, imposing a serious limitation to the safe period of cessation of circulation. The clinical application of this technique for intra-cardiac surgery was first performed by Lewis (1953), who reported the first successful closure of an atrial septal defect using open cardiotomy. This was soon followed by reports of many workers on large series of cases (Swan et al, 1953; Dundee et al, 1953; Williams & Spencer, 1958).

SURFACE COOLING

The objective of surface cooling is to lower the temperature of the external environment adjacent to the skin of the body so that the blood coming to the surface will release its heat. Then returning into the depths of the body, it picks up heat from the core, returning to the surface, gives off the heat, then flows back to the core, then to the surface and so on. This is a slow process, but the technique is well established, simple to achieve, and by far the most desirable in general surgical problems. It is used more than blood-stream cooling or any of its modifications.

Since true homeotherms do not survive profound hypothermia readily, the major effort, particularly with regard to human subjects, has been directed towards the production of moderate hypothermia, the methods employed have most often been immersion in ice water, packing in ice, or the use of blankets through which a refrigerant is circulated. Some attempt has been made to utilize cold air as a way of producing surface cooling.

Water Immersion

The procedure of immersing the subject in water at or near 4°C has been the most widely used technique of inducing hypothermia (Swan et al, 1955; Covino et al, 1954; Fisher et al, 1955; Blair et al, 1956; Hagnauer et al, 1960). It consists simply of partially filling a tub with water and crushed ice and immersing the subject. Cooling occurs more rapidly than with other methods of surface cooling because the largest effective surface area of the body is in direct contact with the cold environment. Other advantages of water immersion are that the necessary equipment is simple, easily available, and inexpensive. Disadvantages for induction of hypothermia in humans are that the method is cumbersome and a degree of discomfort in adult, requiring that the patient be moved to the operating table in the event of ventricular fibrillation, thereby delaying the time when resuscitation can be instituted. The disadvantages are not as serious in experimental hypothermia in animals where this method has been used successfully for many years.

Ice

This method of cooling has been used by a number of investigators in both clinical (Collins et al, 1953; Gray, 1955; Burrows et al, 1956) and experimental (Stupfel & Severinghaus, 1956) hypothermia. Crushed ice, either loose or in bag, is applied to the surface of the body, particularly in the region of the left side of the chest, thereby cooling the tissue in contact with large blood vessels. The method is simple and provides a fairly rapid rate of cooling. It has the clinical advantage of allowing the operation to commence before the desired temperature level is reached, and, therefore, of allowing for immediate application of resuscitation procedures should any untoward envents occur. The principal disadvantage of this technique is the danger of tissue damage and therefore, frequently changing of the position of the ice bags has been recommended.

Blanket

This consists of wrapping experimental animals or patients in two rubber blankets containing coils through which is circulated cold water or a refrigerant. The apparatus, though expensive compared to the equipment needed for cooling by water immersion or ice, has many advantages. First is the great degree of control over the body temperature that it affords. It is possible to adjust the index temperature of dogs to within a fraction of a degree of a desired level and to maintain this level quite constant (Spurr & Barlow, 1959; Spurr et al, 1959). Another advantage is the ability to rewarm simply by heating the circulating fluid, although if care is not exercised surface burns may be produced. The principal disadvantage of the technique is the slow rate of cooling. Even though the temperature of the circulating fluid and of the blankets may be as low as -5°C, the effective area of contact with the body surface is relatively small. Despite the slower cooling rate, this method has been preferred by many workers in the clinical application of hypothermia (Fay, 1940; Scurr, 1954, Waddell, 1957).

Air

The use of cold air as a method of producing hypothermia has not been widespread either experimentally or clinically, although it is possible to employ cold air in both these situations. The experimental use of air as a method of cooling dogs was demonstrated by Bigelow et al (1950), and Spurr et al (1954). Air cooling has been utilized clinically by Cookson (1952), Adams-Ray (1953), Bailey & associates (1954), Biorck et al (1954), Haeger et al (1956), Lundberg & Nielsen (1955) and Forrester (1958). The cooling rate is slow and, at least with the earlier use of the technique, it has been stated that frostbite is likely to occur in the digits and unprotected parts of the body. However, this does not seem to have prevented that continued use of this method.

INTERNAL COOLING

Internal cooling, in contrast to surface cooling, is a technique which by-passes the body's shivering and vaso-constriction defence mechanism against cold. Khalil (1958) described an intra-gastric water balloon apparatus for internal cooling. Human patients had been cooled to a temperature range of 29 to 32°C with this device. This method had been employed by the worker experimentally and clinically, although the rate of cooling is slow. Wangensteen (1958) used localized cooling of the stomach to control upper gastro-intestinal bleeding. Jaeger (1955) has produced hypothermia in dogs by introducing an inlet catheter into the left flank and an out flow drain in the right lower quadrant and circulating cold saline through the periton-:eal cavity.

BLOOD-STREAM COOLING

Blood-stream cooling was first decribed by Boerema et al (1951) and by Delorme (1952), using an arterio-venous cooling technique (Fig. 1), and later Ross (1954) introduced a further development in the form of veno-venous cooling (Fig. 2) which he has successfully used for a large series of cardiac surgical cases (Brock & Ross, 1955, Ross, 1959). The basis of these techniques is that blood is removed from the body, passed thr-:ough a cooling system (usually a coil) and returned again to the body in the cooled state.

From the experimental point of view, arterio-venous cooling is very simple to set up and easy to control, both in cooling and rewarming, and has the great advantage that the experimental subject does not need to be immersed in water or ice, and the necessary procedures to record other physiological variables can be more conveniently carried out. At its simplest, as shown by Delorme, blood can be removed by cannulating the fem-:oral artery, and the systemic pressure is sufficient to drive the blood through the cooling coil and back by another cannula into a suitable vein.

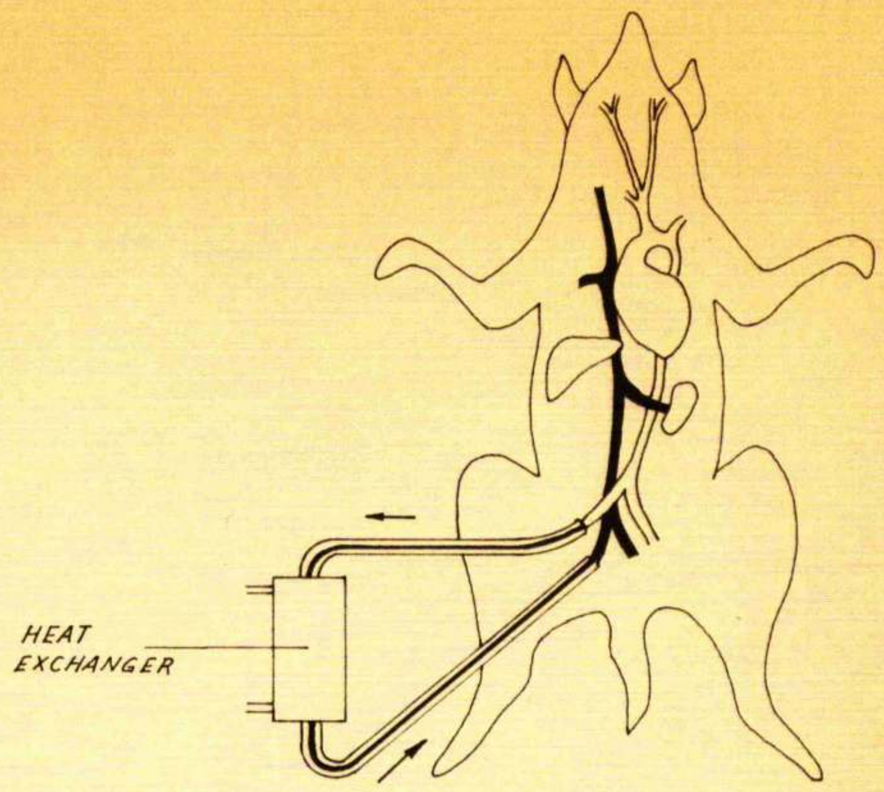


Fig. 1 Course of blood flow in arterio-venous cooling. Cannulae in superficial femoral artery and saphenous vein.

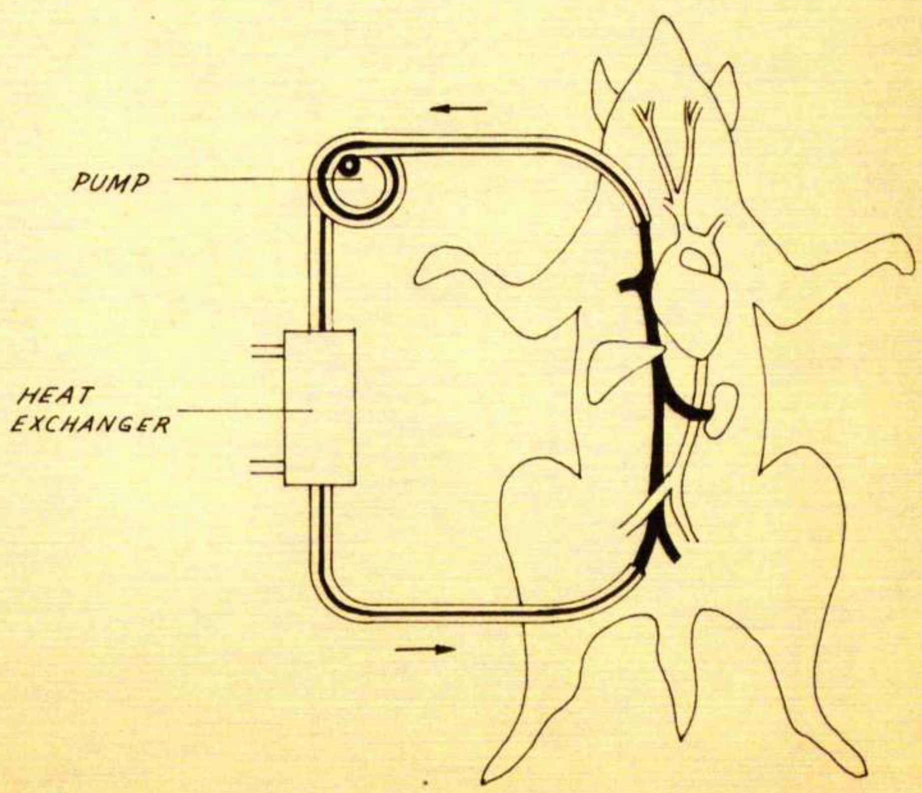


Fig. 2 Course of blood flow in veno-venous cooling. Cannulae in superior and inferior venae cavae.

The principle of veno-venous cooling is that blood is sucked from a vein (usually the superior vena cava) by a hand-driven pump to the cooling coil and is then returned cooled to another vein (the inferior vena cava), where it mixes with other venous blood and then passes on through the heart and out to the body. This method has its main application in thoracic surgery in cases in which the chest is opened, and its advantage is that it avoids arterial cannulation.

The problem associated with whole body perfusion at hypothermia remains numerous and complex. The combination of deep hypothermia, that is, below 20°C, and extra-corporeal circulation logically permits safe perfusion at greatly reduced flow rates. This technique is the most direct, the most efficient and one to be reserved for the most rigidly controlled circumstances. Its effectiveness rests with the employment of highly efficient heat exchanger system. Oxygenation is achieved either by lungs (Drew technique, Fig. 3) or by pump-oxygenator system (Fig. 4). The rate of cooling depends upon (1) the size of the patient, (2) the temperature of the coolant in the heat exchanger and (3) the rate of perfusion. Of these three factors, the most important is the rate of perfusion.

Hypothermia alone has not offered more than a small increase in access to the interior of the heart and it is the development of the heart-lung machine that has most advanced intra-cardiac

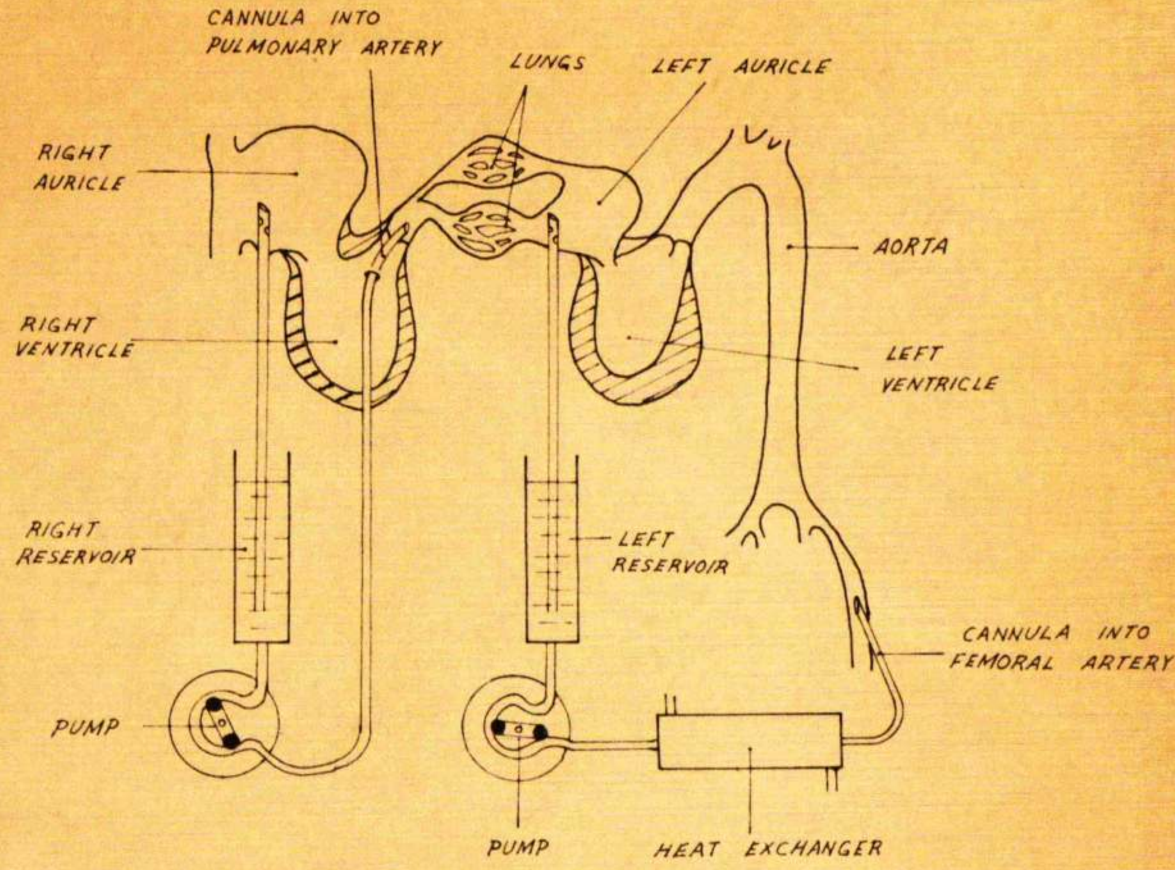


Fig. 3 Flow circuit for profound hypothermia by Drew, using patient's own lungs for oxygenation.

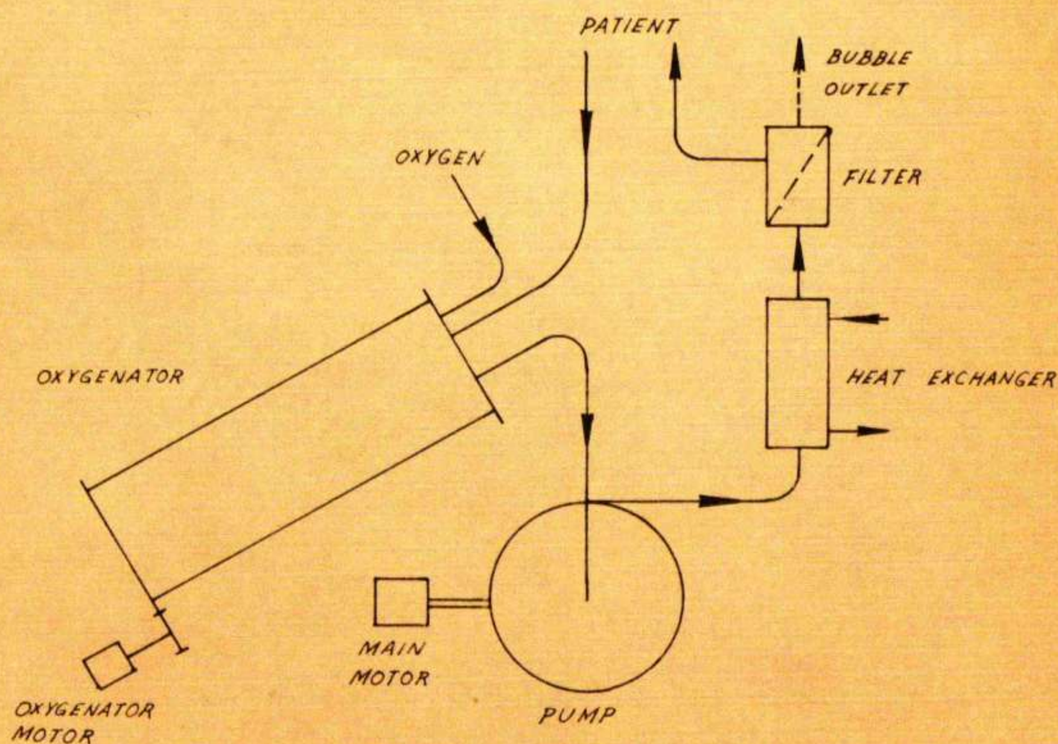


Fig. 4 Line diagram of oxygenator pump unit.

surgery. It is perhaps difficult to decide the beginning of this development, but it is generally accepted that the pioneer work is that of J.H. Gibbon, Jr. in Philadelphia in 1937.

Gollan et al (1952, 1954a, 1954b, 1955) used a small gas dispersion oxygenator incorporating an extra-corporeal blood heat exchanger to reduce the body temperature of dogs to very low levels. He was able to obtain surviving dogs after one hour of cardiac arrest when body temperatures were reduced to 0°C. He maintained a low body perfusion during the period of cardiac arrest. He later reported survivals in dogs after left heart operations during complete circulatory arrest at body temperature below 10°C. Brown et al (1958a, 1958b) reported the successful experimental use of an efficient blood heat exchanger for rapid body cooling and rewarming. Blood was passed through many small bore tubes surrounded by a water jacket. The extra-corporeal blood heat exchanger was combined with a low-flow gas dispersion pump oxygenator and employed clinically by Sealy (1957, 1958).

During the same period, another new and promising approach to the production and reversal of profound hypothermia was developed. Drew et al (1959) reported the experimental production of deep hypothermia below 20°C in dogs. He placed a large cannula into the right atrium and allowed it to drain into a reservoir. The blood was pumped from this reservoir into the pulmonary artery. An identical circuit was used to bypass the left ventricle, except that on the left side he incorporated a blood heat exchanger and a filter and bubble trap. He reported the first clinical application of his technique in seven humans in which the body temperature was reduced below 15°C and total circulatory arrest up to 42 minutes was employed. More recently the results of the operative correction in 90 patients with congenital and acquired heart disease has been reported. Other workers (Bjork et al, 1960; Gordon et al, 1960b) are employing the Drew technique with increasing frequency, which, while using the patient's own lungs to oxygenate the blood, has the advantage of simplicity and avoids the potential dangers associated with mechanical equipment.

REGIONAL HYPOTHERMIA

Regional cooling of tissue involving all the cells of the tissue rather than just the nerve cells was used by Baron Larrey during Napoleon's retreat from Moscow in 1918, producing regional analgesia in amputations of limbs. In 1867 Richardson used an ether spray to produce localized analgesia (Lee, 1953).

Selective cooling of the leg has, of course, been used on many occasions prior to amputation of extremity but the aim here has been partly to reduce the temperature to a level at which the nerves no longer conduct impulses and partly to reduce metabolic absorption from the gangrenous area. Crossman et al (1942) reported 45 such cases which were followed by no thrombosis and no emboli. Mortality was strikingly reduced in these operations, which were done before the introduction of antibiotic agents.

One of the greatest contributions of hypothermia as applied to surgery to-day is in the protection it offers to the brain during arrest of the circulation while its chief drawback is in the tendency of the heart to fibrillate at temperatures below 28°C (Forrester, 1963). The danger of anoxic brain damage limits the operating time within the heart to about ten minutes, and it follows that a selective cooling of the brain to low temperature without cooling the heart should prolong the safe period of permissible brain ischaemia and hence the period of intra-cardiac and neurological surgery available.

Selective cooling of the brain can be achieved by interposing a cooling coil in the carotid artery and this was the technique employed by Kimoto et al (1956, Fig.5). However, cooling of the brain alone does nothing to protect the metabolizing heart, which may suffer ischaemia particularly to its conducting mechanism. A more important consideration than the susceptibility of the myocardium is the vulnerability of the spinal cord, other nerves, liver and kidney, so that it is impractical and probably dangerous to effect a true selective

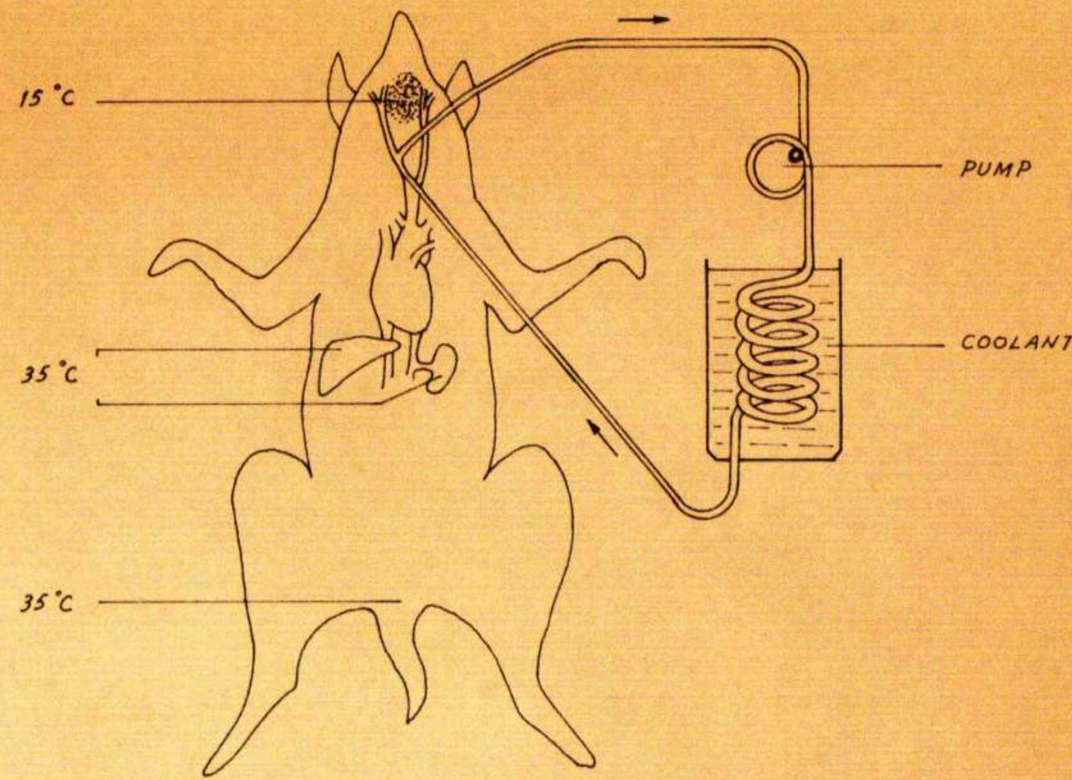


Fig. 5 Selective cooling. A cooling coil interposed in the carotid artery produces cooling of the cerebral tissues.

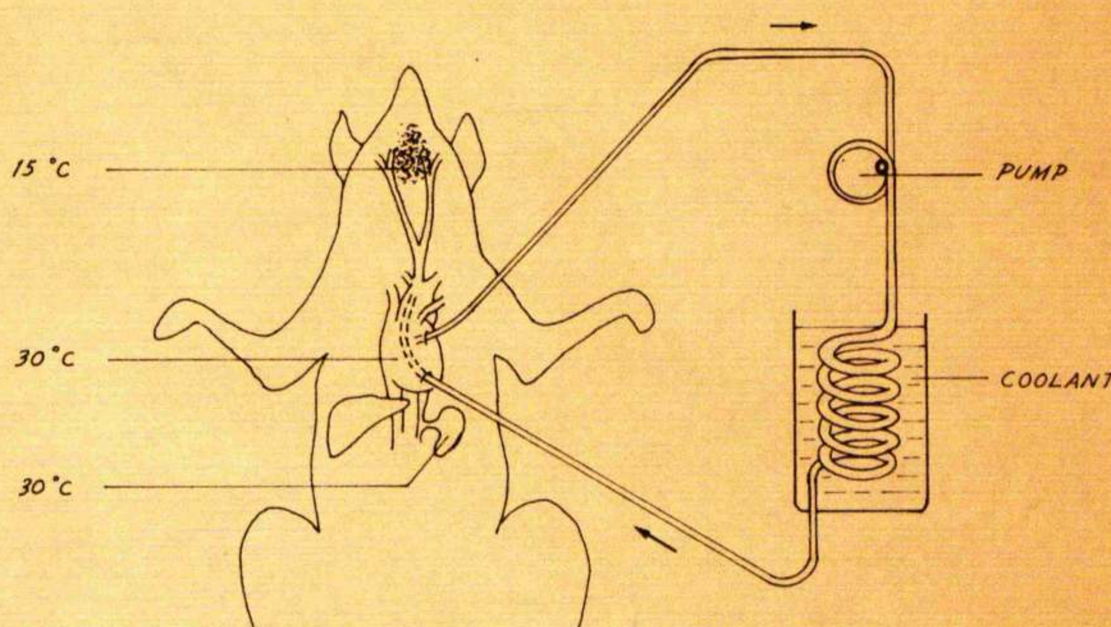


Fig. 6 Differential cooling. A proportion of the left atrial blood is directed into the aortic arch in the region of the cerebral vessels.

cooling of the brain alone, with arrest of the circulation for more than eight to ten minutes. After this time the effect of ischaemia will probably be to cause irreversible changes in these tissues. On the other hand, differential cooling can be used to afford some measure of hypothermic protection to the rest of the body. By differential cooling is meant a mild, general body cooling to say, 30-32°C at which stage ischaemic tissue is not likely to be a problem and ventricular fibrillation will not occur, with a differential reduction of the brain to say, 15-20°C (Fig. 6). Under these conditions periods of the circulatory arrest of thirty minutes or longer may be possible. This technique was, in fact, employed by Parkins et al (1954).

To sum up, hypothermia applied locally, applied to an isolated tissue, or applied to the entire body can produce analgesia. With the observation that body temperatures of below 28°C is associated with a marked increase in the incidence of ventricular fibrillation, the use of hypothermia has developed along several lines. In clinical applications, this has resolved first into use of moderate whole body temperatures of around 30°C, where the danger of fibrillation is less. However, because of the relatively short time the circulation can be arrested at this level, its use (in cardiac surgery at least) has been restricted to the simpler operative procedures. The methods utilized in

producing this level of hypothermia have most often been surface
cooling. With the necessity for performing more complicated sur-
:gical procedures requiring longer periods of circulatory inter-
:ruption, clinical investigators have developed various techni-
:ques for the perfusion of the vital organs with oxygenated blood
by means of extra-corporeal circulatory systems. These techniques
have permitted not only longer periods of circulatory arrest, but
also lower body temperatures. Some groups have commonly performed
cardiac vascular surgery at body temperatures near 15°C with card-
:iac arrest for periods approximately an hour. At present, the
complexity of these techniques restricts their use and requires
the development of highly skilled and well-coordinated teams.
Because of this, the use of moderate hypothermia, produced by the
simpler methods of surface cooling, will probably continue to be
used in those cases which do not demand long periods of circula-
:tory arrest and in those areas where trained personnel and/or
specialized equipment are not available. Furthermore, with sur-
:face cooling, the case can be diagnosed again after active cool-
:ing is stopped, and surgical incision is only made when con-
:firmed necessary. Thus the patient remains intact during cool-
:ing and rewarming.

A possibility is that a deeper level of hypothermia can be
achieved with safety in conjunction with hyperbaric chambers.

EQUIPMENTS FOR THE PRODUCTION OF HYPOTHERMIA

The concept of heat loss is based, on physical laws, upon the temperature potential between the surface of the body and the environment in the case of surface cooling, and between the blood and the cold medium in the case of blood-stream cooling. Since the human body is virtually a heat exchanger mechanism, and the procedure of production of hypothermia is to create an external cold environment to increase heat loss and to disrupt the mechanism which tends to maintain normal body temperature, the thermal aspects of some of the devices now in common use for the production of hypothermia experimentally and clinically, with particular reference to the cooling blanket, cold air cabinet, cooling of cavity, and cooling of the blood-stream, will be considered. Apparatus to be reviewed here is by no means the complete range employed for present day surgical use; only those of special interest from the engineering standpoint are considered in detail.

The principles of conventional blankets can be represented by Bloch and Edgehill's (1963), which has dispensed with the necessity for providing a special coolant fluid and pump unit. The cooling unit basically consists of copper tubing would into three close helices in series (Fig. 7a, b) placed in an ordinary domestic bin containing crushed ice and water. The cool-

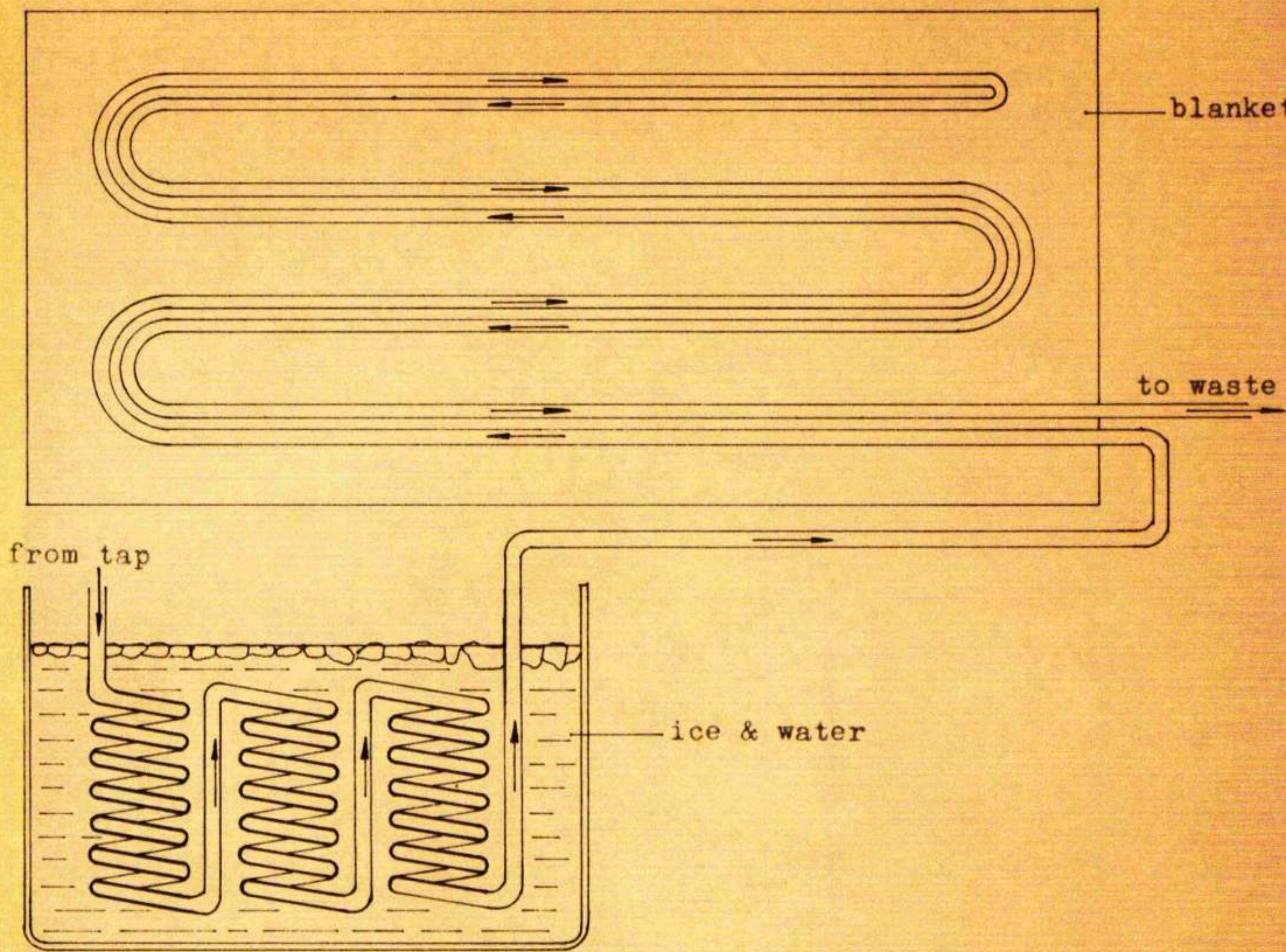


Fig. 7a Cooling blanket. Note pathways arranged in labyrinth pattern so that flow and return run parallel. A temperature gradient across the blanket is thereby avoided.

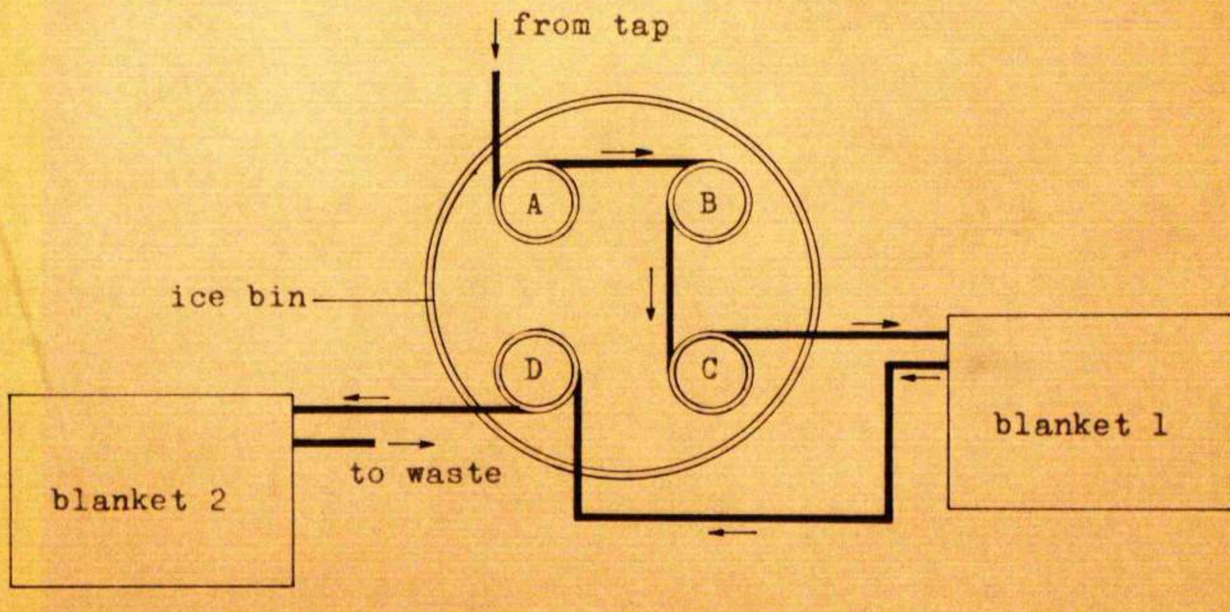


Fig. 7b Simultaneous cooling of two subjects. (Bloch & Edgehill, 1963)

:ing mattress is constructed from polyvinyl chloride (PVC) sheeting formed to enclose pathways arranged in labyrinth pat-:tern so that flow and return run parallel and in contra-flow. The temperature gradient across the blanket is therefore sub-:stantially reduced. Another interesting festure is that cool-:ing of two patients at the same time is achieved by leading the waste water from the mattress through a seperate cooling coil (D) placed in the same bin, and then around a second matt-:ress. The rate of cooling can be controlled by varying the rate of flow of cold water from the tap.

Two typical devices for the production of regional hypother-:mia are as follows: Rowbotham et al (1959) developed an app-:aratus to apply intense cold to a small area of the brain by means of a cooling cannula. This consists of a specially de-:signed cannula, circulating pump, cooling chamber, and circu-:lating fluid reservoir (Fig. 8). The cannula consists of two steel tubes, the one 0.1 in. and the other 0.2 in. in diameter, and about 8 in. in length. The smaller tube is welded within the larger, sealing the latter completely to form the top of the cannula. The smaller tube remains open. The other end of the large tube is closed in the form of an oblique tip. The smaller tube passes down the large tube to within about $\frac{1}{4}$ in. from the sealed tip. An outlet from the outer cylinder takes the form of a side-arm welded as near as conveniently possible

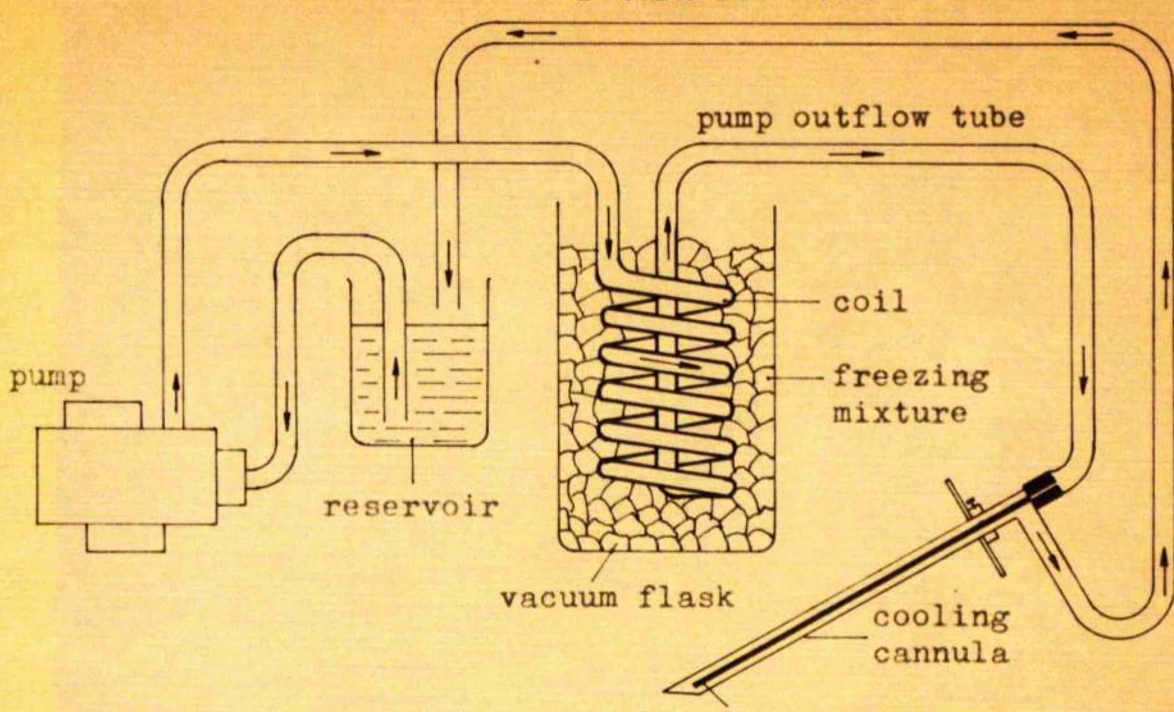


Fig. 8 Cooling cannula unit.

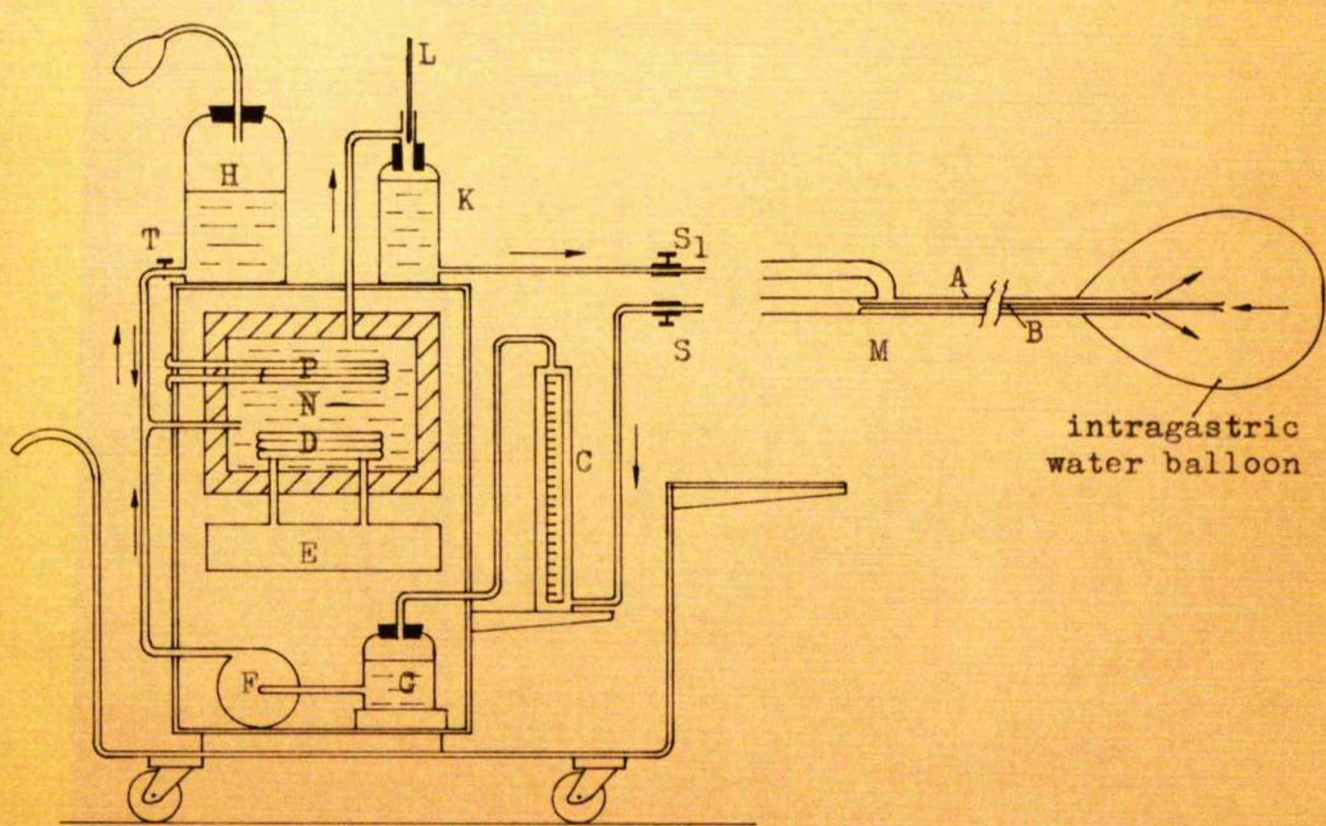


Fig. 9 Intragastric water balloon unit.

to the top. Both cannula top and side-arm are suitably shaped on the outer surface for the easy attachment of rubber connection-tubes. On the outer leading edge of the cannula is soldered a small side-tube through which a thermocouple can be passed into the surrounding brain tissue. An adjustable plate is fitted to the outside of the completed cannula. This is preset, and is used to limit the depth of insertion of the instrument. The pump drives the fluid through the circulating system, which is 95% alcohol, having a freezing point at about -110°C. The rate of fluid in the flow tube, and hence the temperature at the tip of the cannula, is controlled by varying the speed of the miniature pump. In clinical cases, these workers have brought the temperature at the tip of the cooling cannula to -15°C within 15 minutes, whereas the local brain temperature at 12 mm. from the cooling cannula is about 22°C. They proved beyond doubt that it is possible to freeze a local area of the cerebral hemisphere without endangering life.

In 1958 Khalil described a very useful apparatus for intragastric cooling (Fig. 9). It consists of a water tank N, of 10-litre capacity, which can be either cooled by means of a cooling coil D attached to a compressor, or warmed by means of an electric resistance coil P. The temperature of the water is controlled by means of two thermostats. The water tank is surrounded by thick cork jacket which provides thermal insulation.

A suction water-pump F sucks the water from the intra-gastric balloon into the water tank N, and, since the tank is hermetically sealed, automatically drives an exactly equal volume of water to the balloon. In this way, the volume of the balloon remains constant. Air is prevented from entering the balloon or the pump by fitting two air-traps G & K. A graduated 5-litre jar H, with an attached sphygmomanometer pump and a bottom tap T, lies above the tank. Tap T is opened only while filling or empty the balloon. A flow-meter C is placed between the balloon and the pump. The screw-clamps S and S_1 are applied to the thick rubber tubing leading to and from the balloon. They are used to clamp the rubber tubing while the empty balloon is being introduced into the stomach, to prevent water from leaking into it at that time. A special metal junction M is designed to allow to-and-fro currents through the tubes A and B leading to and from the intra-gastric balloon. The outer tube is 1.0 cm in diameter and the inner one 0.6 cm. A thermometer is immersed into the air-trap K to register the temperature of the flowing water at inlet. The whole apparatus is fitted inside a suitable stand with wheels to allow easy transport.

Before cooling starts, the emptied balloon is smeared with catheter oil and introduced into the stomach. About 1.5 litres of water is pumped into the balloon from jar H, and the suction pump F sucks the water from the balloon into the tank, and de-

:livers a constant fresh volume of water into the balloon con:tinuously. Although Khalil could only obtain a groin tempera:ture drop from 36.8 to 26°C in 4 hours with such apparatus, the flow rate and water temperature are well under control. And since water is in fact sucked away from the balloon, there is no danger of the latter being overfilled.

Shortly after J. Adams-Ray and P.O. Persson presented their cooling cabinet in 1953 for animals by means of circulating cold air, several investigators (Biorck et al, 1954; Lundberg & Nielsen, 1955; Haeger et al, 1956; Forrester, 1958) followed to construct similar cooling cabinets to produce hypothermia with air cooling.

The device basically consists of two main parts: one contain:ing the refrigeration unit, heating elements and a fan, the other fitted with a stretcher intended for the patient or an experimental animal. The cabinet is usually made of light tim:ber and is insulated. Of the range of cabinets used, Haeger and co-workers have devised a well-equipped, combined cooling box and swivel operating table, which eliminates the need of transporting the patient or animal from the stretcher to the conventional operating table. The head of the subject to be cooled lies on a head-rest outside the cabinet although in the case of animals sometimes the whole subject is left inside the cabinet. The special stretcher is generally in the form of a strong nylon net on which the subject lies to minimize the area of contact of the body with the supporting surface, providing more exposed area for the cold air, which is directed onto the surface of the body. The rate of cooling can, to some extent, be controlled by setting the thermostat.

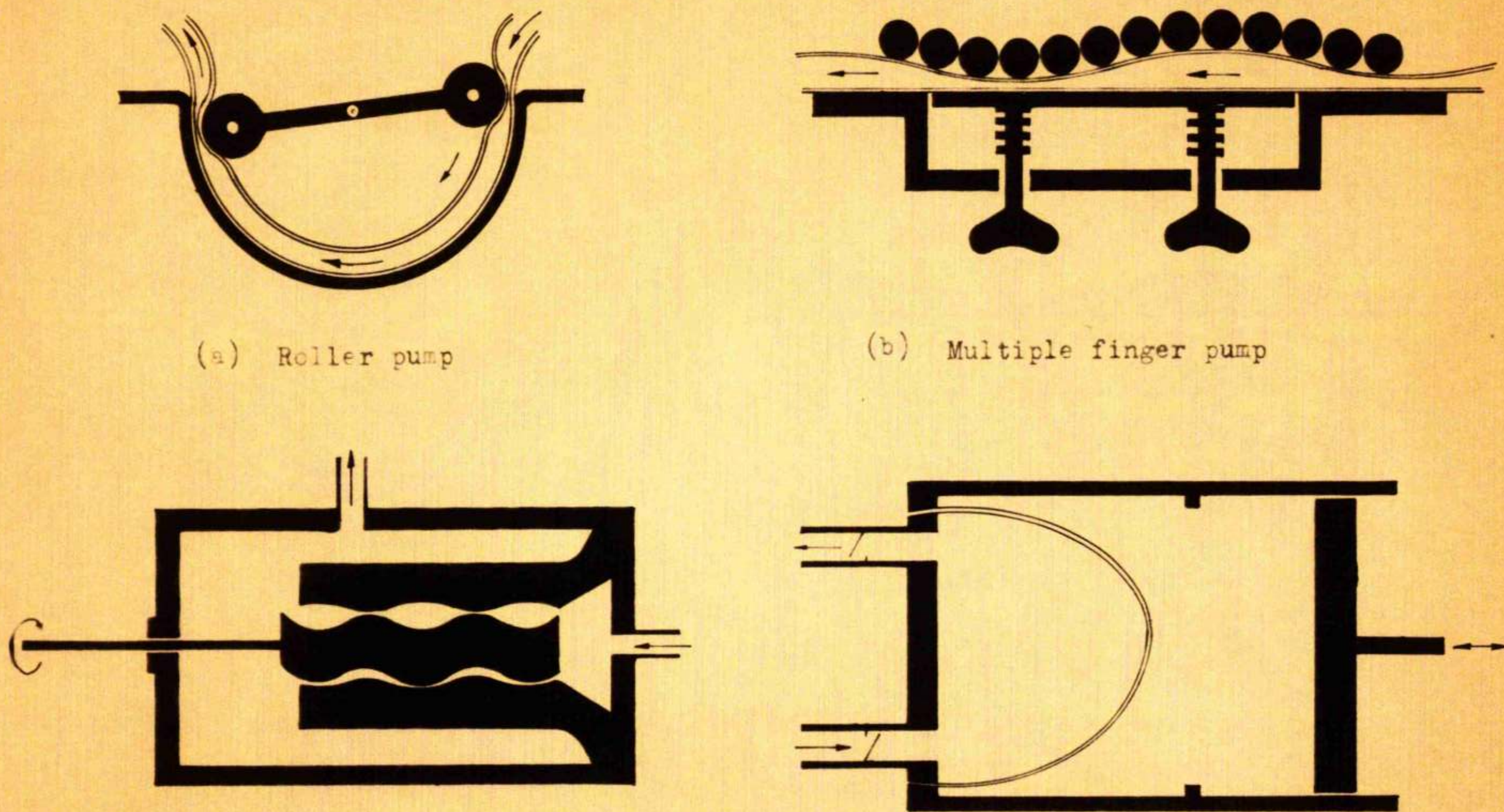
Patient care is well facilitated with these cooling cabinets throughout the periods of cooling and rewarming, since sliding apertures, and boards with electrical connectors are provided for tubings from intravenous transfusion set, electrocardiograph, temperature leads, and other recording instruments, and the condition of the subject can be constantly observed through small transparent windows.

To achieve profound hypothermia by blood-stream cooling, using the patient's own lungs for oxygenation or otherwise, it is necessary to provide some mechanical means to take over the function of the heart. In this way, it is possible to (1) establish a satisfactory pulmonary systemic circulation; (2) continue the cooling process in the presence of a non-functioning heart; (3) rewarm when desired after a long period of circulatory arrest and (4) restore normal heart action.

Apart from the basic essential components, such as oxygenators, pump and tubings, modern heart-lung bypass equipment comprises various auxilary elements which, depending upon the type of procedure planned, may or may not be dispensable. In what follows some of the elements of extra-corporeal techniques are briefly described.

Pumps

In practice, the number of pump types has been reduced to four, and these are the roller pump, the finger pump (Sigma Pump), the Archimedean screw pump and the reciprocating pump. Roller pumps use a progression of rollers along a flexible tube filled with blood to provide the pumping stroke and to give direction to the flow. Occlusion setting makes the pump load-sensitive, but requires an exactly adjusted compression of the resilient tubing to prevent undue blood trauma. In general, the more rollers to a pump, the greater is the haemolysis. Single roller pumps have a circular housing in which a complete loop of tubing is inserted and compressed by an electrically revolving roller. In twin roller pumps a loop of tubing lies in a horseshoe-shaped housing and is compressed by two rollers 180 degrees out of phase (Fig. 10a). Roller pumps are relatively simple in design and remarkably sturdy. In multiple finger pumps, unidirectional flow is produced by series of keys which press in sequence against a resilient tube. The cycles of the operating fingers are timed so that some part of the tubing is always occluded by pressure against a solid plate (Fig. 10b). Any convenient segment of an extra-corporeal circuit can easily be inserted into the pump head. The Archimedean screw (Fig.



(a) Roller pump

(b) Multiple finger pump

(c) Archimedean screw pump

(d) Reciprocating pump (hydraulic drive)

Fig. 10. Four common types of pumps used for hypothermic perfusion.

10c) pump operates on the principle of a solid helical rotor revolving within a resilient helical stator of different pitch so that blood is drawn along the thread. The fluid pockets trapped between the stator and the rotor progress steadily to-ward the outlet end of the pump and provide for a continuous flow. The pump is easily calibrated since there is no possible backflow. Pumps based on the Archimedean flow principle handle blood gently and are capable of a wide range of output. Recip-rocating ventricle pump consists of a compressible chamber mounted in a rigid casing and are activated by displacement of fluid or gas in the casing (Fig. 10d). Unidirectional blood flow is maintained by the insertion of valves at the entrance and exit of the pumping chamber. Incorporated with modern sens-ing and regulating devices, the reciprocating pump appears most promising, because it potentially combines inherent gentleness in blood handling with safety of operation and the reliability of positive displacement pumps.

Blood Filters

Blood filters serve to strain debris from the extra-corporeal blood before it is re-introduced into the organism. Good filters are atraumatic, offer negligible resistance to flow, have enough free surface for blood to pass despite partial plugging, and are easy to clean, assemble and free of gas bubbles.

Bubble Traps

Bubble traps are necessary safety devices in most extra-corp-:oreal blood circuits. Their design is based on theoretical considerations relating the velocity of vertical ascent of the bubbles to the duration of transit of the blood through the bub-:ble trap. A prolonged transit through a relatively shallow layer of blood gives the bubbles the best chance to rise and dissipate. Auxiliary factors such as skimming, centrifugal sep-:eration or anti-foam compounds are used to supplement bubble elimination by buoyancy.

Flow-meters

Since knowledge of the perfusion flow rate is important in heart-lung bypass procedures, some means of measuring flow must be introduced into the extra-corporeal circuit. Occlusive pumps can serve as flowmeters. In the case of non-occlusive pumps, too many variables must be computed to obtain a flow reading which is of practical value. Cumulative recording of flow by temporarily interrupting the circulation is inaccurate. Most frequently used in extra-corporeal circuits are electro-magnetic flowmeters.

Temperature Regulators

Since there is considerable heat loss in all extra-corporeal circuits, devices have been introduced for the purpose of main-

:taining the temperature of the perfused organism within the normal physiological range. Water baths, warm air, infra-red radiant energy and heating wires have been used with varying success. Because of possible thermal injury to the red blood cells, the local temperature of surfaces in contact with blood should never be permitted to exceed 40°C (Forrester, 1963).

Oxygenators

The design of a practical oxygenator dates back about 25 years to the work of Gibbon (1939). The number of different types in use at the present time is very large and this survey merely attempts to outline the principles on which a number of the more/devices work. There are four main types of oxygena-:tors in general use, namely the membrane oxygenator, the screen oxygenator, the bubble oxygenator and the rotating disc oxygena-:tor.

Membrane Oxygenator The first membrane oxygenator practical for human perfusion resulted from a development of the multi-layered lung originally described by Clowes et al (1956). Oxy-:gen is passed along one side of a highly diffusable membrane and blood is passed along the other side, as in the lungs (Fig. 11). The net result is a diffusion of gases across the membrane, functioning as it does, across alveolar capillary membrane in hu-:man lungs. Venous blood is carried by a vertical column and

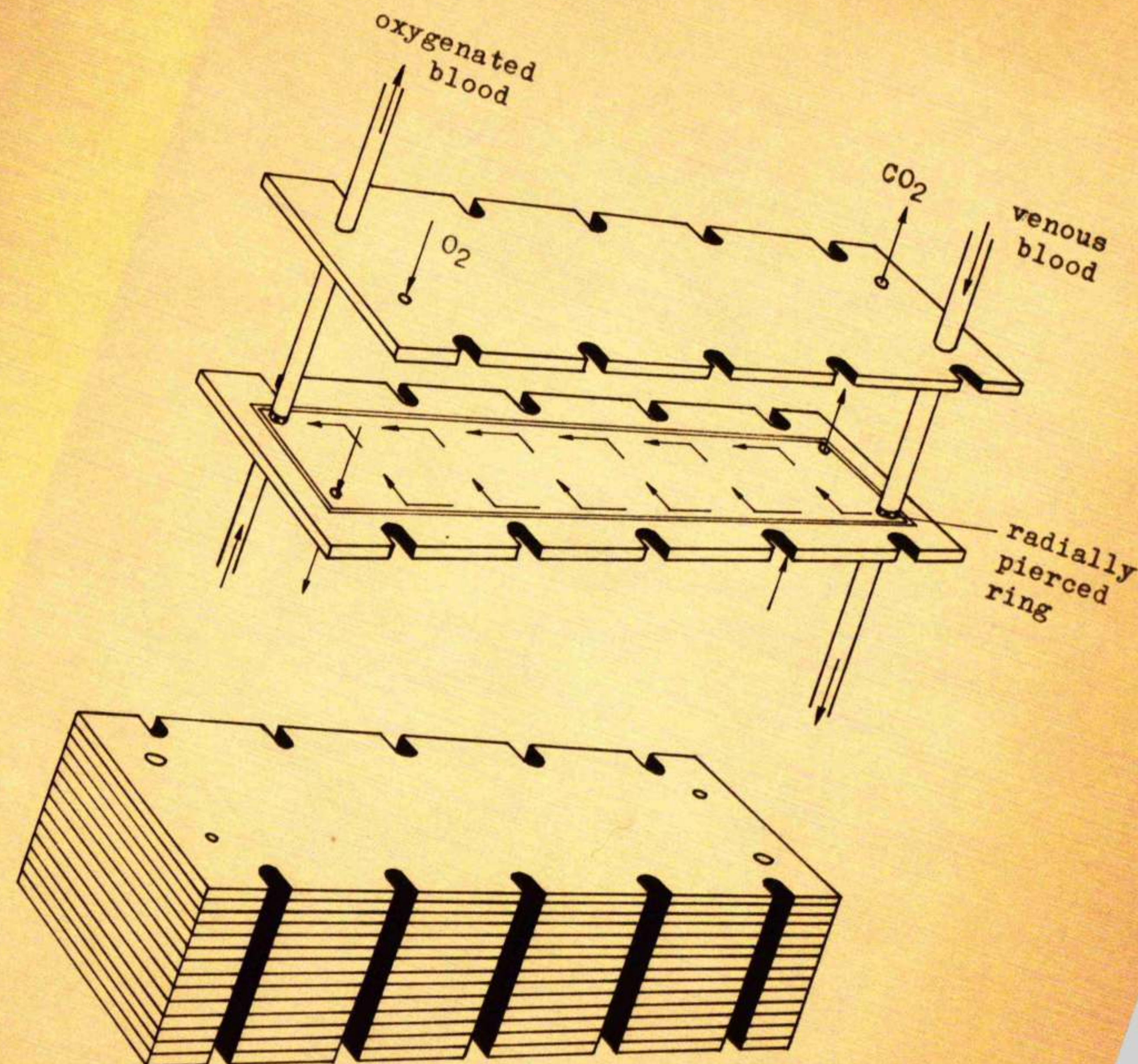


Fig. 11. Multilayered membrane oxygenator proposed by Clowes et al. (1956).

distributed between each pair of membranes by a radially pierced ring. Arterialized blood is collected in a similar column at the opposite angle of the assembly. Oxygen is circulated thr-:ough grooves in the supporting plates or through interspaces of woven spacers between consecutive blood layers. In order to maintain a constant blood volume within the oxygenator, over-stretching of the membrane must be avoided. This is done by keeping pressure and flow in the apparatus constant. Gentle handling of the blood, disposability of parts in contact with blood, freedom from gas bubbles and simplicity of volume con-:trol are the outstanding virtues of the membrane lungs. Diff-:iculty of assembly and high cost of the disposable membranes are among the drawback.

Screen Oxygenator A relatively simple stationary screen oxygenator was described by Kay and Anderson (1958). It is re-:presented in Fig. 12a. Its foremost feature is the use of the recirculating pump to prevent the venous blood from reaching the arterial outlet without first going over the oxygenating screens, which are made of stainless steel wire mesh. This el-:iminates seperate storage containers for the venous reservoir, coronary sinus reservoir, artérial blood reservoir, arterial filter and bubble trap. Venous blood enters the unit on one side as does the blood from the coronary sinus suction tip. Mixed blood consisting of venous and recirculating arterialized

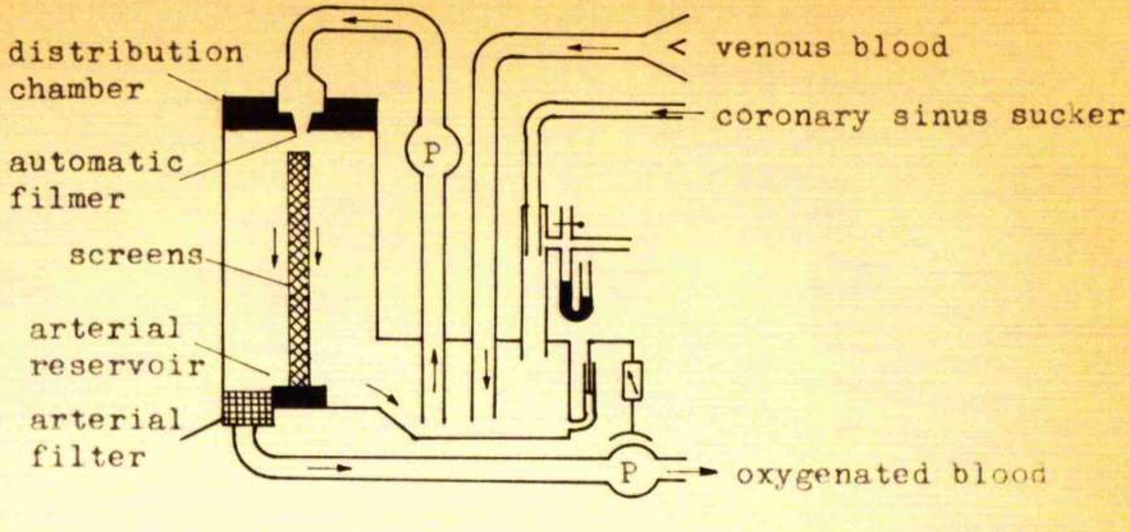


Fig. 12a. Single-chambered screen oxygenator of Kay & Anderson (1957).

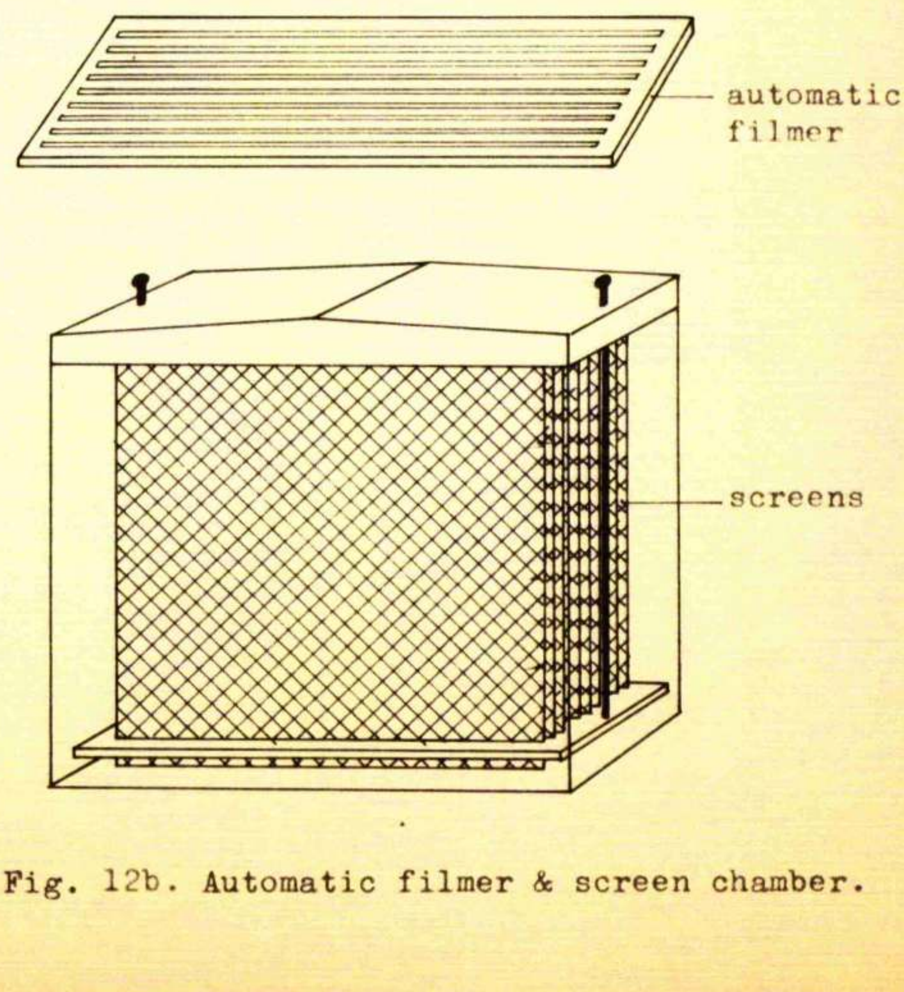
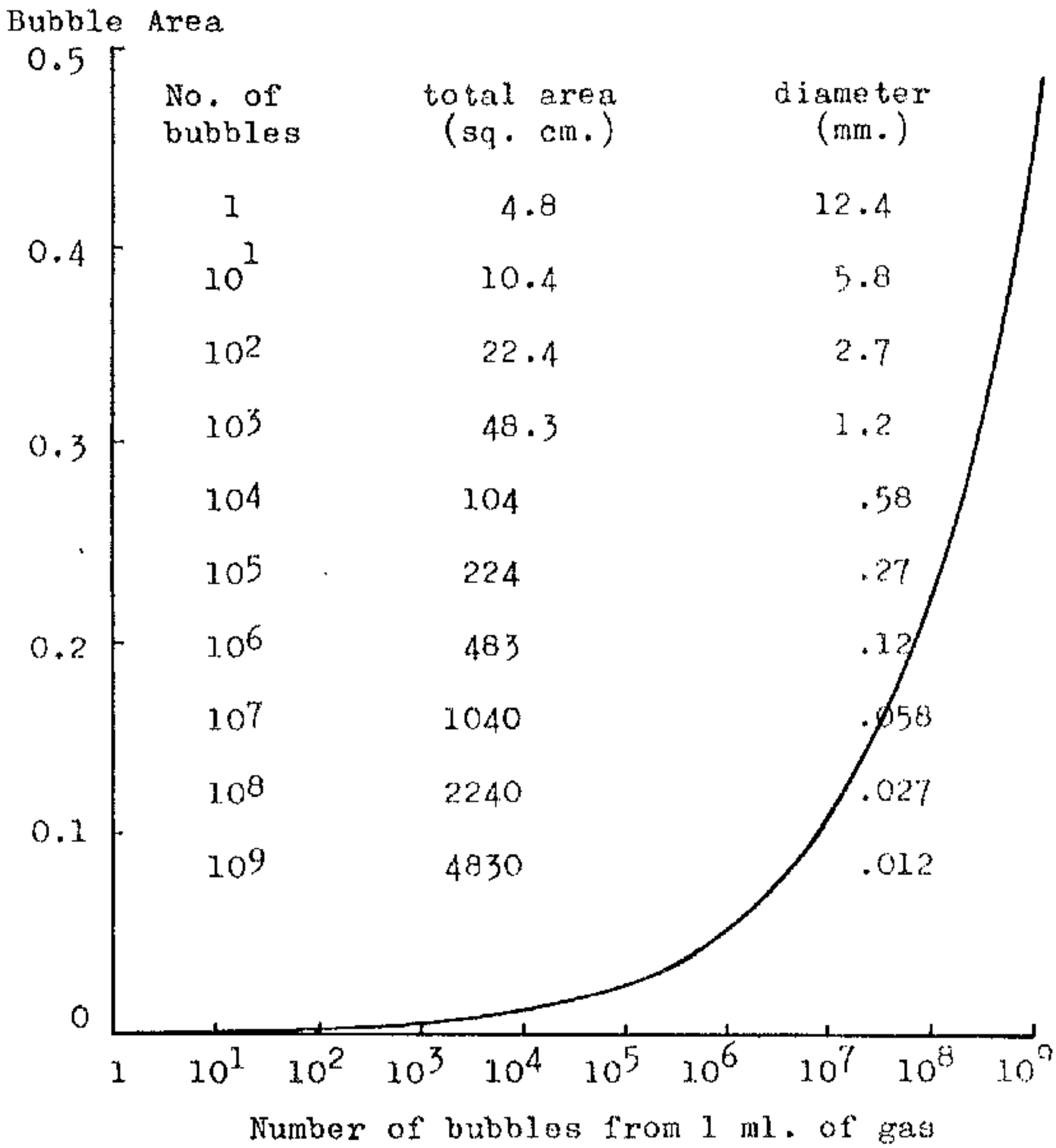


Fig. 12b. Automatic filmer & screen chamber.

blood reaches the screens via the internal circuit pump. The distributing chamber at the top of the artificial lung is emptied of air and filled completely with blood before starting the oxygenation. This provides equal pressure throughout the distributing chamber and causes similar flow through all the openings. The filmer (Fig. 12b) establishes a film of blood on the screens by simply lowering the former. Oxygen molecules are passed across the face of the film to oxygenate the blood. Fully oxygenated blood collected at the other side of the unit is distributed to the organism via the arterial pump. The speed of perfusion is regulated by the aortic pressure. The apparatus is capable of oxygenating and delivering an amount of blood equal to normal cardiac output in adults and children.

Bubble Oxygenator   Bubble oxygenators take advantage of the fact that a large gas-blood contact surface can be created in a relatively small amount of blood by bubbling oxygen through the blood. The greater the number of small bubbles, the larger the gas exchange surface will (Fig. 13). A typical bubble oxygenator was presented by Cooley et al (1958) as shown in Fig. 14. It is made entirely of stainless steel and thus can be cleaned and sterilized as surgical instruments. It consists of four principal parts: (a) a diffusion head for oxygen dispersal; (b) an oxygenating column; (c) a defoaming chamber and (d) an inclined helical trough. The diffusion head is perforated by



No. of bubbles	total area (sq. cm.)	diameter (mm.)
1	4.8	12.4
10^1	10.4	5.8
10^2	22.4	2.7
10^3	48.3	1.2
10^4	104	.58
10^5	224	.27
10^6	483	.12
10^7	1040	.058
10^8	2240	.027
10^9	4830	.012

Fig. 13. Table & Graph showing the total surface area produced by 1 ml. of gas when divided into an increasingly larger number of bubbles of progressively smaller diameter. (Modified from Clark, 1959)

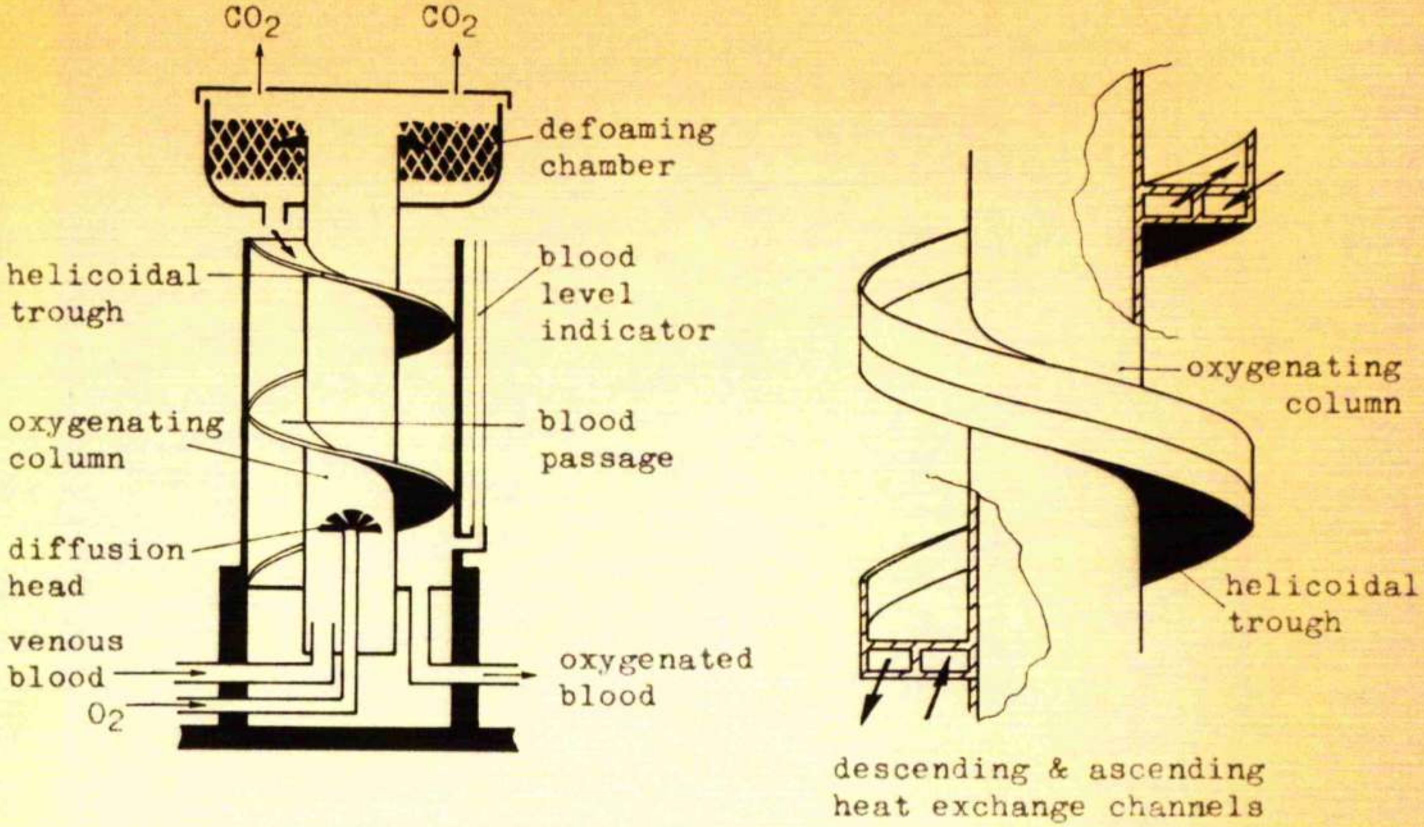


Fig. 14. Bubble oxygenator by Cooley et al. (1958) (left); & heat exchanger incorporated by Goetz (1963) (right).

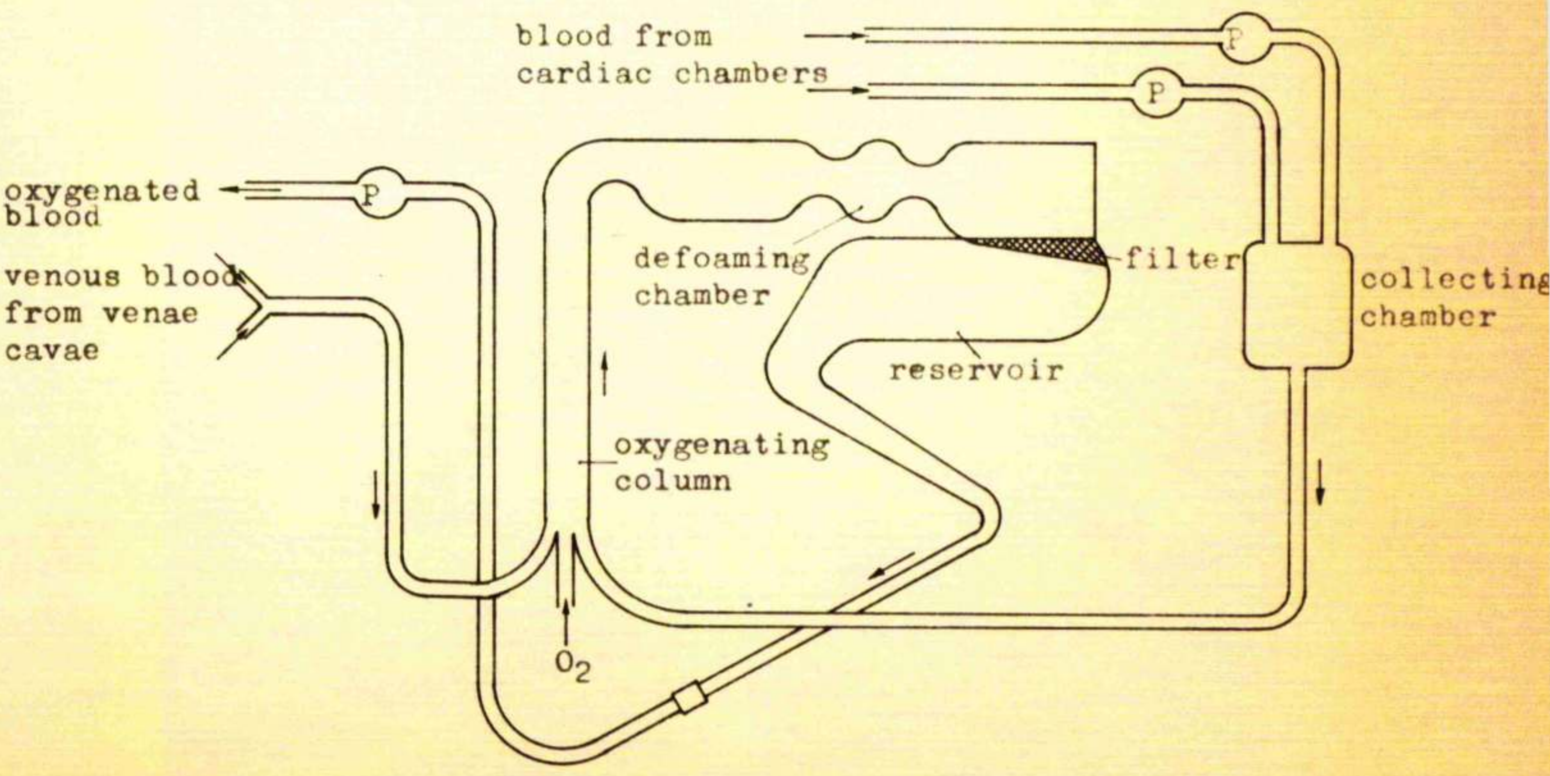


Fig. 15. Disposable plastic bubble oxygenator by Cooley et al. (1962).

approximately 150 small holes, 0.5 mm in diameter, around which the venous blood enters. On top of the oxygenating column is the defoaming chamber, into which the blood-gas mixture overflows. This chamber contains disposable stainless steel scouring sponges sprayed with anti-foam. From the defoaming chamber the liquid blood, purged of its gas bubbles, is drained through a spigot and passes into the inclined helical trough that leads to an arterial reservoir. Attached to the reservoir is a side tube to indicate the blood level. The apparatus provides blood flows up to 3 litres/min with a priming volume between 1 and 1.5 litres.

In 1963 Goetz incorporated a highly efficient heat exchanger in the Cooley oxygenator, without additional blood contact surfaces or priming volume. Cooling or rewarming of the blood is effected by circulating water of varying temperatures through two heat exchange coils formed by two parallel running helices around the oxyengating column. These two coils form an inner and an outer channel. The division is not, however, carried entirely to the end so that the two channels communicate with each other at the uppermost part of the helical coil. It is obvious from Fig. 14 that the roof of the channels is formed by the helix which carries the blood down. All parts being made of stainless steel, the helix readily takes on the temperature of the water running in the channels. Cooling and rewarming of blood primarily takes place as it is running down the helix.

However, as is apparent from the figure, one side of the inner channel is formed by the central bubble chamber or oxygenating column, so that this, too, forms part of the heat exchange sys-:tem with the result that the bubbles arrive already cooled in the defoaming chamber. At the lower end of the helix, the chan-:nels are connected to two tubes which are brought out of the oxygenator through the base plate and fitted with connections serving for water inlet and outlet. Cooling and rewarming of the blood is thus accomplished by circulating water at any de-:sired controlled temperature through the heat exchanger.

Another type of bubble oxygenator worth mentioning is the one described again by Cooley et al (1962). It is a disposable pla-:stic bubble oxygenator. Blood is withdrawn from the venae cavae by gravity drainage using plastic catheters into the base of the oxygenating column which is located below the level of the venae cavae. The flow of oxygen provides the driving force for the blood through the vertical column (Fig. 15). The blood-oxygen mixture enters the defoaming chamber which contains a stainless steel sponge coated with anti-foam. Oxygenated blood then passes through a filter located between the defoaming chamber and the reservoir. The arterial flow rate to the femoral artery is ad-:justed to equal the volume of blood returned to the oxygenator. Blood aspirated from the cardiac chambers during bypass is re-:turned to a disposable collecting chamber by means of individual roller pumps from which it flows by gravity into the oxygenating chamber. Flow rates in excess of 3.5 litres per minute are possible with this oxygenator with complete oxygenation.

Rotating Disc Oxygenator Perhaps one of the most successful rotating disc oxygenator is that described by Osborn et al (1960) as shown in Fig. 16. It incorporates a water jacket for rapid cooling and rewarming of the blood during the period of oxygenation. The improved model reduces the danger of foam formation by reducing the clearance between the discs and the cylinder wall to 0.4 mm, which is small enough to be easily and consistently spanned by the centrifugally formed blood seal. This continuous meniscus of blood is maintained all around the disc, and the whole adjacent interior cylindrical surface is wet with non-stagnant blood and thus can be used as a heat-transfer surface. However, since this arrangement leaves room for neither blood nor oxygen to flow axially through the oxygenator, Osborn and associates have provided blood flow by a longitudinal channel at the bottom of the cylinder. Oxygen flow is made possible by one 5/8 in. diameter hole located in each disc near the shaft. On assembly, each hole is oriented at 180 degrees to those in adjacent discs, so as to encourage mild gas turbulence.

This oxygenator has the advantages of having high perfusion rate, being 4½ litres per minute; it does not produce foam; it has high ratio of oxygenating surface to priming volume; it em-

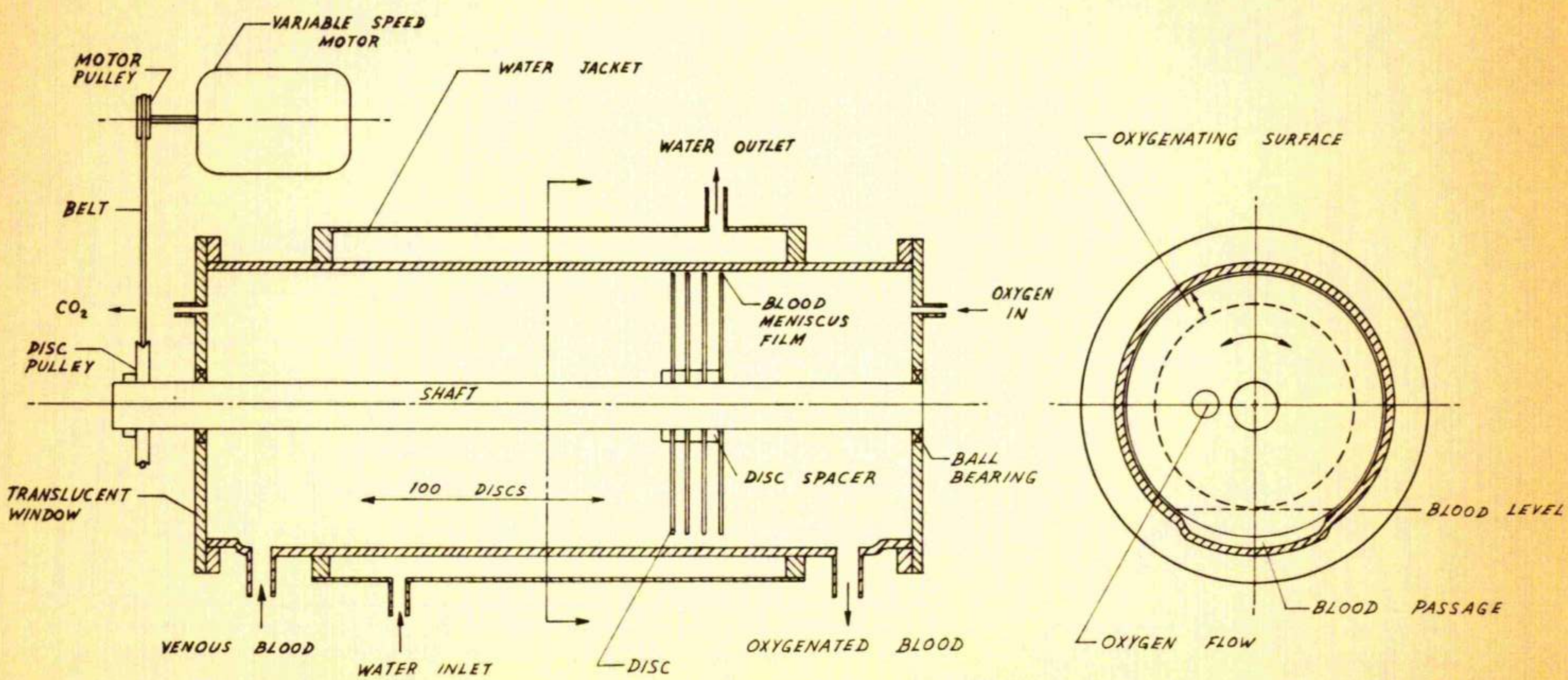


FIG. 16. SECTIONAL SKETCH OF THE OSBORN OXYGENATOR, WITH HEAT EXCHANGER.
HALLIKAINEN INSTRUMENTS LTD., LONDON.

:bodies heat exchange characteristics which, without additional blood contact surfaces or priming volume, allows perfusions to be combined with rapid cooling and rewarming of the circulating blood, and the cleaning process is simply performed on the shaft-disc assembly as a unit, without disassembly.

Heat Exchangers

Heat exchangers are used to cool rapidly and rewarm the or:ganism during surgical intervention in order to benefit from hypothermic conditions. These devices can decrease the oesopha:geal temperature of the perfused organism by 1-3°C per minute at flow rates from 1 to 4 litres per minute. The rate of re:warming is somewhat slower. In addition to their efficiency of heat transfer, heat exchangers must meet the same require:ments as all other components of extra-corporeal circuits, namely non-toxicity of construction materials, no possibility of mixing between the blood and the coolant, low priming volume, minimal resistance to flow, and ease of cleaning and steriliza:tion. Some of the typical experimental and clinical heat ex:changers are discussed briefly below:

The Brown-Harrison (Brown et al, 1958b) stainless steel heat exchanger has been widely used. It consists of an outer cylind:rical jacket 15½ in. long and 2¼ in. in diameter through which 24 straight thin-wall tubes 0.18 in. bore run longitudinally. The ends of the tubes are welded into a header plate (Fig. 17)

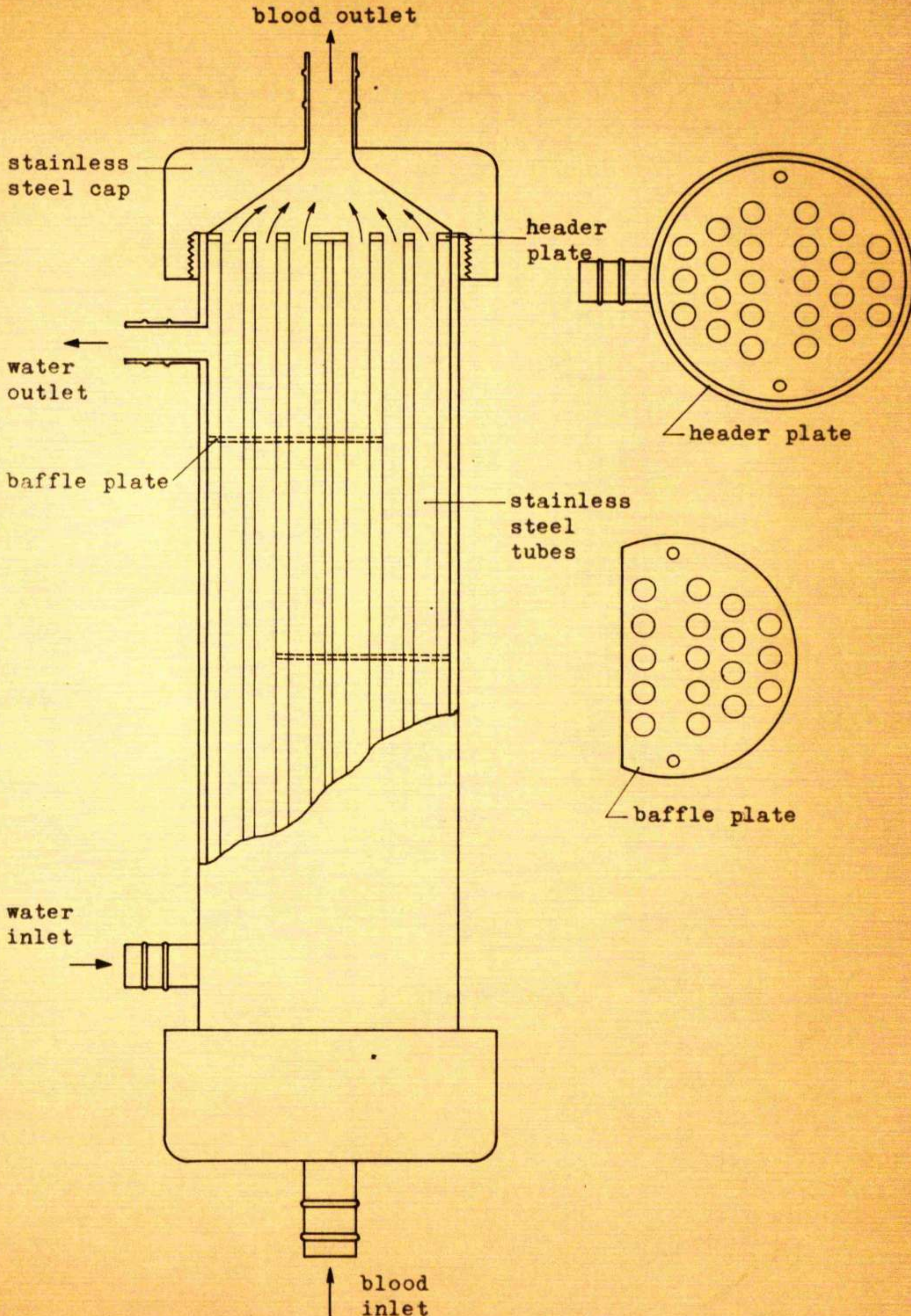


Fig. 17. Blood heat exchanger by Brown et al. (1958).

at each end and the surfaces in contact with blood are highly polished. Each end of the exchanger cylinder is threaded to take a stainless steel cap fashioned with a beaded tube to which usual plastic blood inflow and outflow tubing is attached. The interior of each cap is conically shaped, providing sloping sur:faces for the flowing blood at each end of the exchanger to avoid the trapping of any gas bubbles. Near the bottom of the exchanger jacket is a water inlet through which cold or warm water enters the exchanger jacket and flows upward to a similar outlet at the top of the exchanger. Baffle plates within the jacket of the ex:changer ensure thorough circulation of the cooling or warming water around the thin tubes carrying the blood. The heat exch:anger is mounted in a vertical position.

In 1961 Hufnagel and co-workers reported a very efficient heat exchanger with low priming volume (only 22 ml). The blood cir:cuit is interposed between two surface contact areas for heat exchange. The film of blood is 0.125 cm thick and the total sur:face area available for heat transfer is approximately 2,000 sq. cm. This is provided by a hollow tubular outer jacket and an inner hollow cylinder, each of which seperately connected to the heating and cooling circuits (Fig. 18). The length of the exch:anger is 50 cm. The internal diameter of the outer jacket is 6.65 cm and the outside diameter of the inner cylinder is 6.4 cm. The inner cylinder is centrally suspended within its jacket so

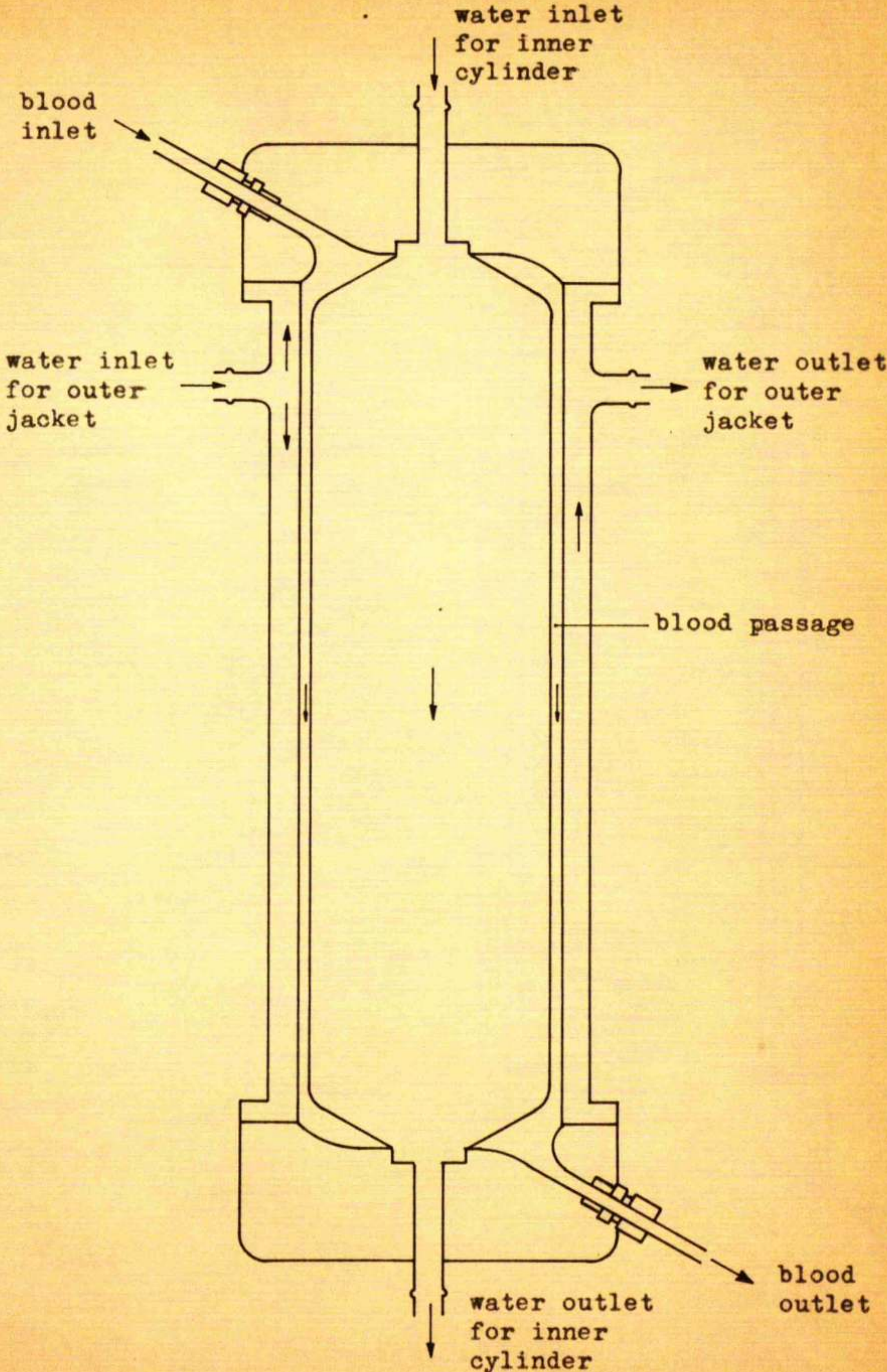
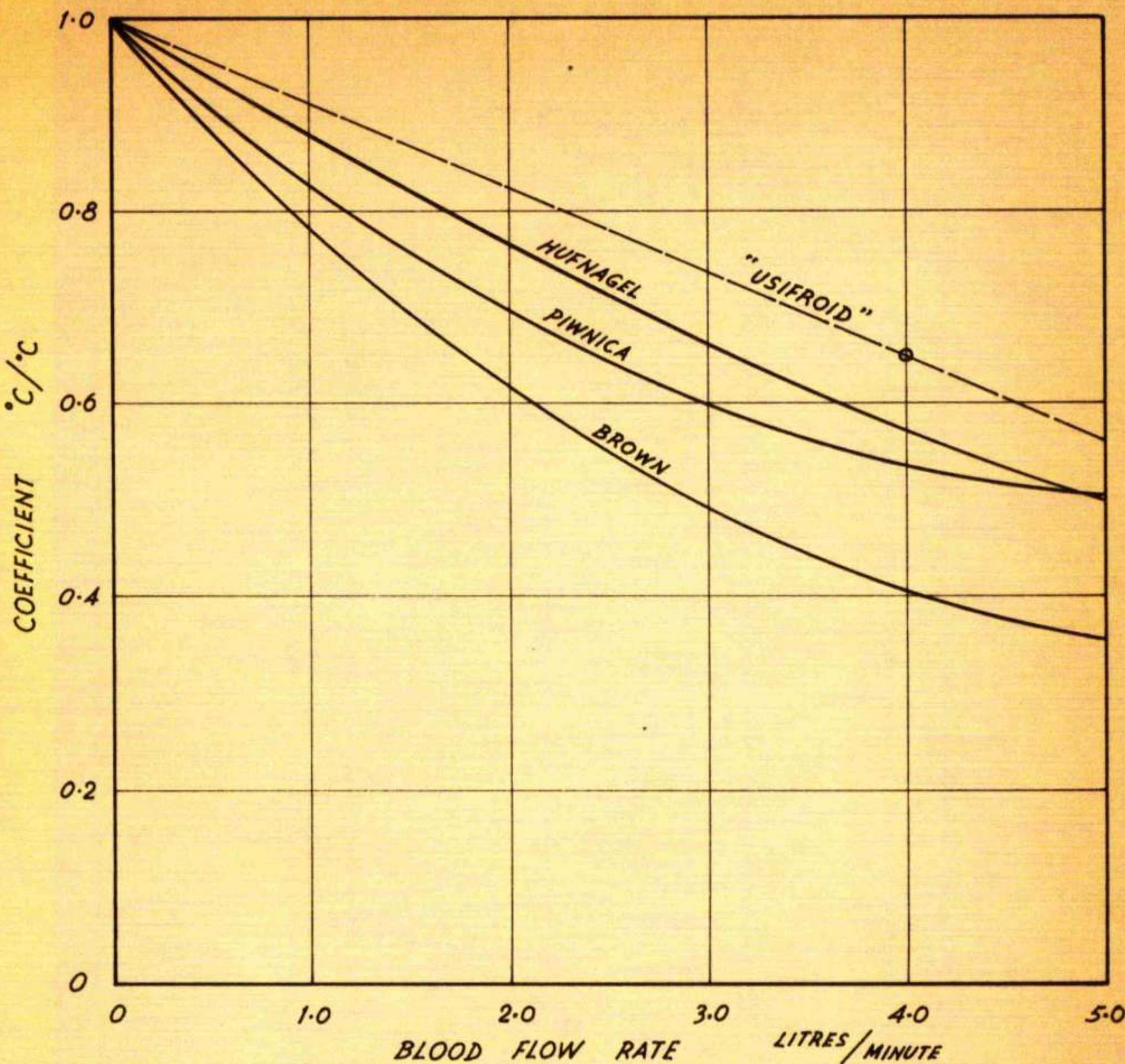


Fig. 18. Blood heat exchanger by Hufnagel et al. (1961).

that there is a uniform space of 0.125 cm between the two walls through which the blood passes for temperature regulation. The ends of the inner cylinder are cone shaped. Blood is passed in a laminar flow through the exchanger, minimizing trauma. The exchanger components are maintained in alignment by highly pol-:ished end plates through which blood is introduced and removed. The entire unit may be taken apart for easy cleaning and silicone coating. It may be autoclaved as a single unit when reassembled.

Performance of heat exchangers, in terms of blood cooling or rewarming, can be measured and adequate comparision of different devices has been established (Fig. 19).

At about the same period the annular type of heat exchanger used by Drew (1961) features also concentric cylinders. It is a double annula type, consisting of four concentric cylinders having a central annular blood passage surrounded by an inner and outer water jacket. The blood passage is formed by four hel-:ical grooves $1\frac{1}{2}$ in. wide and 1/16 in. deep, machined into the inner blood cylinder. The cylinders containing blood are made of stainless steel and there are no welded joints within the blood passage. Although the priming volume of the unit is only 425 ml, the surface area for heating and cooling is 5 sq. ft. (approx. 4,650 sq. cm.). The blood inlet and outlet connections to and from the helical channels are via a common circular header channel, terminating in 3/8 in. bore stainless steel tubing, pro-



(modified from Peirce, 1962)

Fig. 19. Comparison of efficiency of heat transfer in certain heat exchangers used in hypothermic perfusion. The Coefficient defined as the blood temperature change across the heat exchanger -- from inlet (T_{bi}) to outlet (T_{bo}) per degree C. of temperature difference between the inlet blood temperature and the inlet water temperature (T_{wi}):

$$\text{Coefficient} = \frac{T_{bi} - T_{bo}}{T_{bi} - T_{wi}}$$

For example, at a flow rate of 4 l/min, the coefficient for the "USIFROID" is 0.65. If blood enters at 36°C. and the exchange fluid is 2°C., the blood temperature will change by (36-2)x0.65 or 22.1°C. Hence the blood outlet temperature is (36-22.1) or 13.9°C.

:tuding from the heat exchanger. The blood cylinders, when assembled, form an integral unit available for mounting with the inner water jacket. The blood assembly slides over the in:ner water jacket and is seperated from it by means of helical strips forming the water passages. Water connections to the inner and outer jacket are supplied from the base of the complete assembly. The inner water connection is a fixed stainless steel tube, while the water connections to the jacket are supplied in a transparent plastic material to permit removal of the blood assembly. This heat exchanger is produced by A.P.V. Ltd., Sus:sex, following long experimental trials in collaboration with the Westminster Hospital, London.

In France, a very compact heat exchanger has been developed. It consists of stainless steel tubes with rods inserted axially within the blood tubes to improve heat exchange, because the bl:ood path is reduced to an annular space in direct contact with the heat exchange fluid (Fig. 20). This "USIFROID" exchanger has very high thermal efficiency (Fig. 19) even at high blood flow rate (4 litres per minute). It is capable of cooling a body weighing 80 kg down to 10°C in 15 minutes, but at the same time maintains a low priming volume of only 200 ml.

The principle of concentric cylinders has also been employed in Italy by DeGasperis and co-workers (1962). The interesting fact is that their concentric cylinders are bent into an inverted "U" tube. The heat exchanger is mounted vertically on a stand. It

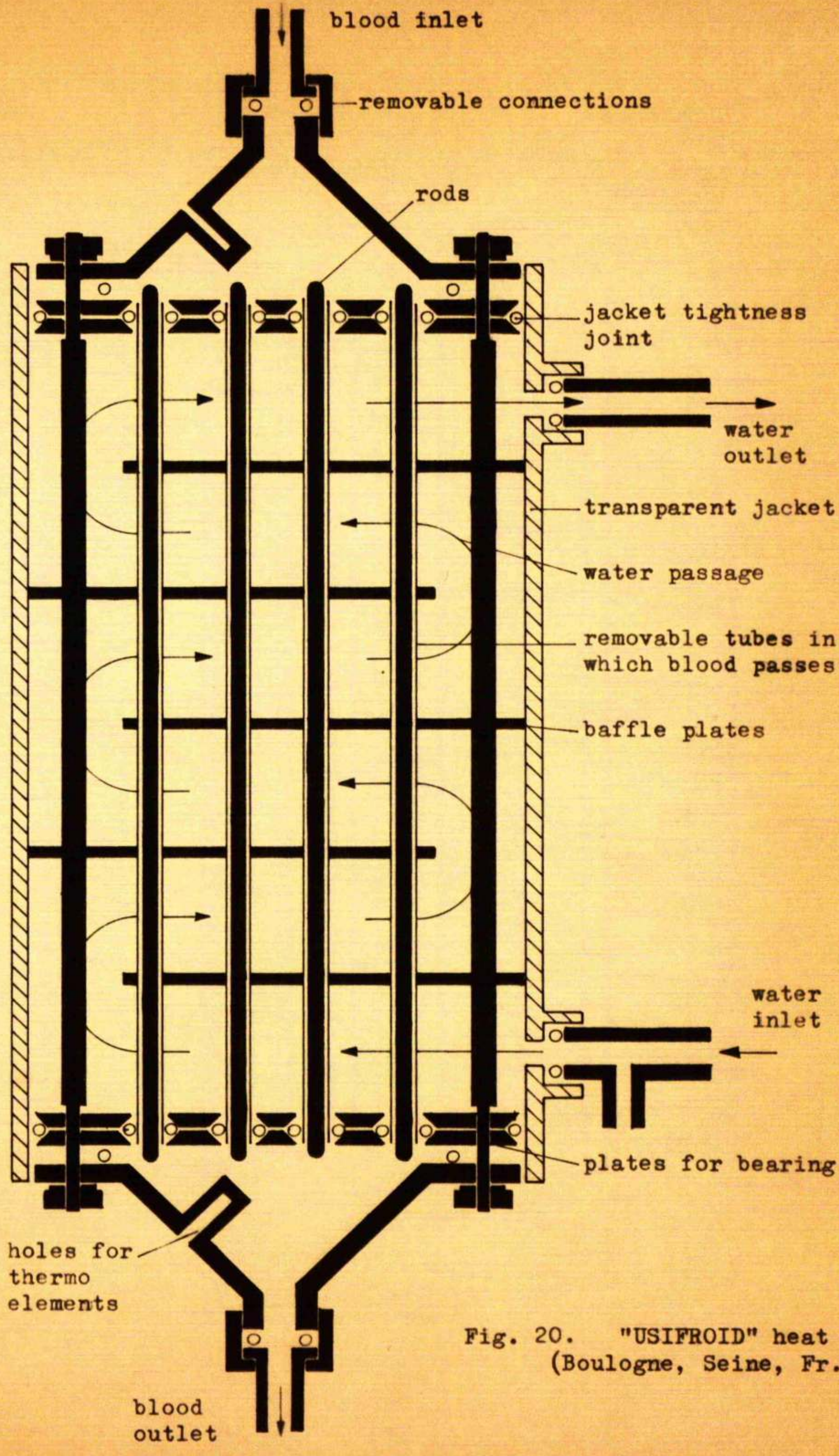


Fig. 20. "USIFROID" heat exchange
(Boulogne, Seine, Fr.).

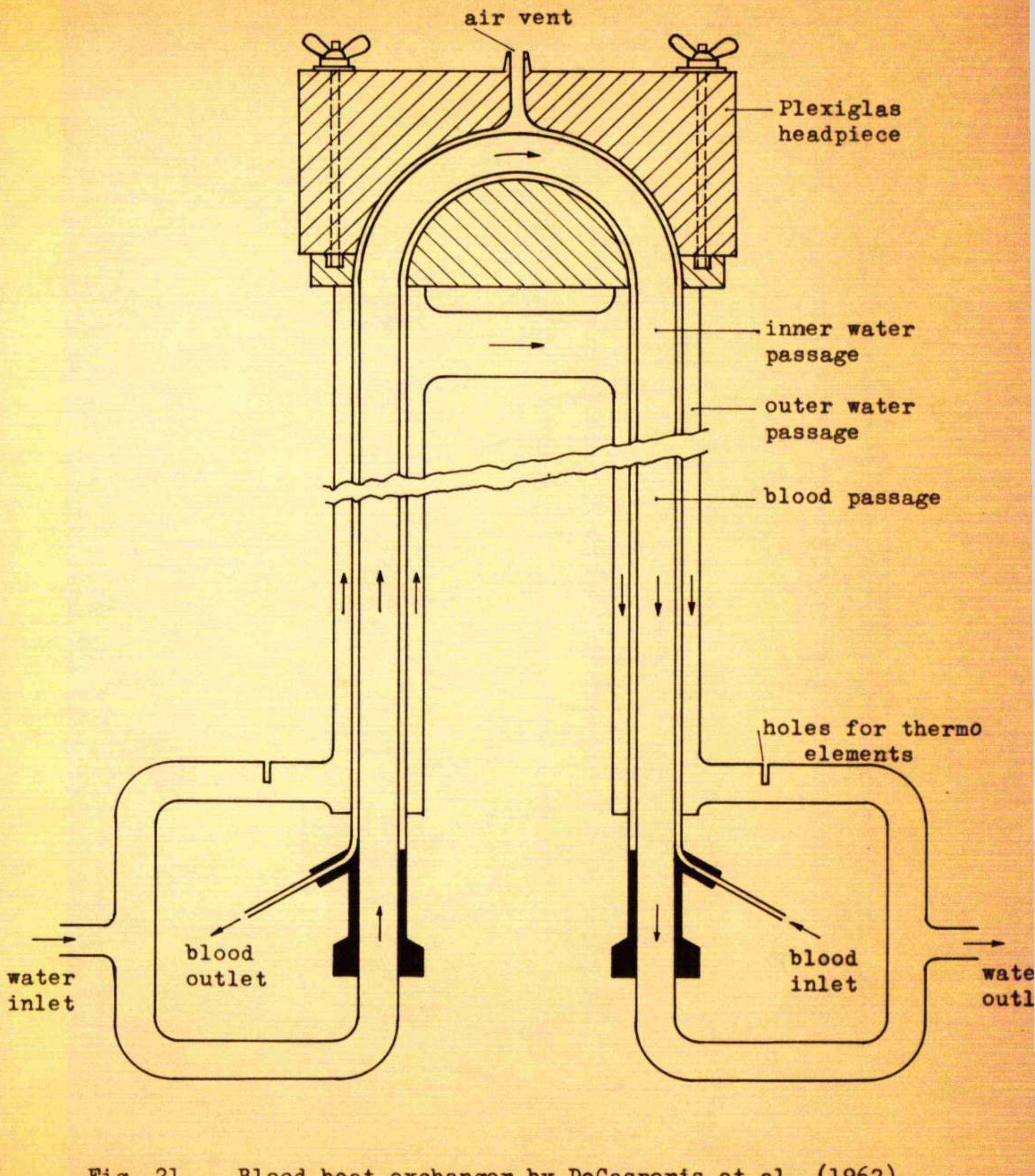


Fig. 21. Blood heat exchanger by DeGasperis et al. (1962).

is made of stainless steel, the branches of which are placed in water jackets formed by two concentric cylinders (Fig. 21). The outer surface of the "U" tube and the external surface of the inner cylinder form a narrow space, "blood chamber", containing the circulating blood. Both these surfaces are highly polished. A Plexiglas headpiece at the upper end of the water jackets covers the curvature of the "U" tube, completing the blood chamber in that portion. The cold or warm water circulates inside the "U" tube along the internal surface and inside the water jackets along the outer surface of the blood chamber with the exception of the portion covered by the Plexiglas headpiece, which allows priming of the apparatus and elimination of residual air bubbles through an air vent. The "U" tube is 150 cm long with an inner diameter of 0.5 cm. The width of the blood chamber is 0.15 mm, and the heat transfer surface measures 3,542 sq. cm. The prim-:ing volume amounts to only 300 ml. The water flows in opposite direction to the blood strea, establishing a maximal temperature gradient at all points along the exchange surface.

The Melrose-N.E.P. perfusion unit features also the annular design of heat exchangers. These are commercially available in three sizes, giving heat exchange rates for the various surgical approaches. The surface areas range from 1,935 to 419.3 sq. cm. and the low priming volumes are from 80 to 20 ml at flow rates of 4.2 to 0.16 litres per minute. However, the rate of cooling is comparatively slow, for example, with the largest size of exchangers, it takes 40 minutes to cool a body weighing 65 kg to 10°C. Nevertheless, the oncstrucion of these exchangers is very simple and assembly is made very easy.

Since the heat exchanger is the most vitally important of elements for perfusion hypothermic production, it is therefore given particular consideration as to design and heat transfer phenomenon. For a practical heat exchanger, the design criteria are as follows:

(1) the material in those parts of the apparatus in contact with blood must be non-toxic and the blood path construction in such a way as to produce minimal damage to blood cells.

(2) the exchanger must be easy to clean, must be capable of being sterilized by heat, and must be easy to assemble under aseptic conditions.

(3) the complete extra-corporeal circuit must be capable of being primed with blood without the possibility of air entrainment during assembly or while it is in use.

(4) the pressure loss (resistance to blood flow) and the rate of pressure loss in any part of the apparatus should be minimal.

(5) there must be no possibility of mixing between the blood and the circulating liquid used to effect heat exchange.

(6) to avoid damage to cells in the blood, at no time must it

be subjected to a temperature outside the range of 4-40°C.

(7) it must be possible to deliver blood from the heat exchanger at any temperature within this range so that the rate of cooling and rewarming in subjects of varying size may be strictly controlled.

(8) the priming volume of the heat exchanger should be small, in order to minimize the number of blood donors necessary.

Viscous Flow   Whole blood is a complex non-Newtonian fluid. Its flow curve of shear stress against the rate of shear of the fluid is not linear, i.e. the "viscosity" of a non-Newtonian fluid is not constant at a given temperature and pressure, but depends on other factors such as the rate of shear in the fluid, the geometry of the apparatus in which the fluid is contained or even on the previous history of the fluid. Blood itself is a suspension of small particles (red cells) in a fluid (plasma), its flow in the tubes differs from that of simple fluids. For a given sample of blood there is a decrease in viscosity as the shear rate increases.

Non-Newtonian rheology, when observed, is usually ascribed to the high hematocrit. The first comprehensive study of the effect of hematocrit on non-Newtonian rheology of whole blood appears to be that of Wells and Merrill (1961a). Their results are summarized in Fig. 22 (without anti-coagulants). The graph variation of apparent viscosity (ratio of point values of shear stress to shear rate) with shear rate appears to exhibit a steeper gradient than Newtonian fluids.

Further work on whole blood by the same authors (1961b) showed that addition of anti-coagulants lowered the general level of viscosity and caused the blood to approach a Newtonian flow (less variation of viscosity with shear rate).

One of the design criteria of heat exchanger is that the pressure loss (resistance to blood flow) in any part of the apparatus should be a minimal. A quantitative measure of this resistance across the heat exchanger with annular passage has been made by Shore (1963). It is found that when either flat plate sections or annuli formed by concentric cylinders are used, the rate of shear strain at the wall is greater than that in the equivalent tube diameter. Thus, for materials which show a marked reduction in viscosity at high values of shear strain, there is considerable advantage due to the improved velocity distribution following the reduction in viscosity at the duct wall. The main disadvantage of the tubular design is the distribution problem of feeding several channels with an equal flow rate, which greatly reduces the hydrodynamic efficiency of the exchanger.

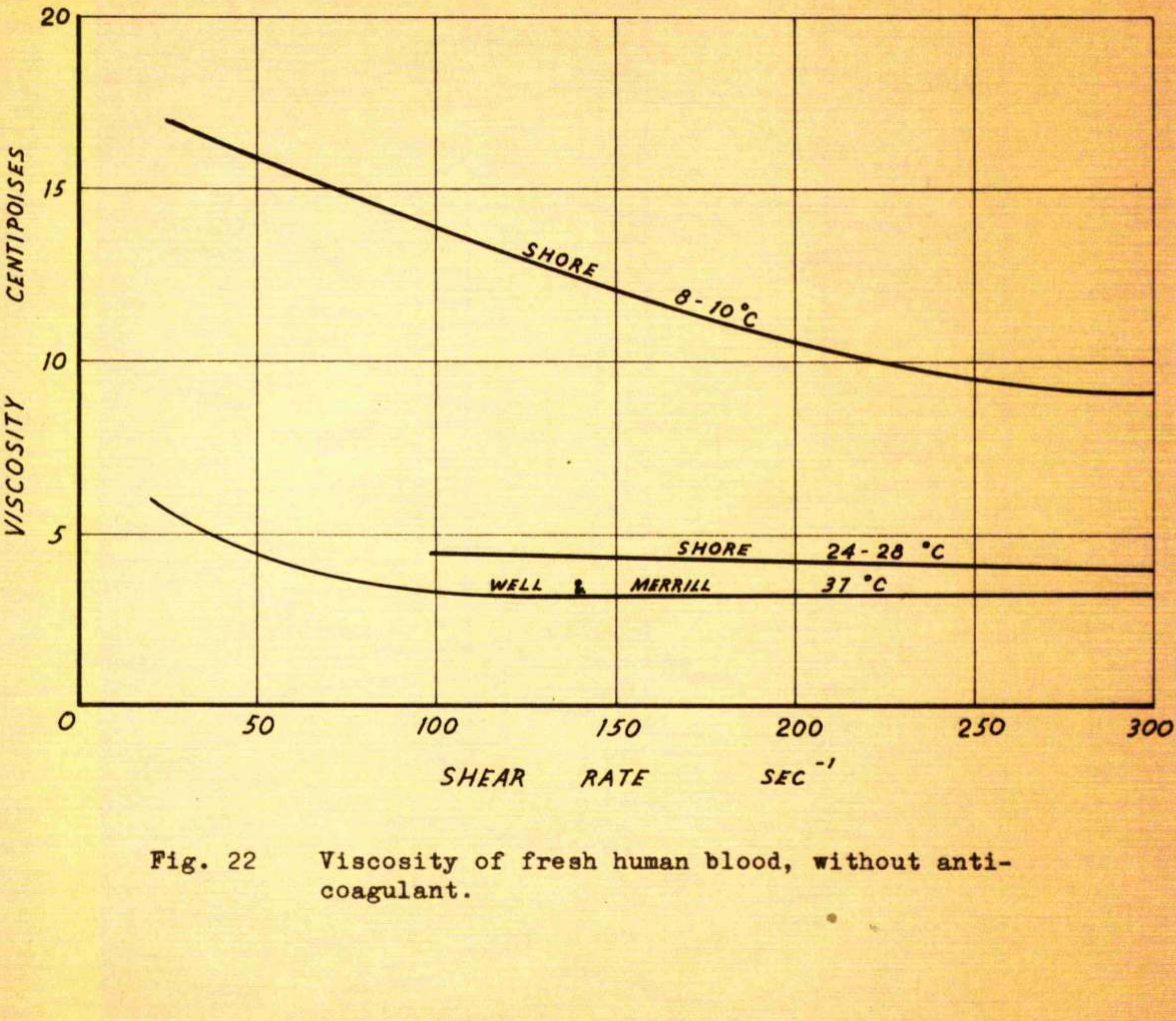


Fig. 22 Viscosity of fresh human blood, without anti-coagulant.

H E A T   T R A N S F E R   P H E N O M E N O N

PHYSIOLOGICAL ASPECTS

The human body is a heat exchanger divided into three thermal zones -- superficial, intermediate and deep, or core.

Superficial Zone   The superficial zone consists of the skin and subcutaneous tissue. It serves as the outer layer for ex:change of heat between the deep zone and the outside. This act:ivity depends upon the amount of blood flowing in the skin and subcutaneous layer. With high flow rates (vaso-dilatation), heat exchange is active. This is the final step in preventing over-heating. With reduced or no flow (vaso-constriction), heat ex:change is a minimal or absent, as in cold. This is the final step in heat conservation. In fact, in extreme cold the super:ficial zone varies with blood flow, the outside temperature, hu:idity and air velocity. Fluctuation is over a wide range and is continuous in response to environmental factors and to the rate of heat production and/or heat loss by the body. The rate of heat exchange is proportional to the body surface area, to tissue conductance, and to the difference in temperature between the core and the skin.

Intermediate Zone   This zone consists of the skeletal mus:cles. Heat loss is mainly from this site during the initial phases of induction of hypothermia. Under ordinary conditions the skeletal muscles play a small role in heat production, most coming from the viscera. However, when chilling occurs and the critical core temperature is in danger of dropping, the skeletal muscles are energized into production of heat. The large muscle mass is the most efficient part of a relatively inefficient heat exchange system, because of an extensive blood supply and because blood flow rate can increase when needed. Blood is the carrier mechanism in the human heat exchange system. Therefore, those areas with the best potential flow are the most efficient parts of the machine.

Deep Zone The deep zone, or core, consists of all structures which lie within the body cavities. The normal temperature is generally given as 37°C, accepted as the reference point (Cooper & Ross, 1960; Blair, 1964). There is a small gradient normally between the core and the intermediate zones, amounting to about -0.5 to -1.0°C. The gradient between the core and the superficial zone is larger, about -2 to -3°C. The core is the crux of the entire thermal system and the maintenance of its normal temperature under conditions of cold and warm outside temperatures is the characteristics of the homeotherm.

Temperature Gradients

In both methods of surface and blood-stream cooling, core cooling can be accomplished only when heat loss exceeds heat production. The key to the matter then is to promote the loss of heat while suppressing its production. Heat loss is accomplished by transfer of heat from the body to a cold medium. In surface cooling the subject is placed in a cold environment, the superficial zone temperature drops from say, 35° to 10°C, enlarging the core to superficial gradient. There is, however, a delay of about 15 minutes before the intermediate and core temperatures begin to fall. This time lag is due to failure to lose heat as a result of the intensive vaso-constriction in the superficial zone. This resistance is broken when the vaso-constriction is replaced by vaso-dilatation and the skin is flooded with blood, thereby permitting the skin to do its job as a heat exchanger. The mechanism of skin vascular dilatation in extreme of cold has been elaborated by many workers (Burton & Edholm, 1955). Lewis (1930) presented the "hunting" phenomenon -- vaso-constriction follwed by vaso-dilatation, caused by prolonged exposure of body or part of the body in a cold medium. With the increased flow, heat loss is rapid and the core temperature falls. The skin temperature continues to fall until it approaches the temperature of the environment and then stabilizes. The muscle temperature falls to a lesser degree.

When the subject is removed from the cold environment, an interesting and dangerous phenomenon occurs. The body core temperature continues to drop. The continued decline is termed "after-fall" and is characteristic of all surface cooling techniques. The fall averages 2°C and may go as high as 5°C (Behnke & Yaglou, 1951; Lewis & Tauffic, 1953; Virtue, 1955; Spurr et al 1956; Cooper, 1960). The amount of drift is influenced by a number of factors. These include rate of cooling, size of subject, degree of peripheral vascular dilation, ambient temperature, activity of reflexes, and core to skin gradient. The result is that the level of hypothermia becomes deeper. Great care must be exercised in timing cessation of the active cooling period or the descent will carry the subject to potentially dangerous levels.

In order to demonstrate in a qualitative fashion the time-lag and after-fall phenomenon, a water model was constructed (Waters & Mapleson, 1961) to indicate how the temperature changes arise. A row of water containers is set up (Fig. 23), each one connected by a narrow-bore tube to its fellow. The end jar has an outlet which is allowed to drain into a sink. The jar on the left represents the centre of the body; the jar on the right represents the surface layer. The flow of water from left to right represents the flow of heat from centre to surface. If water is drained from the end jar, the level in that jar falls rapidly. Then the next jar begins to show a fall. The process continues until the jar on the left is responding. But there is an appreciable delay defore this happens, i.e. the jar representing the centre of the body shows a lag phenomenon. The cooling is now

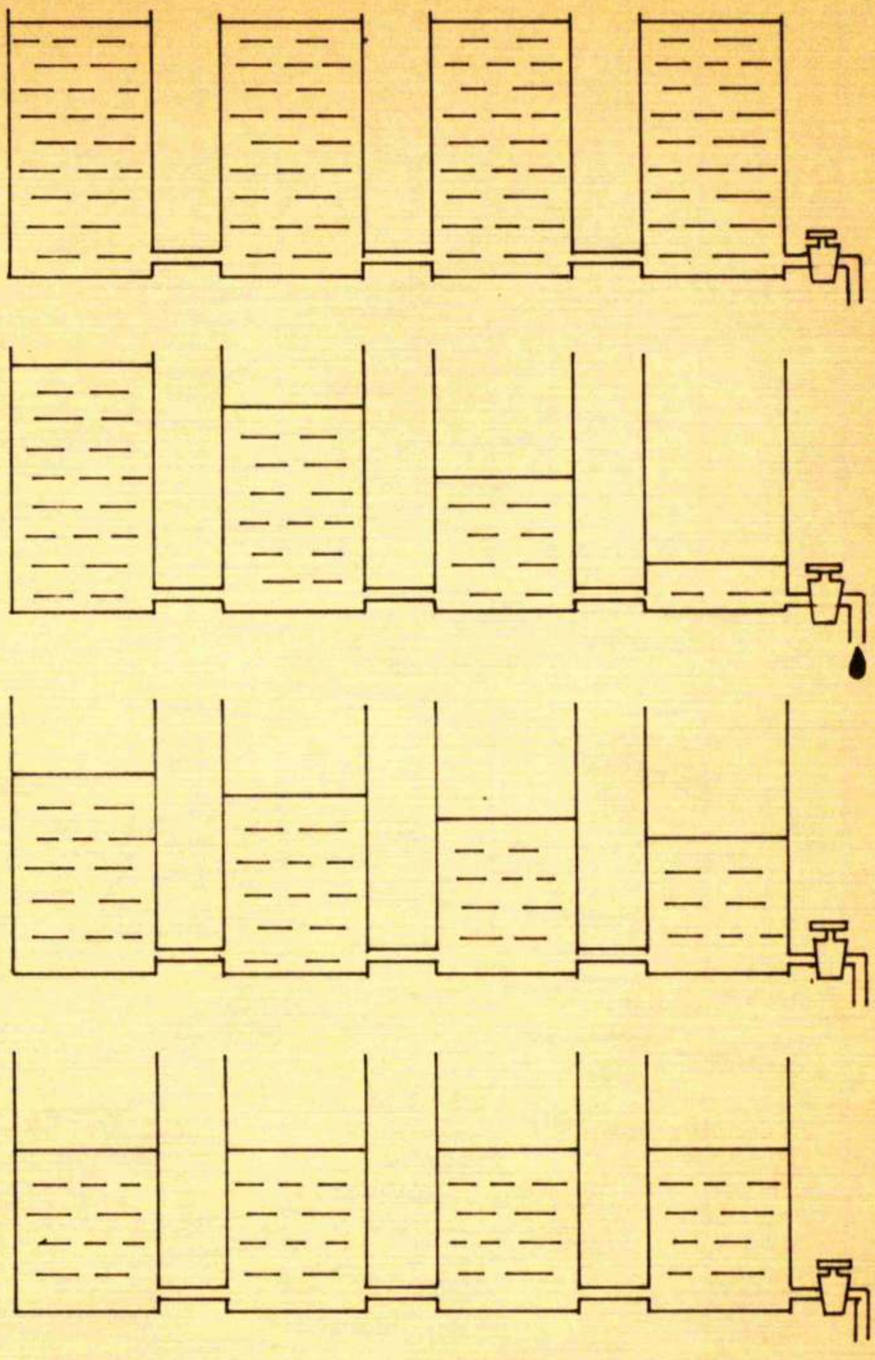


Fig. 23 Water model to illustrate temperature changes in the body during surface cooling (Waters & Mapleson, 1961).

1st row: before immersion; all regions at the same level of temperature

2nd row: during cooling; different levels in different regions

3rd row: soon after cooling has stopped; levels beginning to even out

4th row: finally, a new equilibrium established.

stopped, i.e. the tap draning into the sink is turned off. At the moment at which it is turned off the levels in all the jars are different. But now a process of levelling-out occurs and two things happen: there is an after-rise in the jar on the right and an after-fall in the jar on the left, representing a temperature rise in the superficial zone and a further fall of temperature in the core of the body.

HEAT TRANSFER THEORY

Extra-corporeal Cooling

Although the intra-corporeal transport of heat by circulating blood has been recognised for some time as an important factor in thermal physiology, the quantitative description of this concept is still not satisfactory. This is certainly owing, in part, to the extreme difficulty associated with making experimental measurements of quantities such as the local blood flow rate and the local rate of heat generated by metabolic reactions.

However, in order to adequately interpret temperature profiles in the human under hypothermic conditions, one must be able to account for the following factors: (1) local generation of heat by metabolic reactions, (2) conduction of heat due to thermal gradients, (3) convection of heat by circulating blood, (4) countercurrent heat exchange between adjacent large arteries and veins (5) the storage of heat.

The human body, from the heat transfer point of view, can be hypothetically divided into six elements, consisting of the trunk, the head, two arms and two legs. Each element is assumed to be a homogenous cylinder of bone and tissue covered with a layer of fat and skin. For a homogenous, isotopic cylinder, in which only the radial conduction of heat is considered, the transient state heat conduction equation may be written as:

$$\rho c \frac{\partial t}{\partial s} = k \left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r}\right) \qquad \text{Eq. 1}$$

Due to the previously mentioned conditions, this equation has to be modified when applied to the human thermal system under normothermia to the following form

$$\rho c \frac{\partial t_n}{\partial s} = k \left(\frac{\partial^2 t_n}{\partial r^2} + \frac{1}{r}\frac{\partial t_n}{\partial r}\right) + q_m + (VS)_n(t_{an} - t_n) \qquad \text{Eq. 2}$$

This equation is simply a mathematical statement of the first law of thermodynamics written for an infinitesimal element of tissue. The term on the left-hand side of the equation is the rate of accumulation of thermal energy per unit volume. This equals the sum of the three terms on the right which represent, in order, the rate of conduction of heat into the element, the rate of heat generation by metabolic reactions, and the rate of heat transfer from blood to tissue. However, for hypothermia, where heat loss exceeds metabolic heat generation, the body temperature falls, the net heat loss being known as the heat debt, Eq. 2 will be re-written as

$$\rho c \frac{\partial t_n}{\partial s} = - k \left(\frac{\partial^2 t_n}{\partial r^2} + \frac{1}{r}\frac{\partial t_n}{\partial r}\right) + q_m + (VS)_n(t_{an} - t_n) \qquad \text{Eq. 3}$$

where $t_{an} < t_n$ since heat is conducted away from the element and heat flows from tissue to blood. Here radiation and evaporation heat loss is negligible. These equations must be solved subject to the following boundary conditions

$$- k\frac{dt_n}{dr} = h\ (t_n - t_a) \qquad \text{Eq. 4}$$

at $r = a_n$

This equation states that the rate of conduction of heat to the surface through the tissue equals the rate of heat transfer from the surface to the environment.

Surface Cooling

The hypothermic heat transfer concept with air cooling is essentially one of forced convection and transient heat conduction, whereas evaporation and radiation heat loss, during active cooling id negligible. Metabolic heat production amounts to about 10% of total heat loss during cooling (see Section VI).

Here the cooled air has a velocity imposed upon it by means of a fan, and is brought into contact with the skin surface of the subject. The factors on which the rate of heat flow q under conditions of forced convection depends are likely to be the linear size l of the body, the difference in temperature θ between the body and the air, the conductivity k_a of the air, its absolute viscosity μ, its specific heat C_p, its velocity v and its density ρ.

According to the method of dimensional analysis

$$q = f(\theta, k_a, C_p, \rho, \mu, l, v) \qquad \text{Eq. 5}$$

It follows that

$$q = \frac{k_a \theta}{l} \left(\frac{\mu C_p}{k_a}\right)^x \left(\frac{\rho v l}{\mu}\right)^y \qquad \text{Eq. 6}$$

or

$$\frac{q l}{k_a \theta} = f\left(\frac{\mu C_p}{k_a}, \frac{\rho v l}{\mu}\right) \qquad \text{Eq. 7}$$

Hence the Nusselt number $(ql/k_a\theta)$ is a function of the Prandtl $(\mu C_p/k_a)$ and Reynolds $(\rho vl/\mu)$ numbers.

i.e. $$N_u = f(P_r, R_e)$$

Another transient heat conduction phenomenon for both surface and blood-stream cooling requires that, if the subject is space-wise isothermal, i.e. having little or no temperature gradient in the body, the temperature varies only with time. If a certain small body of finite thermal conductivity at some uniform tempera-ture when at time zero is placed in an environment of a different temperature, the problem is to determine the change in temperature with time as a function of the system characteristics. Consider-ing the heat balance on the subject, equating the change in heat capacity with the convective heat loss, yields

$$\rho C V \frac{dt}{ds} = -h A_s (t - t_a) \qquad \text{Eq. 8}$$

where V is the volume of the body and A_s is the surface area. The appropriate initial condition is $t = t_o$ at $s = 0$. The ambient temperature t_a is a constant. Eq. 8 can be re-written in the form of a differential equation for the excess temperature where θ is the temperature difference $(= t - t_a)$

$$\frac{d\theta}{\theta} = -\frac{h A_s}{\rho C V} ds \qquad \text{Eq. 9}$$

The appropriate condition for the evaluation of the single constant appearing in the solution of Eq. 9 is the initial condition, the temperature of the subject at time zero,

$$s = 0 \qquad \theta = \theta_o$$

With the use of this boundary condition the solution for Eq. 9 becomes

$$\frac{\theta}{\theta_o} = e^{-\frac{h\,A_s}{\rho CV} s} \qquad \text{Eq. 10}$$

It is clear that a plot of Eq. 10 for $\log_e (\theta/\theta_o)$ versus s will yield a family of straight lines with $(hA_s/CV\rho)$ as a parameter. Eq. 10 can be re-written to advantage as

$$\frac{\theta}{\theta_o} = e^{-\left(\frac{hL}{k}\right)\left(\frac{\alpha s}{L^2}\right)} \qquad \text{Eq. 11}$$

where (hL/k) = Biot modulus

$(\alpha s/L^2)$ = Fourier Modulus

α = thermal diffusivity

The value L in the Biot and Fourier moduli is recognised as a significant dimension of the system and is derived as the ratio of the volume of the body to the surface area. Thus for simple geometrical shapes the value of L can be readily obtained.

For cylinder: $$L = \frac{\pi r_o^2\, l}{2\pi r_o\, l} = \frac{r_o}{2} \qquad l \gg r_o$$

The Biot and Fourier moduli are dimensionless and have the great advantage that when used in the manner of Eq. 11 the temperature-time histories for all bodies can be reduced to a single universal plot for all values of the convection boundary condition.

Thus if the human body were divided into six elements of homogenous cylinders consisting of the trunk, the head, the two arms and two legs, Eq. 11 is best applied, provided a mean body temperature is established.

In 1961, Forreter and Brown reported a method of attaining a pre-determined oesophageal temperature in human subject using a new approach to the technique of air cooling. By measuring the temperature difference of cooled air between inlet and outlet in a specially constructed and calibrated hypothermic cabinet, and by equating the amount of heat loss of the patient to the heat gained by the cooled air, they were able to show that the cessation of cooling is independent of the oesophageal temperature obtaining at that time and that the desired final temperature is determined solely by the amount of heat which has been given up by the patient. With this method it is possible to predict the "after-fall" which inevitably occurs when active surface cooling stops.

Prior to this, no systematic method was found available for the determination of the pattern of heat given up by subjects under hypothermic conditions, nor was there any means of investigating the variations, if any, of tissue conductance and conductivity with the core temperature during the period of hypothermia. An extension of their work is developed and presented here.

The differential heat balance with this method of surface cool-

:ing is given by (see Appendix III)

$$Q = W C_d \frac{dt}{ds} = M C_p (t_d - t_{de}) \qquad \text{Eq. 12}$$

It follows

$$\sum (t_d - t_{de}) = \frac{W D}{K} \qquad \text{Eq. 13}$$

Considering a thick cylinder of surface area A_s, radius r at temperature t_s in contact with cold air at uniform temperature t_a, at any time s from the start of the cooling operation, the quant:ity of rate of heat Q transferred in the short time ds depends upon the surface area of the cylinder, the difference in tempera:ture between air and the surface of the body, and a factor h, the coefficient of heat transfer from the surroundings to the surface

$$Q = -h A_s (t_a - t_s) \qquad \text{Eq. 14}$$

The convective heat loss from the cylinder to the outer-sur:face is directly proportional (1) to the mean thermal conducti:vity k of the body, (2) to the mean surface area A_m normal to the direction of heat flow and (3) to the temperature difference $(t_s - t_i)$ between the points from and to which the heat is flow:ing and is inversely proportional to the length $(r_s - r_i)$ of the path of heat flow.

Thus

$$q = -k \frac{dt}{dr} \qquad \text{Eq. 15}$$

This quantity of heat loss by conduction to the surface through the tissue equals the rate of heat transfer from the surface to the environment. Hence the equation of heat transfer can, for practical assessment of the problem, be written as (see Appendix III)

$$Q = A_m q = -k A_m \left(\frac{t_s - t_i}{r_s - r_i}\right) = -h A_s (t_a - t_s) \qquad \text{Eq. 16}$$

E X P E R I M E N T A L   S C H E M E

The hypothermia investigations reported on were carried out as part of an experimental programme on cerebral blood flow in normothermia and hypothermia on the dog undertaken by the Depart:ment of Anaesthetics of the Royal Infirmary, Glasgow. The sur:face cooling technique chosen was that of Forrester-Brown which permits effective control of the after-fall essential in experi:ments of the type undertaken.

Table 1   General Surface Cooling Hypohtermia

Device	Cooling	"after-fall"	Control	Safety factor	Patient care
ice bath	rapid	large	poor	fair	poor
blanket	slow	small	good	v. good	v. good
cold air	fair	small	good	good	v. good

Table 1 shows a qualitative comparision of the surface cooling techniques available. It is seen that the cooling blanket would appear to be the best choice for hypothermia induction. However, it does not give a good contact surface of the body with the cool:ing medium, creating a non-isothermal surface. It was for this reason that air cooling, although expensive, was decided on as it further permits by an extension of the Forrester-Brown concept, the reliable pre-determination of the amount of total heat ex:traction.

For this series of experiment, a hypothermic cabinet was spec:ially design and constructed, to enable the following investiga-

:tions to be carried out:

(1) to attain a pre-determined level of oesophageal temperature of the dog.

(2) to follow the temperature-time history and the muscle temp:erature gradients during and immediately after active cool:ing.

(3) to assess the overall specific heat of the perfused animal.

(4) to correlate the heat extraction, rate of fall of temperature and body weight.

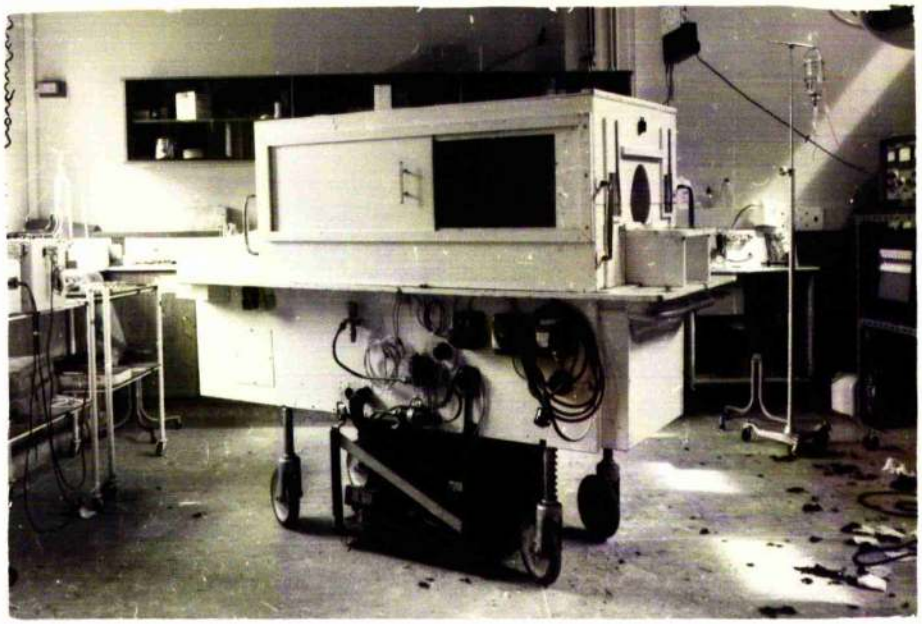
(5) to investigate variations of muscle thermal conductivity and conductance of the animal.

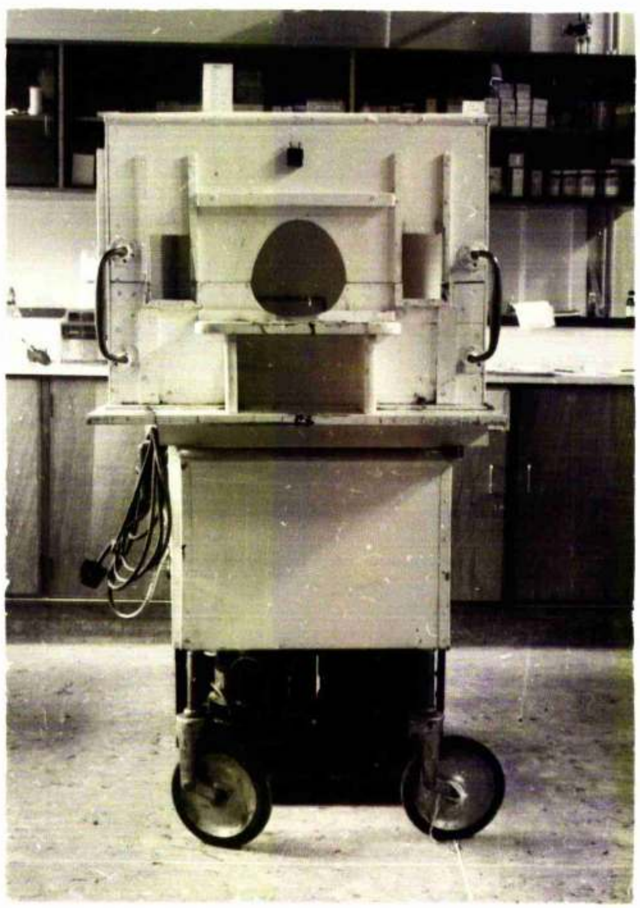
D E S C R I P T I O N   O F   A P P A R A T U S

The hypothermic equipment (Figs. 24-27) is divided into two compartments, the upper one for the dog forming the cabinet it:self, and the lower one for the cooling equipment and a fan. The cabinet measuring 75" x 60" x 30" is constructed of light timber enclosing "Polyzote" insulation on the detachable hood, on the sides (except for the sliding door), and on the ends. A circular aperture at one end allows the head of the animal to be supported on a rest outside the cabinet. The interior of the cabinet is illuminated by electric light. The temperature leads, tubing from intravenous transfusion set and sphygmomanometer emerge from one of the two perspex windows on one end through which observation of the subject's chest movements is possible, permitting minor adjustments made if desired.

The wooden base of the cabinet supports a stretcher composed of strong open nylon net on which the dog lies, thus minimizing the contact surface area. This also serves as an operating ta:ble. The inlet for air is formed by seven apertures located at the base of the cabinet, with the air stream circulating under the subject and directed onto one side of it. The outlet duct is of rectangular shape at the other end of the cabinet, which forms an integral part of the wooden table. The detachable hood of the cabinet fits air-tight against flanges along the edges of the table during the induction of hypothermia.

Figs. 24 & 25 Hypothermic Cabinet





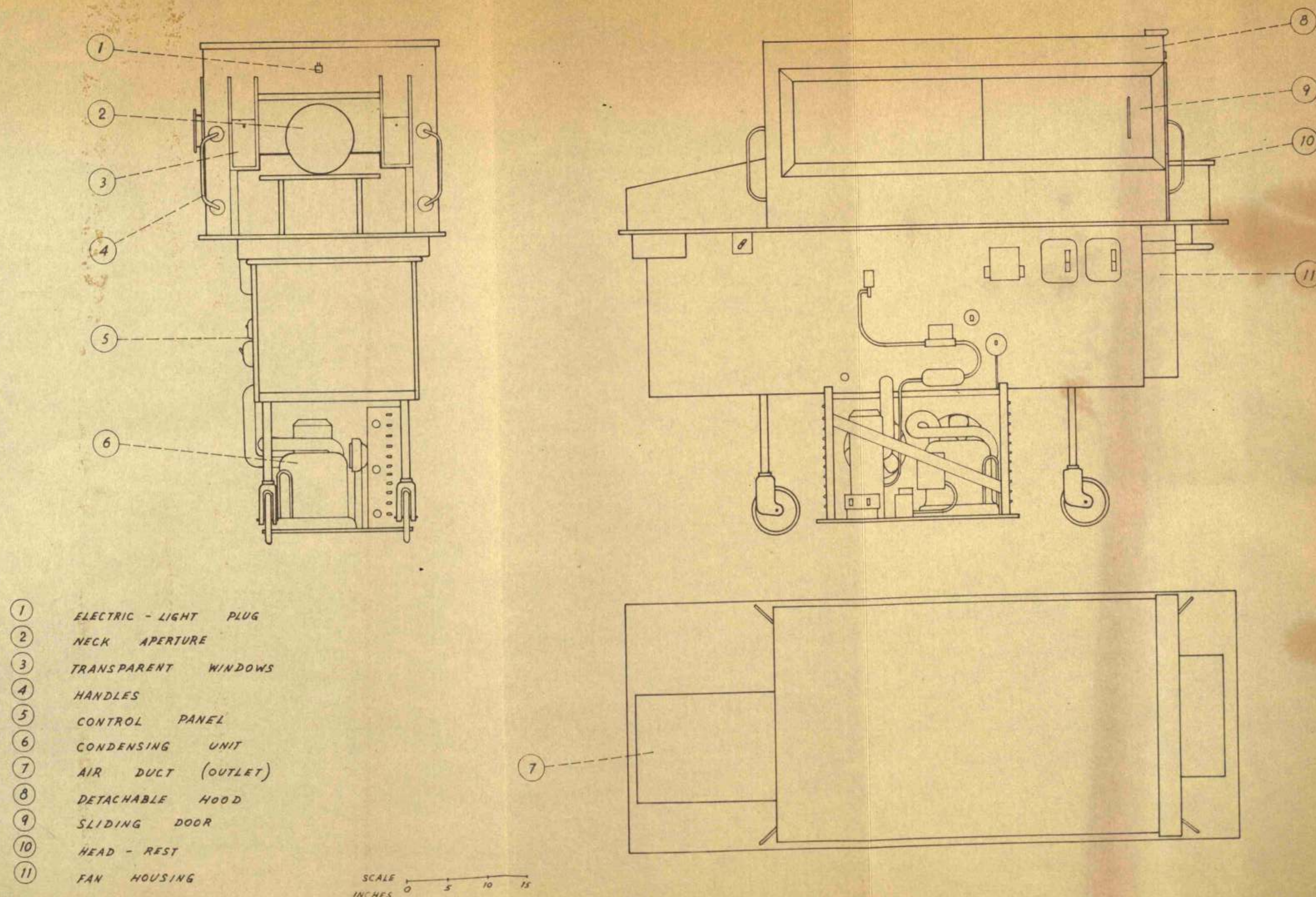


FIG. 26 HYPOTHERMIC CABINET

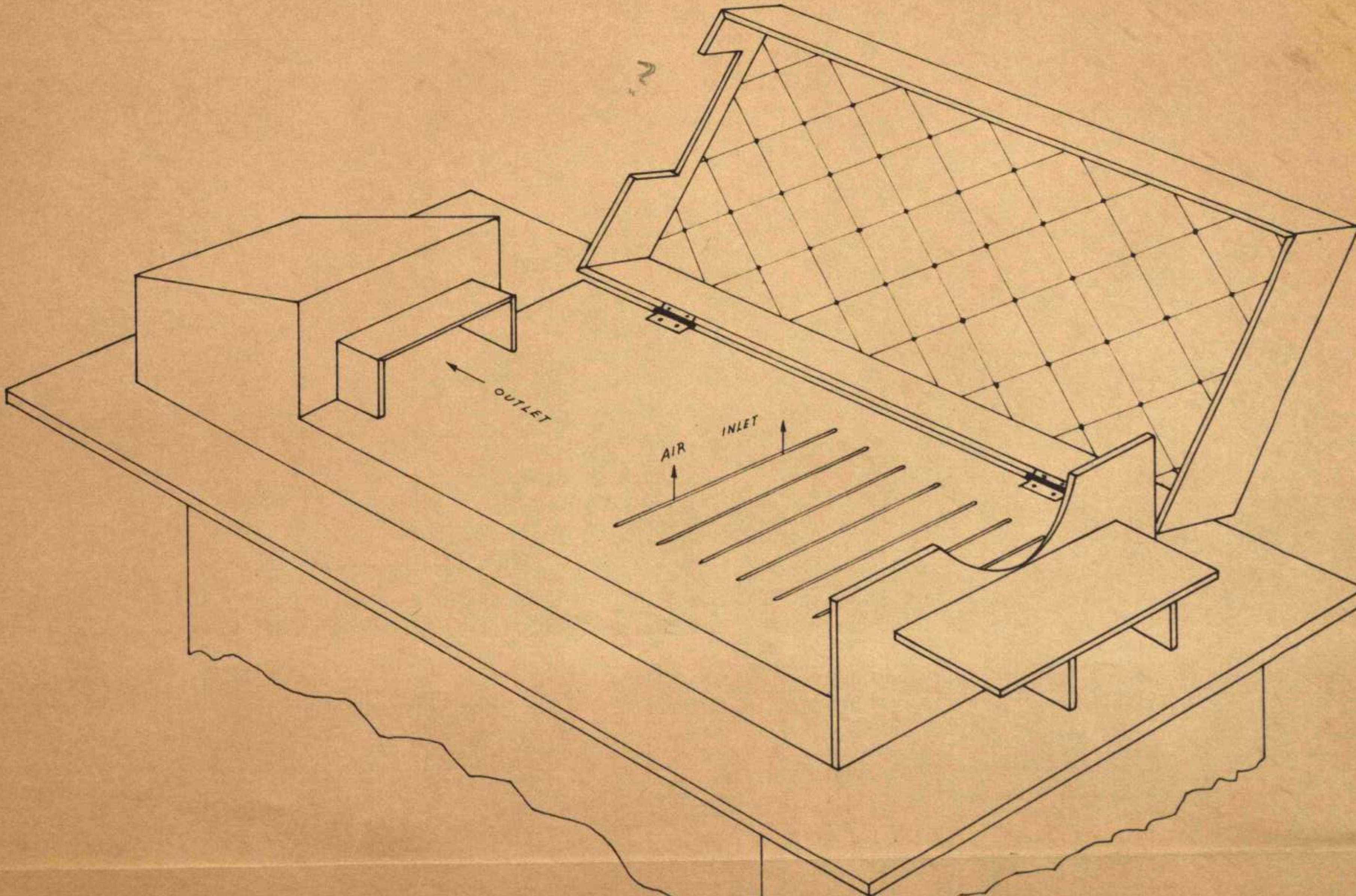


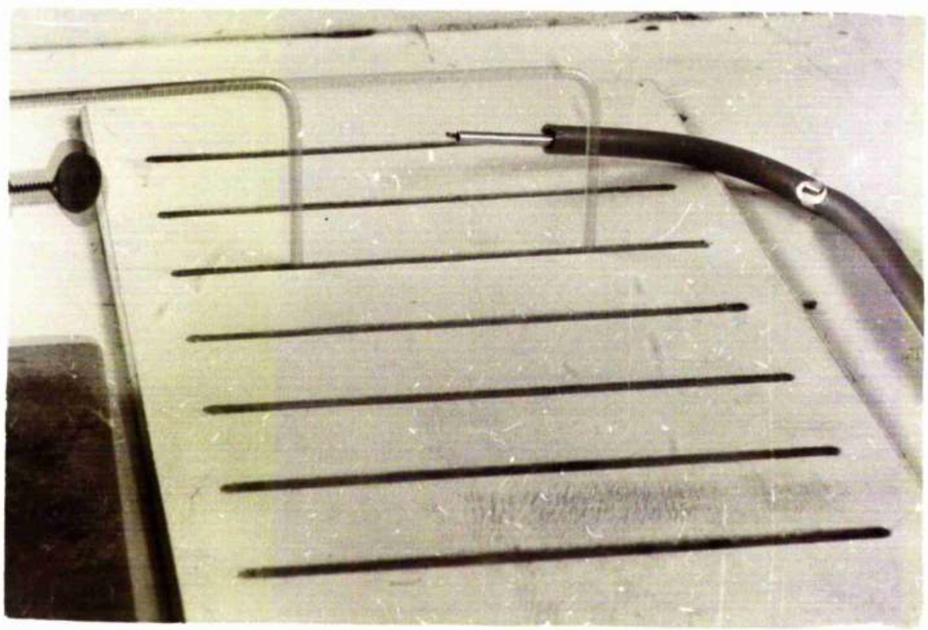
FIG. 27 CABINET WITH HOOD DETACHED, SHOWING NET STRETCHER & AIR DUCTS.

The cooling unit comprises a 1 h.p. hermetically sealed con-:densing unit (Tecumseh BTU18-LT) to work in conjunction with a forced draught evaporator (Frigidaire SWF-360). The capacity of the refrigeration unit is 1,200 kcal/hr at -5°C. The temperature of the air within the cabinet is controlled by a thermostat set to -10°C in the inlet air stream. The cooling unit fan is driven by a 1/10 h.p. A.C. motor and is wired to operate continuously.

For air temperature measurements at inlet and outlet, copper-constantan thermocouple wires are used. The high thermal con-:ductivity of metal thermocouples can introduce an appreciable error by conduction of heat along the wires, but this can be re-:duced by using very fine wires, due allowance being made for durability and rigidity. These are first inserted into fine-bored plastic tubings and then into ordinary small bore garden hose for insulation and protection against any tendency of cor-:rosion, kinking or damage of any form. The thermo-junctions of the wires are soldered and metal sheaths are used. The cir-:cuit is so designed for this part that since temperature diff-:erence between outlet and inlet air is required, no reference junction is necessary. The signal of air temperature change is picked up in a Cambridge indicating potentiometer, with an op-:tional external spot-light galvanometer attached. The set-up provides, for a temperature range of 40-28°C, an amplified sen-:sitivity of 0.1°C, considered acceptable as far as potentiom-:meter-indicators are concerned. This is chosen because once

Fig. 28 A type of Thermocouple Needles

Fig. 29 Air Flow Measurement



the null point is achieved, there is no current flow and hence no heating effect is developed along the length of the thermocouple wires. The muscle probes are also made up of copper-constantan wires (Fig. 28), with junctions soldered as close as possible to the tips of the needles, the cannular space of which is filled with araldite. The length of the delicate wires runs inside fine-bored plastic tubing to ensure protection. The needles are connected to an ice junction through a toggle switch and then to the Cambridge potentiometer. Each needle is marked in lengths of 1 cm to 3 cm along the stem from the junction at the tip.

C A L I B R A T I O N S

Calibration of Thermocouples

Prior to installation in the cabinet, copper-constantan thermocouple wires were calibrated. The probes were soldered point junctions submerged in a water bath with a thermostatically controlled immersion heater. The reference junction was kept at ice point and connected to a Cambridge indicating potentiometer via ordinary copper leads. An electric stirrer was fitted in the water bath to minimize the convection effect, and a standard thermometer was attached to the thermocouple, with the probe located as close as possible to the mercury capsule of the standard thermometer. The thermostat was set at different levels of temperature to give a series of readings of electrical potentials (e.m.f.) set up in the thermo-junction of the thermocouple. The computed result gave the value of temperature difference between the two junctions per electrical potential of the circuit.

Calibration of Hypothermic Cabinet

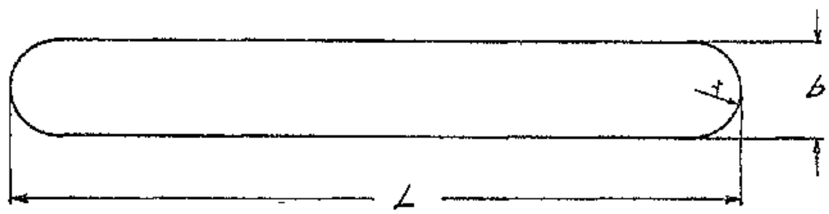
When air passed from the inlet apertures to the outlet duct, it picked up heat from the walls of the insulated cabinet. This loss of heat, hence the change of air temperature, of the empty cabinet varies with the ambient temperature and with time. It could be evaluated by calibrating the empty cabinet at various and repeated ambient temperatures, reproducing the environmental conditions of the operating theatre. Although there were seven apertures at the cold air inlet, it was reasoned that one of the thermocouple junctions should be kept fixed permanently at the same aperture throughout the period of both empty cabinet cali-:bration and cooling of the animal, thus minimzing any possible discrepancy.

Maximum ambient temperature range encountered in the operating theatre was from 19-24°C. Calibrations obtained were shown in Fig. 30.

Air Flow Measurements

The criterion here, for this particular cabinet, was that the cold air inlet apertures were located at the side of the dog's trunk when in position, hence the air stream was directed right onto it. The air flow rate used in the analysis was that measured at inlet. The technique of measurement and relevant calculations are as follows and tabulated in Appendix I:

The seven inlet apertures were divided into fourteen stations, i.e. two stations per aperture for the measurement of air flow, for which a pitot-static tube with water gauge column was used. Mean values of the heights of water column were recorded.



Sketch of an aperture

$$\text{Area} \quad a = \pi r^2 + (L - 2r)2r$$

$$= \tfrac{1}{4}\pi b^2 + (L - b)b$$

$$= b\left[L - b(1 - \tfrac{1}{4}\pi)\right]$$

$$= b(L - 0.215b)$$

$$\text{Total area} \quad A = \sum b\ (L - 0.215\ b)$$

E X P E R I M E N T A L   P R O C E D U R E

Evaluation of Cabinet Constant

A series of nine dogs varying in weight from 10-37 kg were used in determining the cabinet constant. Immediately after anaesthetization the dog was placed onto the nylon net stretcher of the hypothermic cabinet. It was shaved all round the trunk, which was immediately above the cold air inlet apertures. An oesophageal temperature probe was inserted for a length of app-:roximately 20 cm for the estimation of the core temperature, which was near to the heart level. A mercury-in-glass thermo-meter was also placed in the oesophagus to counter-check the thermocouple reading.

After the animal had been prepared and control observations made at the environmental temperature, the hood of the cabinet was placed and fitted in position. Any space between the circu-:lar aperture of the cabinet end and the neck of the dog was sealed off with foam sheets, preventing escape of the cold air. The thermostat controlling the refrigerator was set at -10°C, and the fan and cooling unit was switched on. This represented the active cooling phase. The oesophageal temperature gradually dropped and was recorded at 5-minute intervals, as was also the air temperature change between inlet and outlet. The graph of oesophageal temperature was plotted against time, giving warning when the core temperature tended to 30°C. Generally at about 32°C the refrigeration was shut off and immediately the hood of the cabinet removed. During this period, a steady rise of the skin temperature began, but the oesophageal temperature still declined, though at a decreasing rate, indicating that the core was still losing heat to the intermediate and outer-layers of muscle. Finally an equilibrium was established when the oesophageal temp-:erature reached a steady level, which normally persisted for an hour or so, enabling control data at this temperature level to be obtained. Graphs showing rate of fall of oesophageal temp-:erature were plotted (Fig. 31-35). From this data, the cab-:inet constant was determined.

Application of Cabinet Constant to attain the pre-determined oesophageal temperature

It was now possible to predict the amount of heat to be ex-:tracted from the dog in terms of the evaluated constant K and the body weight of the dog. This was performed prior to active cooling. Having calculated the summation of temperature differ-:ence of the cold air, and the animal having been prepared as before, the active cooling phase began. Readings of oesophageal temperature and air temperature difference were taken at 5-min-:ute intervals until the summation of the latter reached the pre-determined value, when active cooling was stopped. Further readings of the fall of the oesophageal temperature however, were noted. A series of eleven dogs of weight from 8.7-35.4

kg were used in this part of the experiment. This data was used to compare the actual after-fall with the predicted after-fall calculated in the manner in Appendix V.

Study of Muscle Temperature Gradients

Another series of eleven dogs varying in weight were used to determine muscle temperature gradients. The procedure was identical as before, except that the right hind leg of the dog was partly shaved, permitting a skin thermocouple probe to be attached to the area of the leg. At the same time, needle thermocouples were located in the subcutaneous tissue at 1-3 cm into the region of the semitendinous muscle as far as possible in the same radial plane as that containing the skin probe, the needles being kept as closely normal to the skin surface as conditions allowed. During active cooling and immediately after, the probe readings at different depths were recorded, from which temperature gradients shown in Figs. 42-52 were evaluated.

R E S U L T S   A N D   D E D U C T I O N

Construction of Graphs

For hypothermic cabinet calibration, cases No. 4-12 are re-:ported. The rate-of-cooling curves are plotted in Figs. 31-2, the reason being that some dogs had their initial oesophageal temperatures raised, where appropriate, with an electric fan heater during the preparation period. It is reasoned that if these curves of all the nine dogs were plotted in a single graph the pattern of the lines joining the co-ordinates wouldno longer be consistent. The "staggering" effect is simply due to the different body weights of the animals.

Fig. 33 represents the degree of accuracy of the preditive result of the oesophageal temperature. The co-incidence of these cooling curves and the base lines of 30°C is apparent in most cases.

Figs. 95-98 show the comparision of heat extraction of the dog with and without metabolic heat production. Group A shows the slower rate of heat loss whereas Group B, the higher rate of heat loss (and hence the shorter period of active cooling).

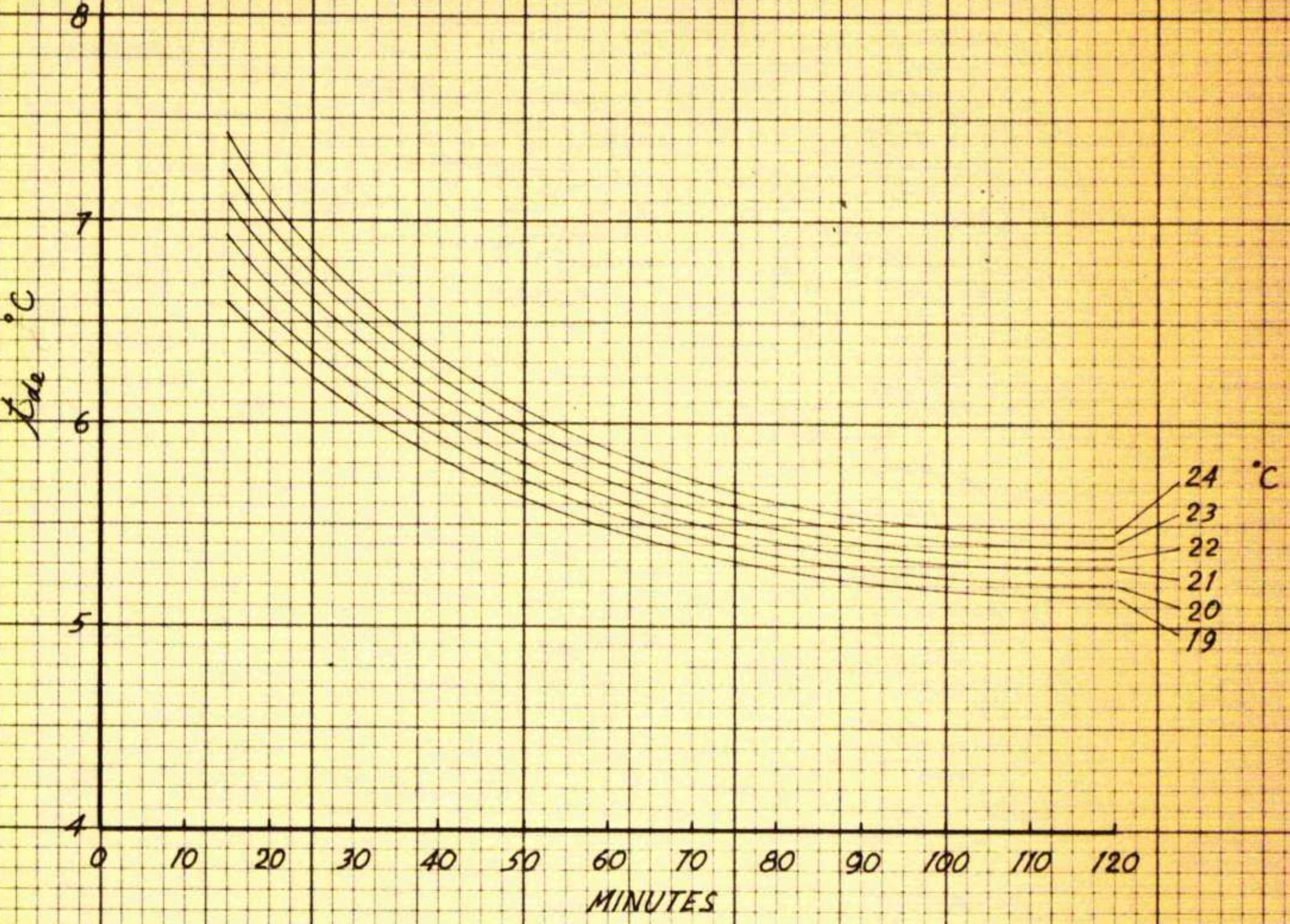


FIG. 30 GRAPH SHOWING AIR TEMPERATURE RISE WHEN CABINET IS EMPTY (t_{de}) AT VARIOUS ROOM TEMPERATURES.

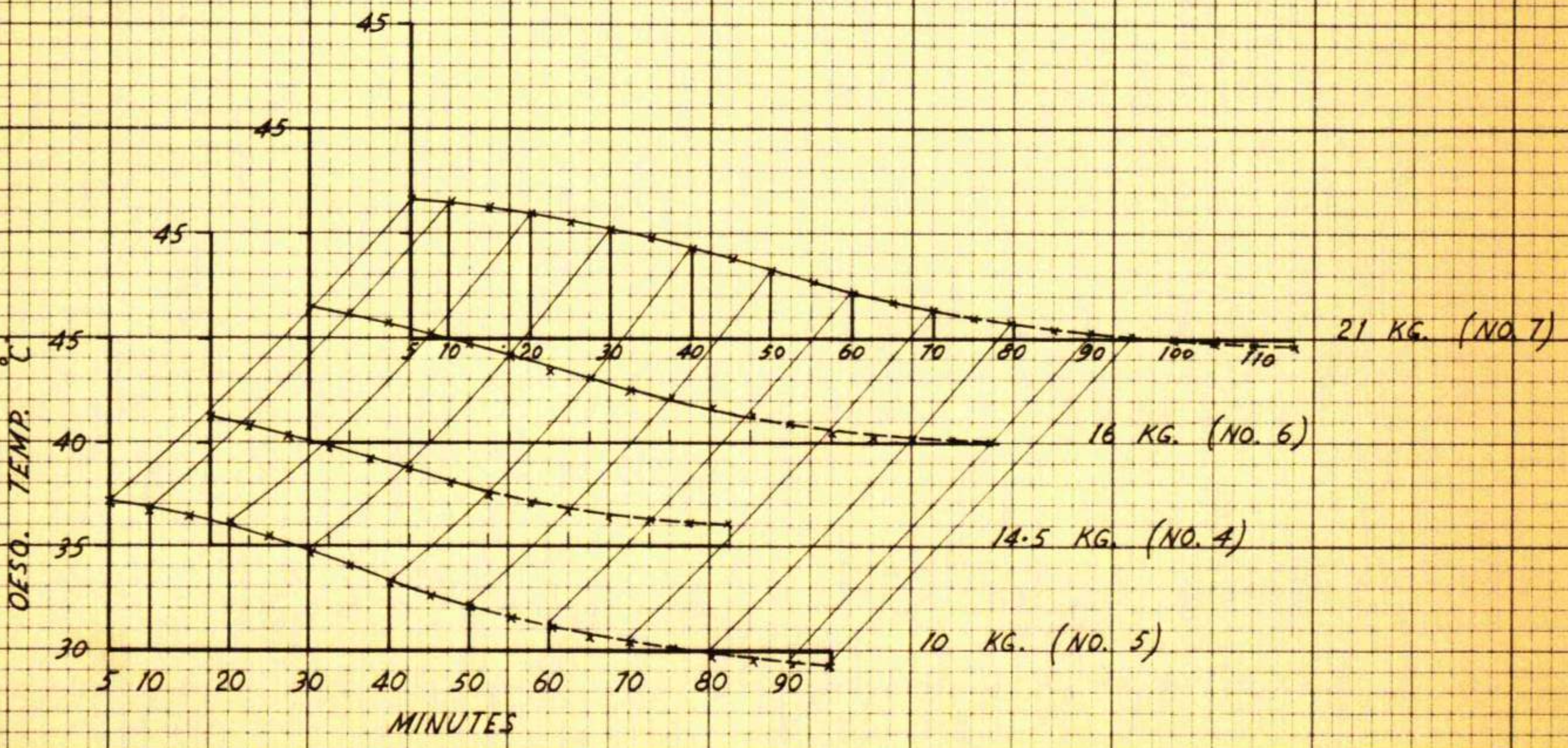


FIG. 31 COOLING CURVES FOR CABINET CALIBRATION.
DOGS WITH LOW INITIAL OESOPHAGEAL TEMP.
AFTER-FALL REPRESENTED BY DOTTED LINE.

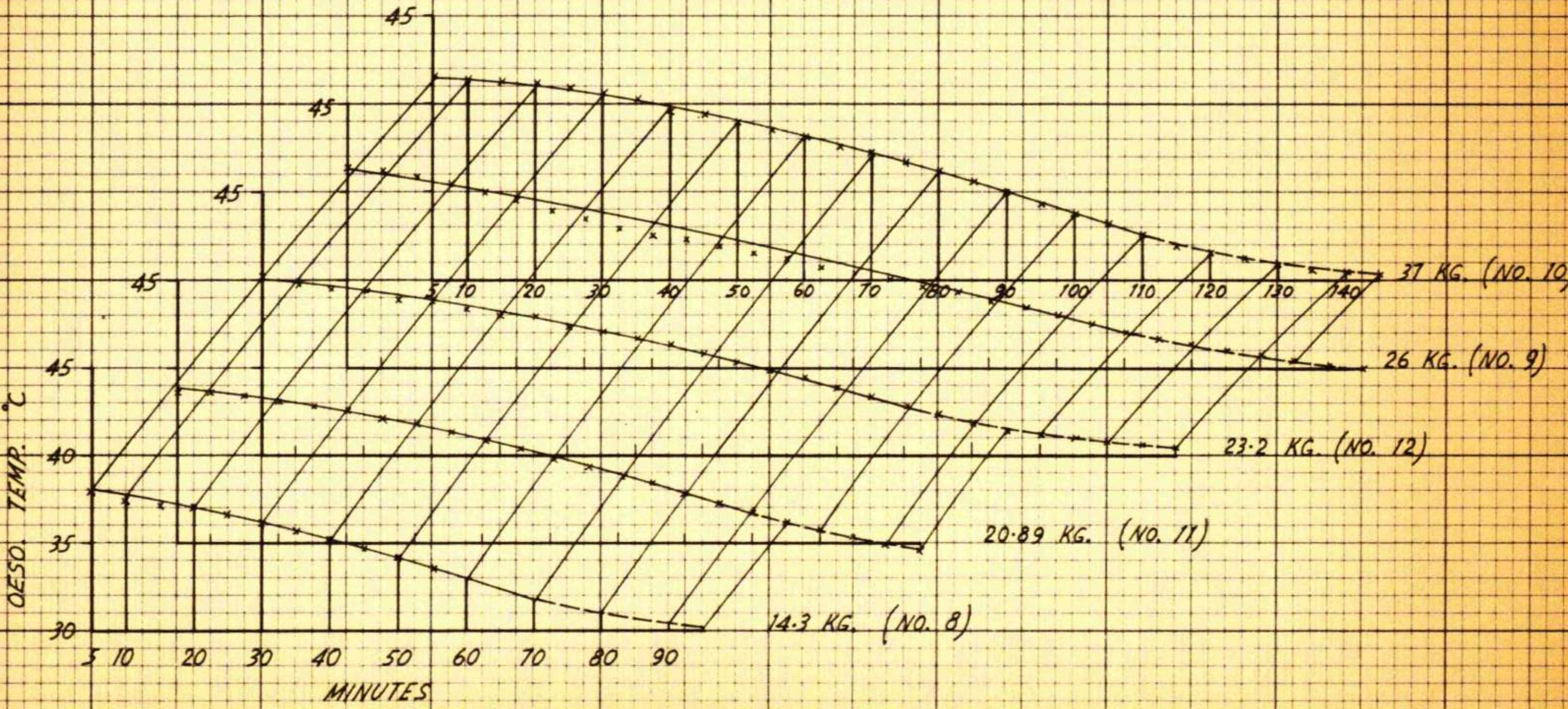


FIG. 32 COOLING CURVES FOR CABINET CALBRATION.
DOGS WITH HIGH INITIAL OESOPHAGEAL TEMP.
AFTER-FALL REPRESENTED BY DOTTED LINE.

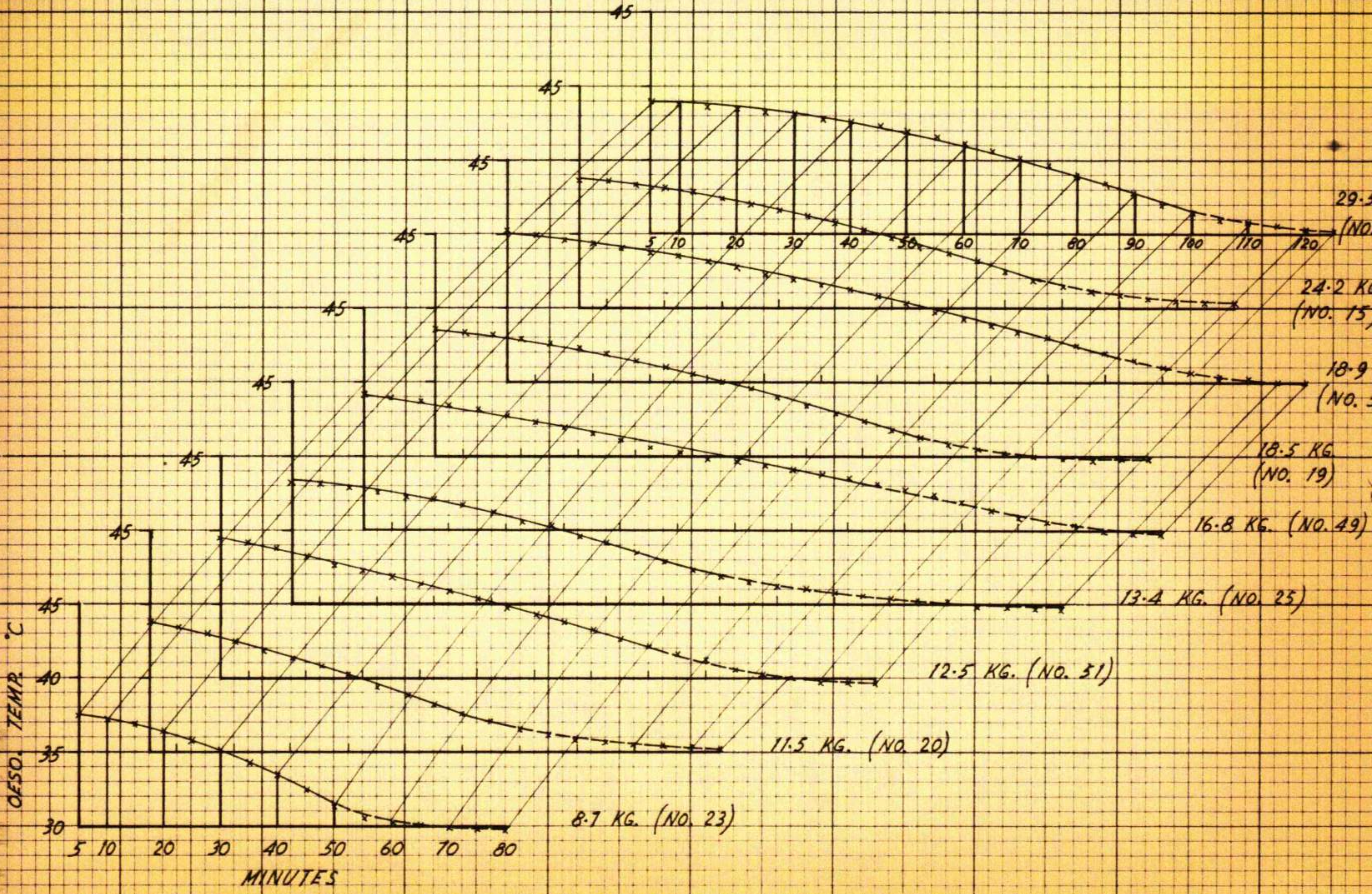


FIG. 33 COOLING CURVES OBTAINED WITH APPLICATION OF CABINET CONSTANT. AFTER-FALL REPRENTED BY DOTTED LINE.

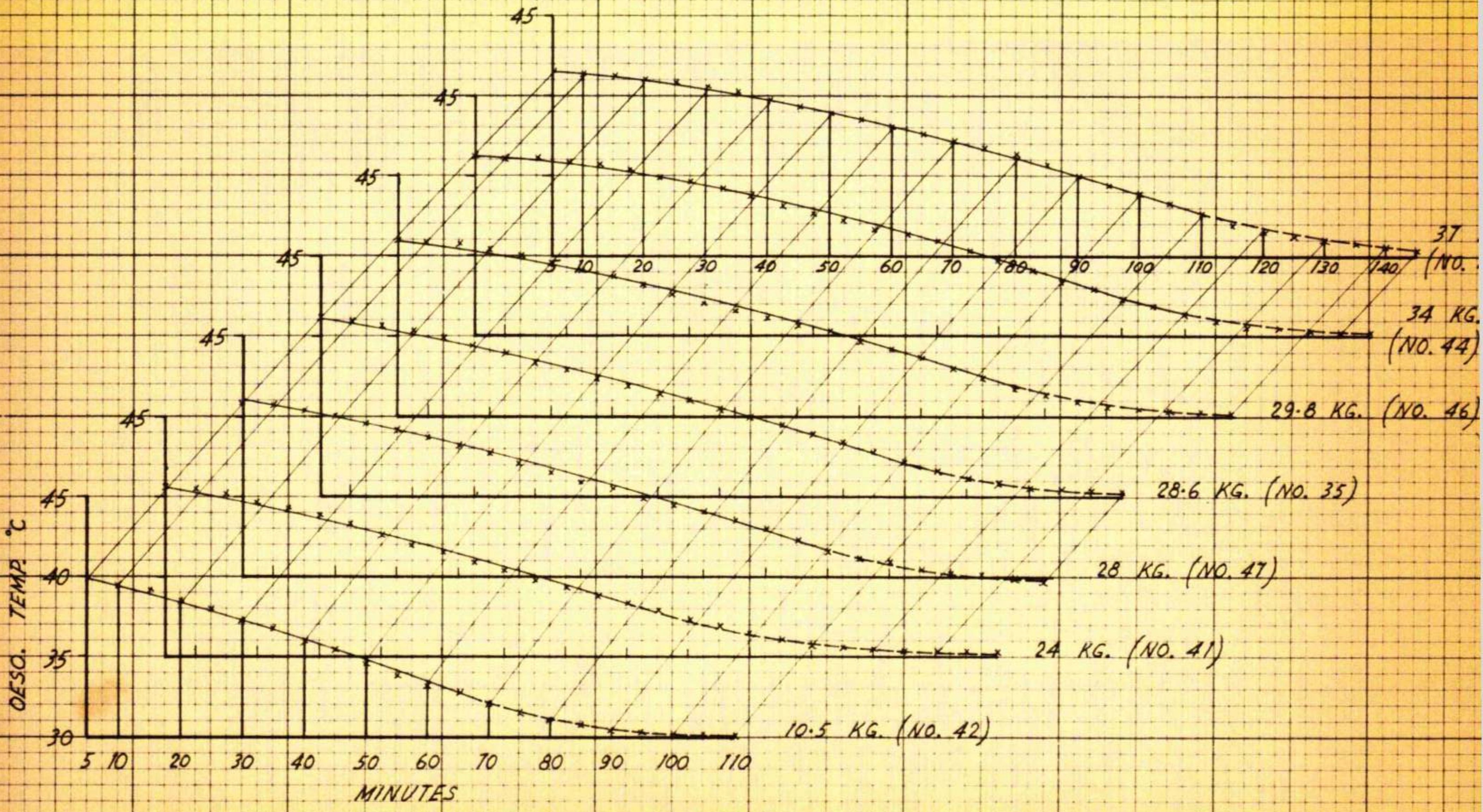


FIG. 34 COOLING CURVES OF DOGS (GROUP A). AFTER-FALL REPRESENTED BY DOTTED LINE.

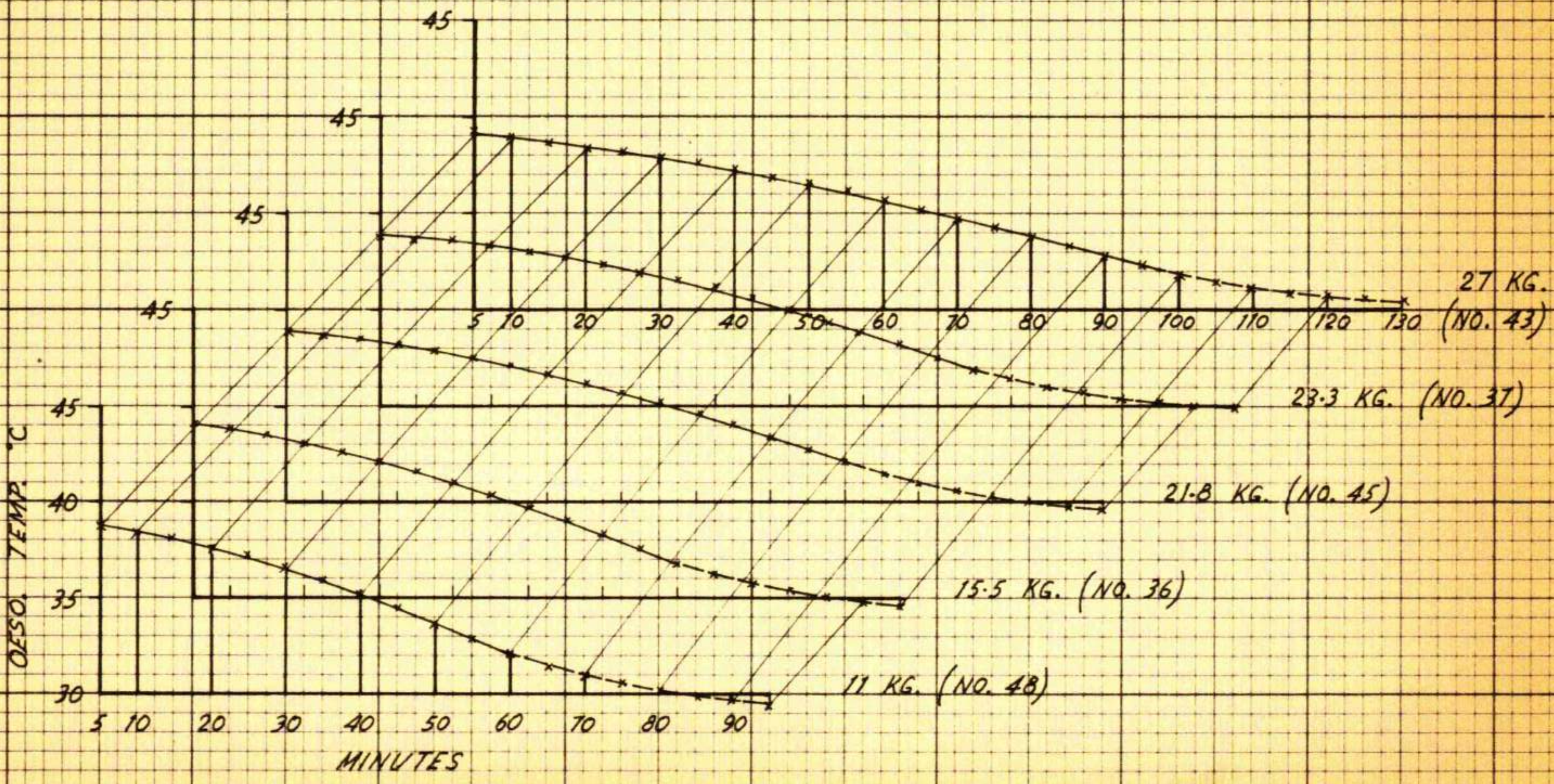


FIG. 35 COOLING CURVES OF DOGS (GROUP B). AFTER-FALL REPRESENTED BY DOTTED LINE.

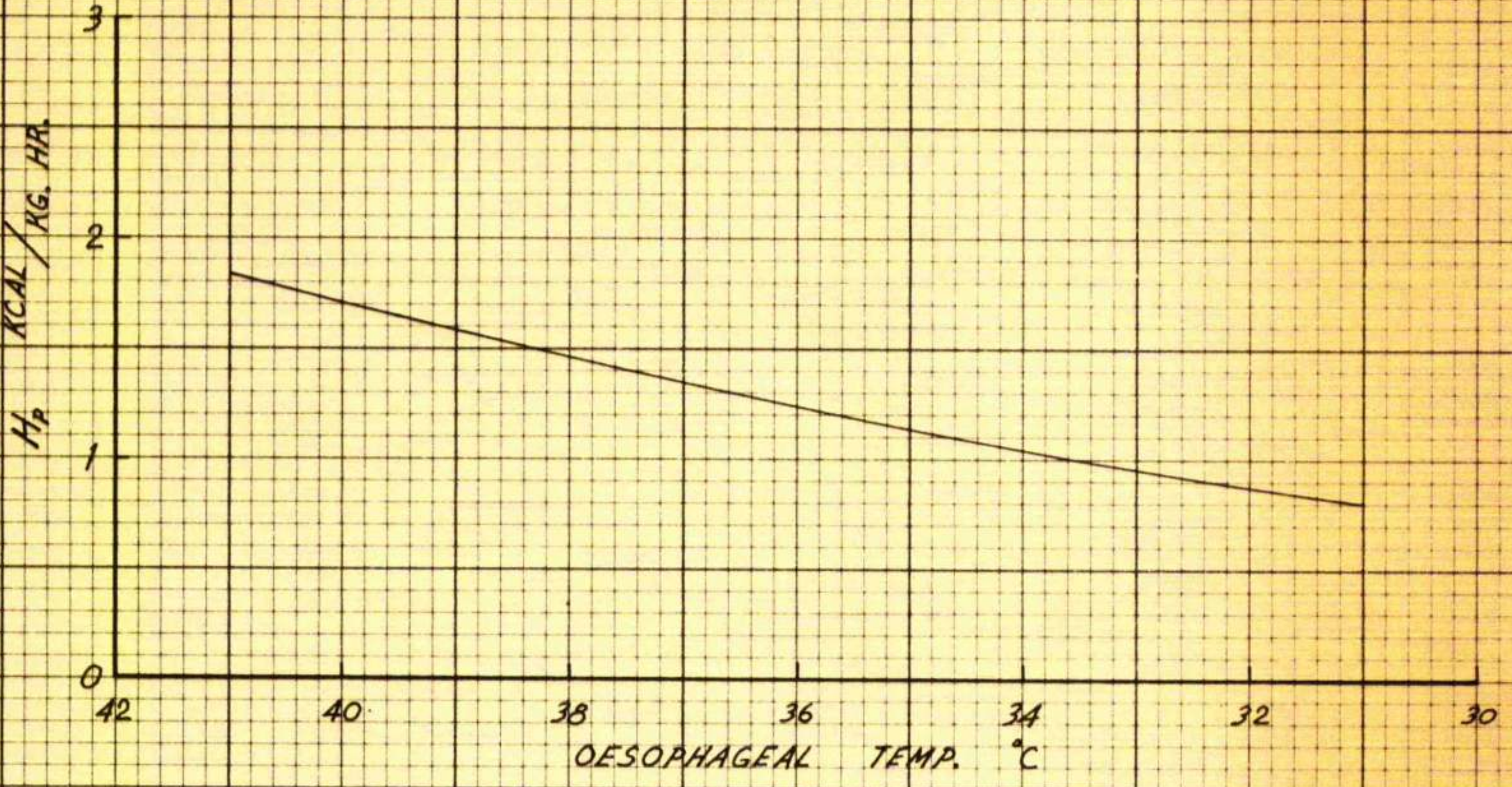


FIG. 36 GRAPH OF BASAL METABOLIC HEAT PRODUCTION OF DOGS. MODIFIED FROM KELLER (1956).

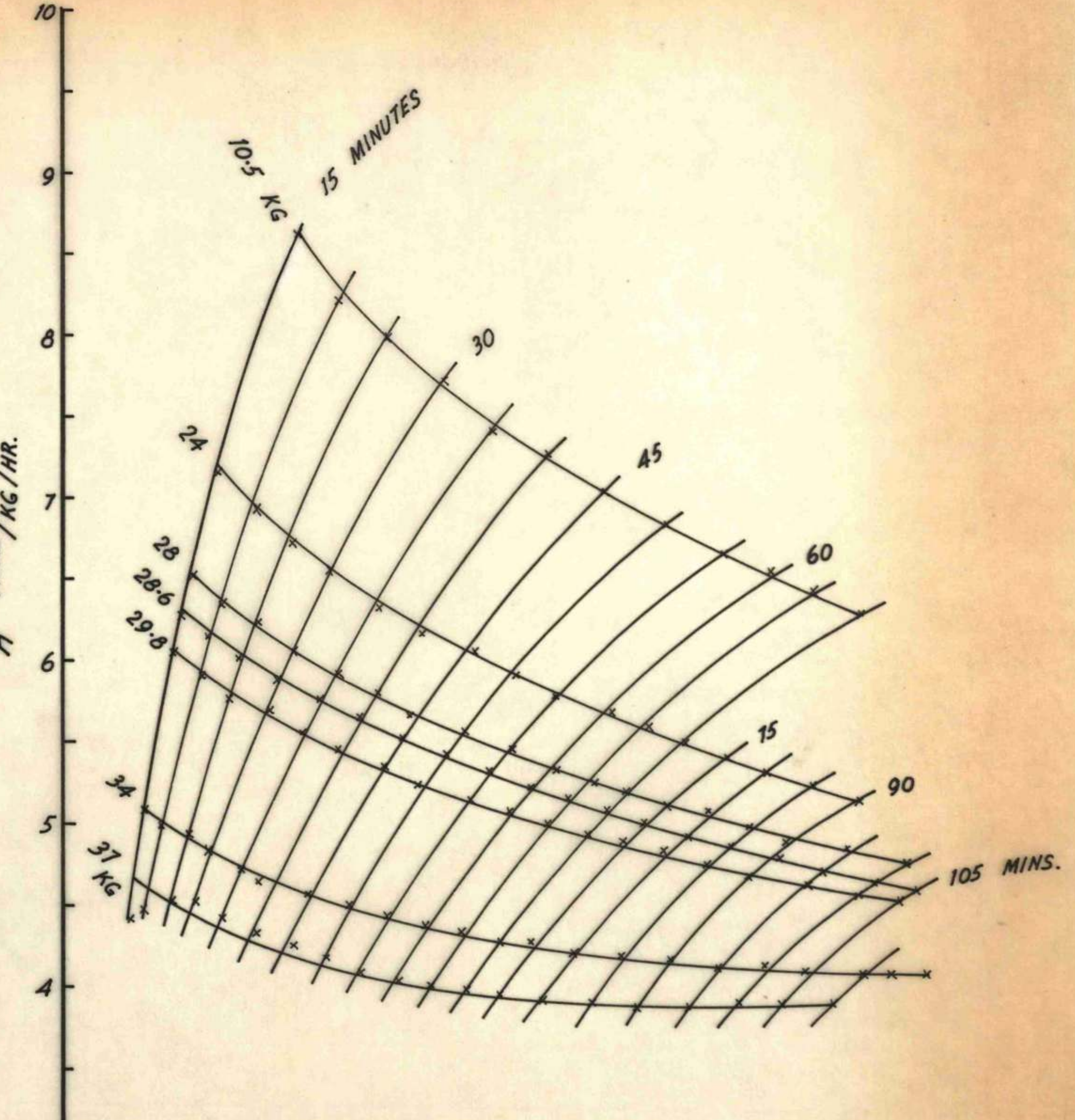


FIG. 37 HEAT EXTRACTION OF DOGS IN VIVO (GROUP A)

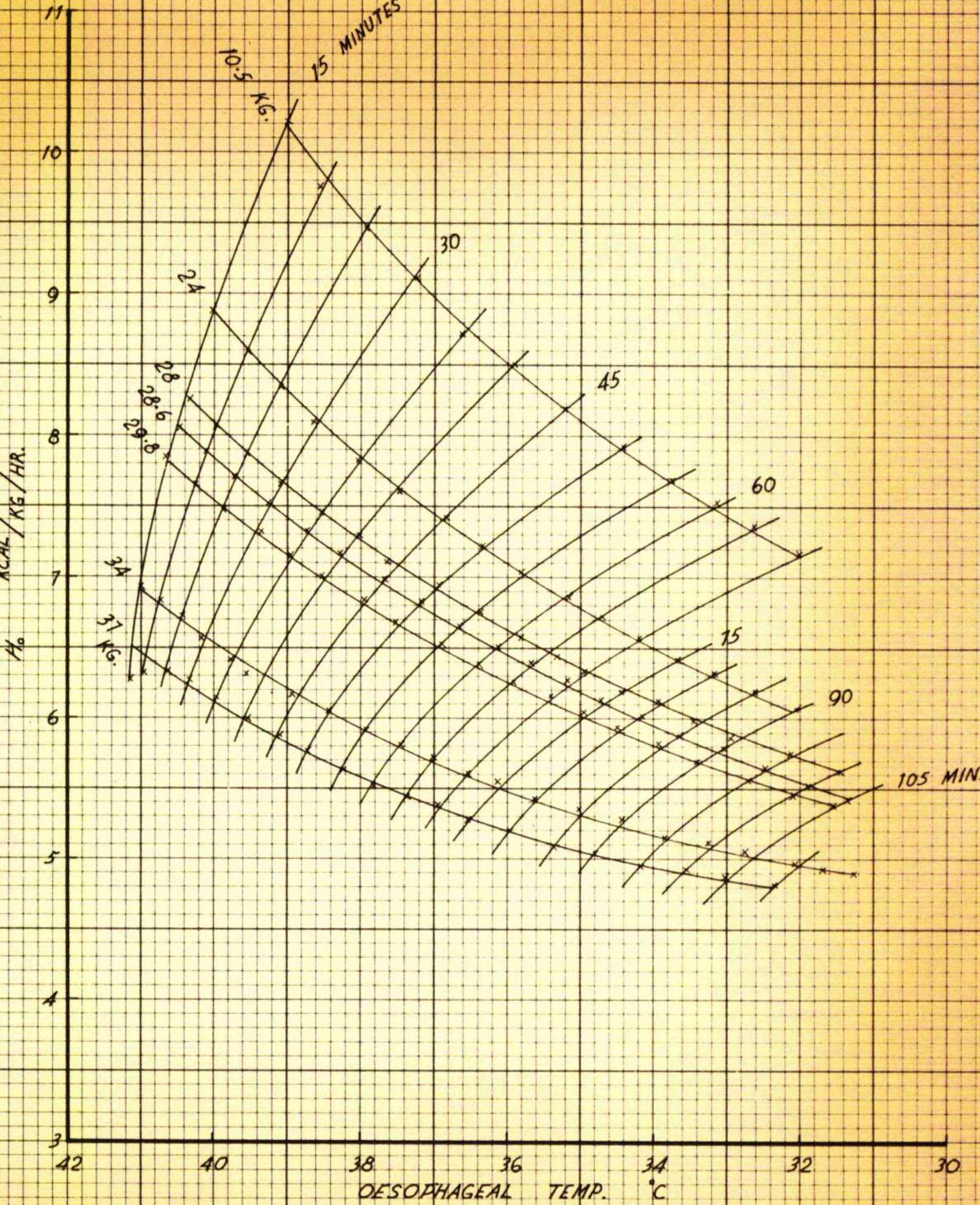


FIG. 38 HEAT EXTRACTION OF DOGS WITHOUT METABOLIC HEAT PRODUCTION (GROUP A)

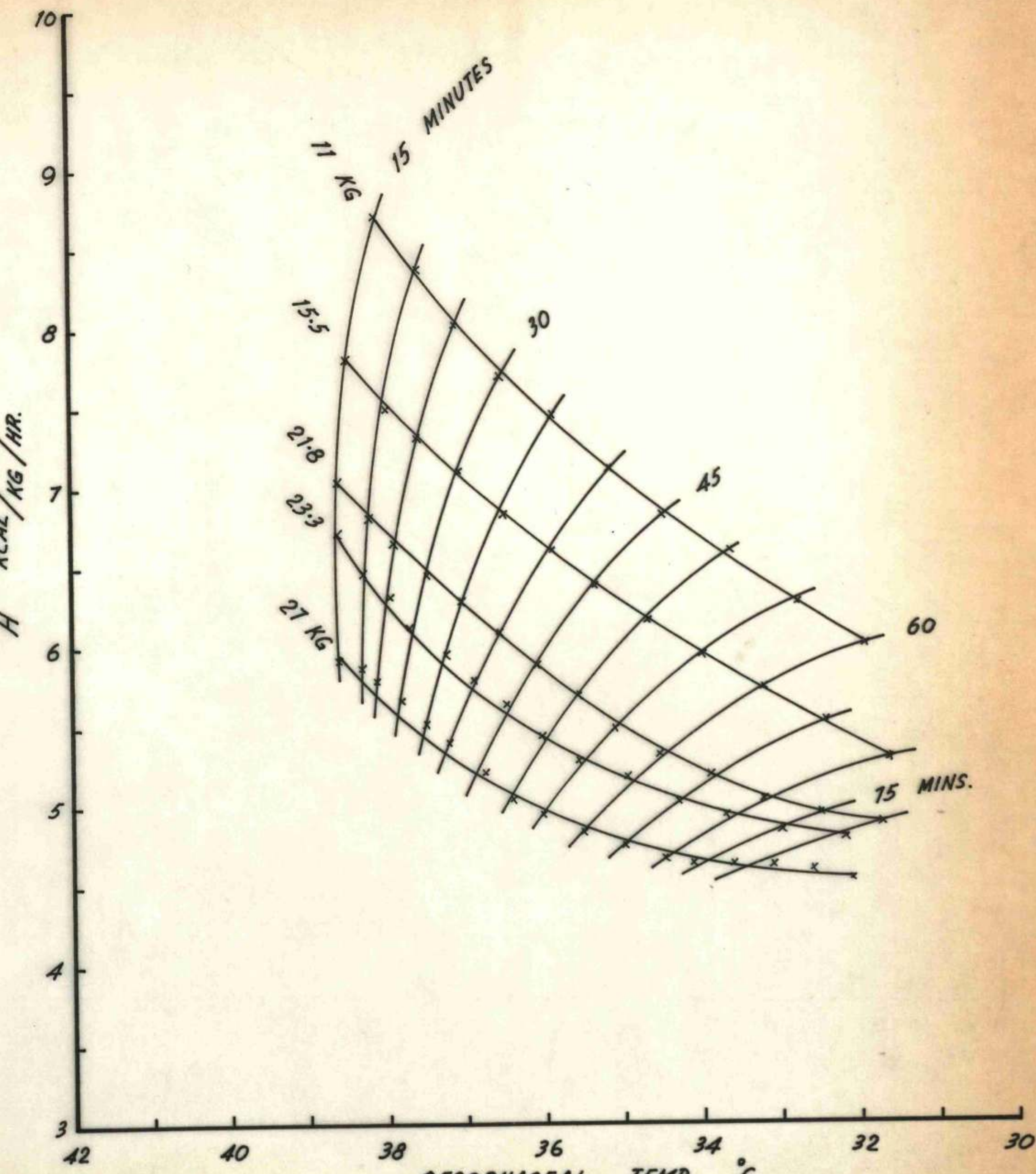


FIG. 39 HEAT EXTRACTION OF DOGS IN VIVO (GROUP B)

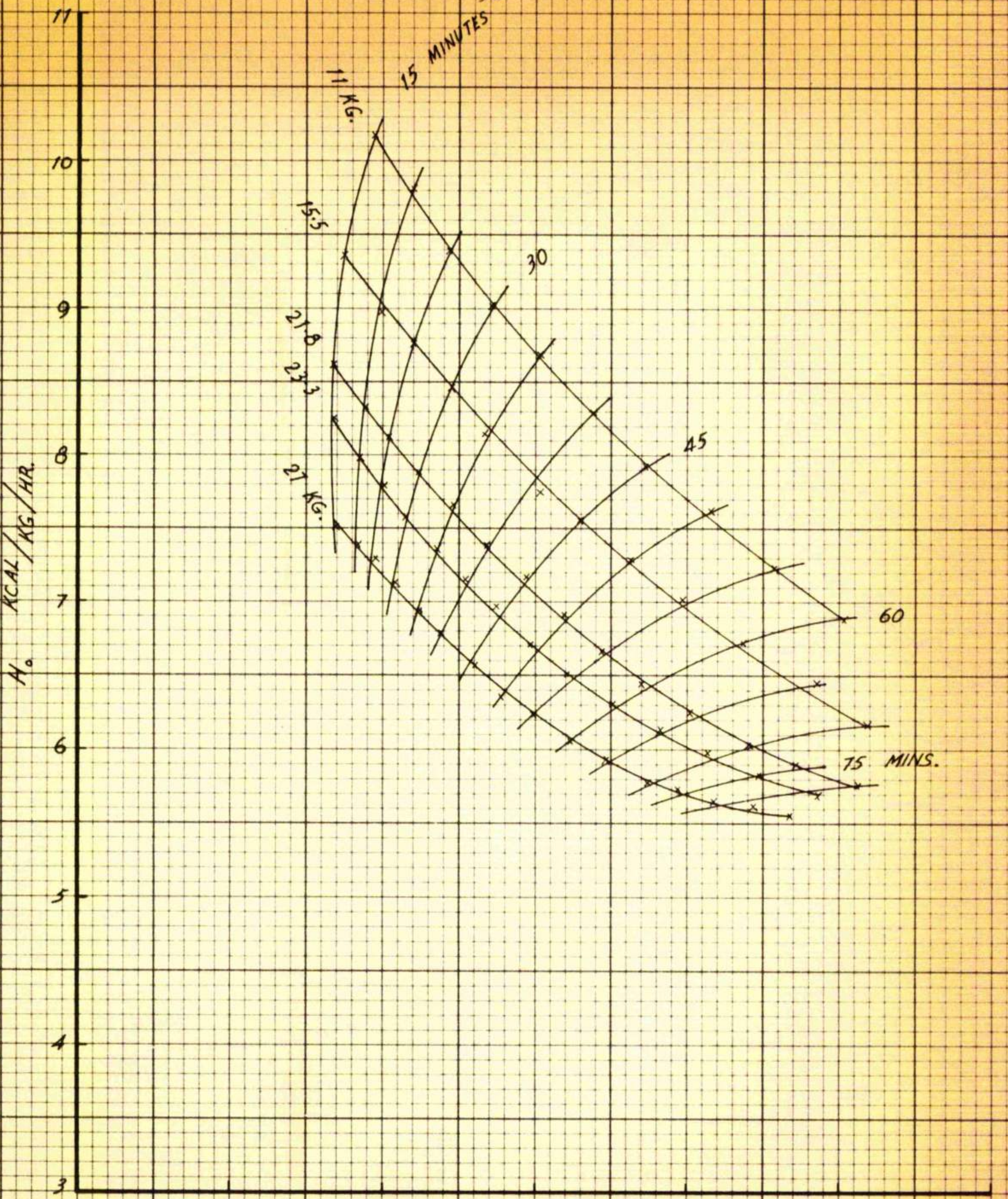


FIG. 40 HEAT EXTRACTION OF DOGS WITHOUT METABOLIC HEAT PRODUCTION (GROUP B)

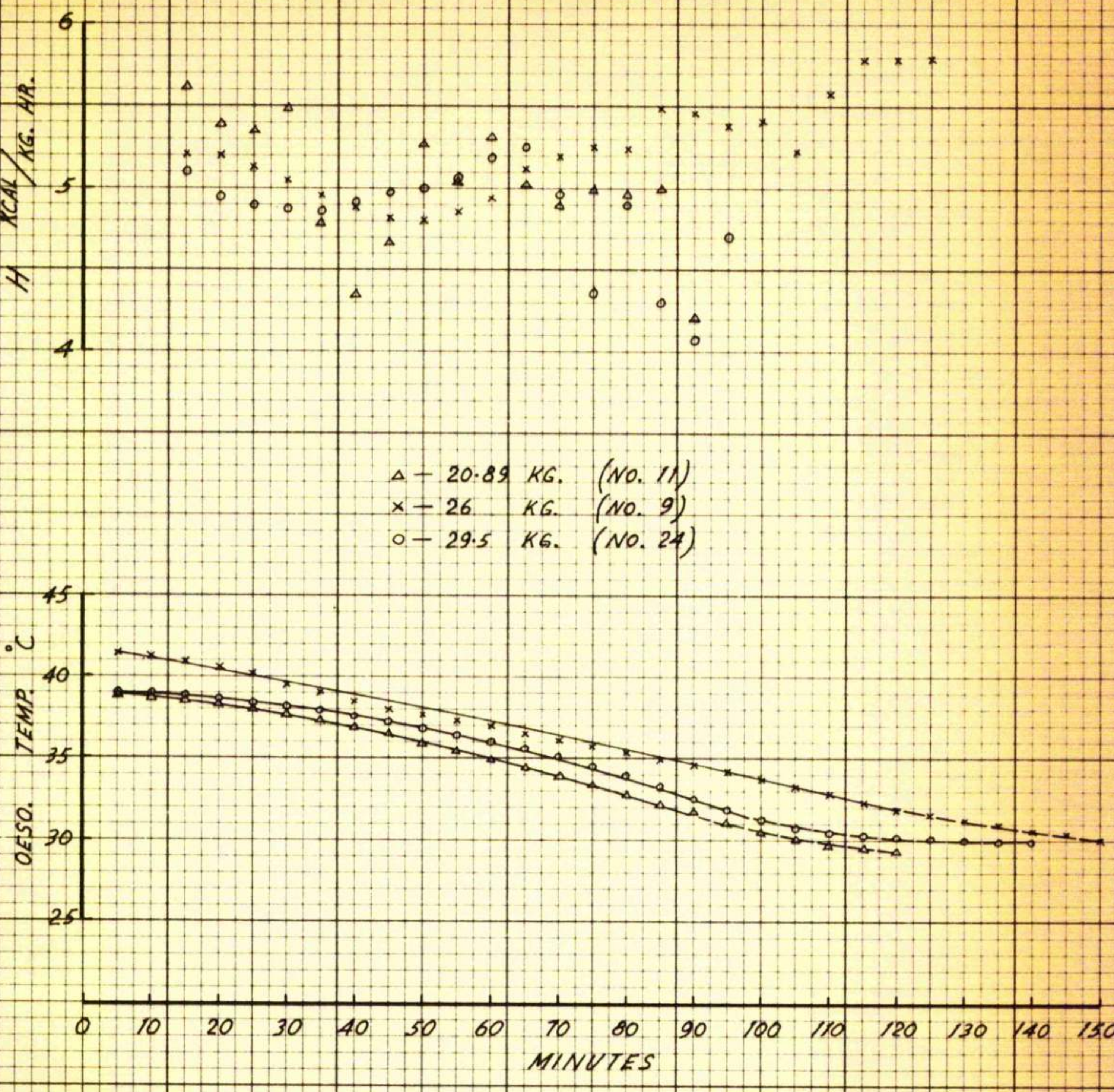


FIG. 41 GRAPH SHOWING HEAT ABSTRACTION (H) OF THREE DOGS. VARIATIONS OF H IN RANDOM FASHION INDICATING VASOCONSTRICTION PERSISTS (TOP). COOLING CURVES (BOTTOM).

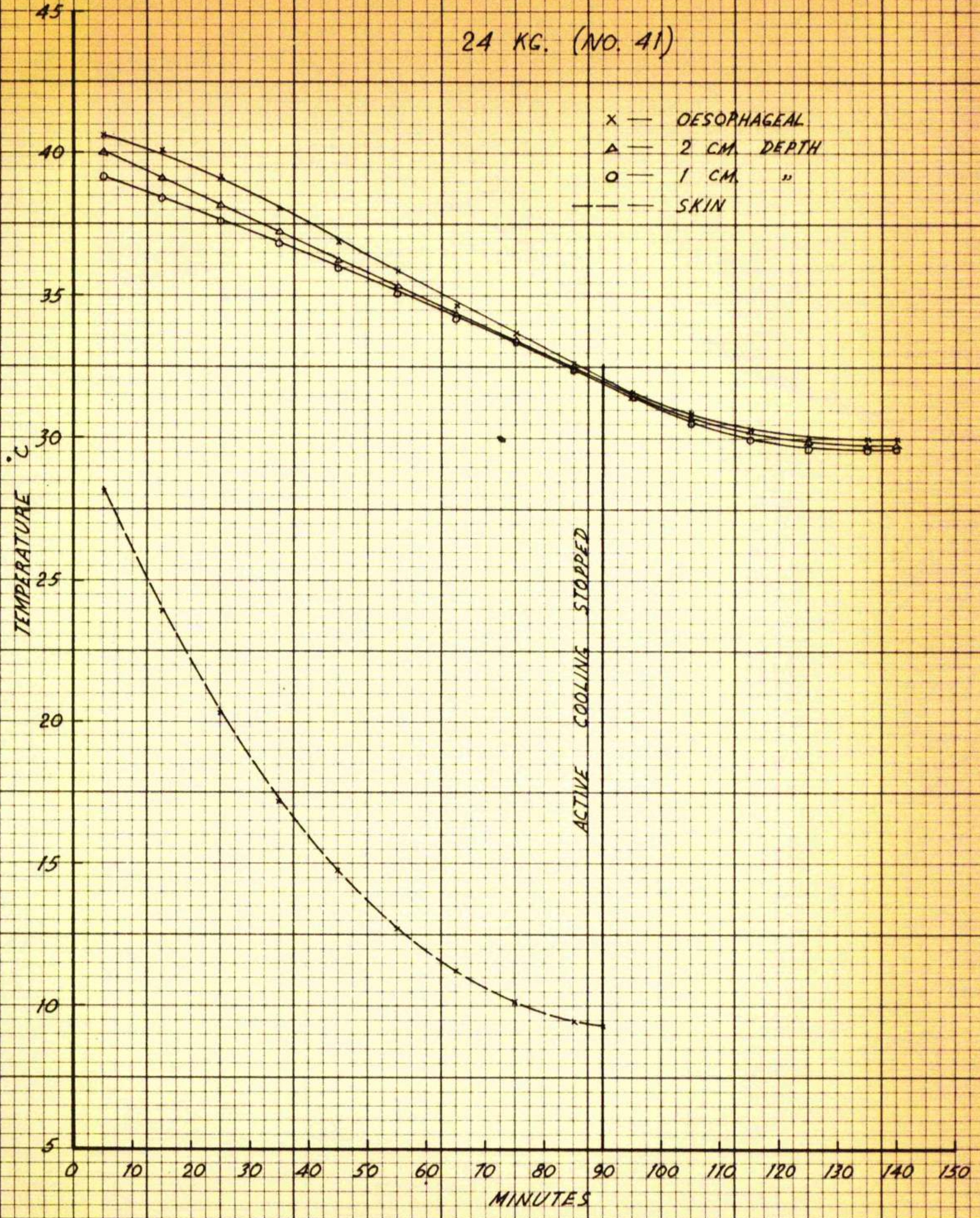


FIG. 42 TEMPERATURE DISTRIBUTION

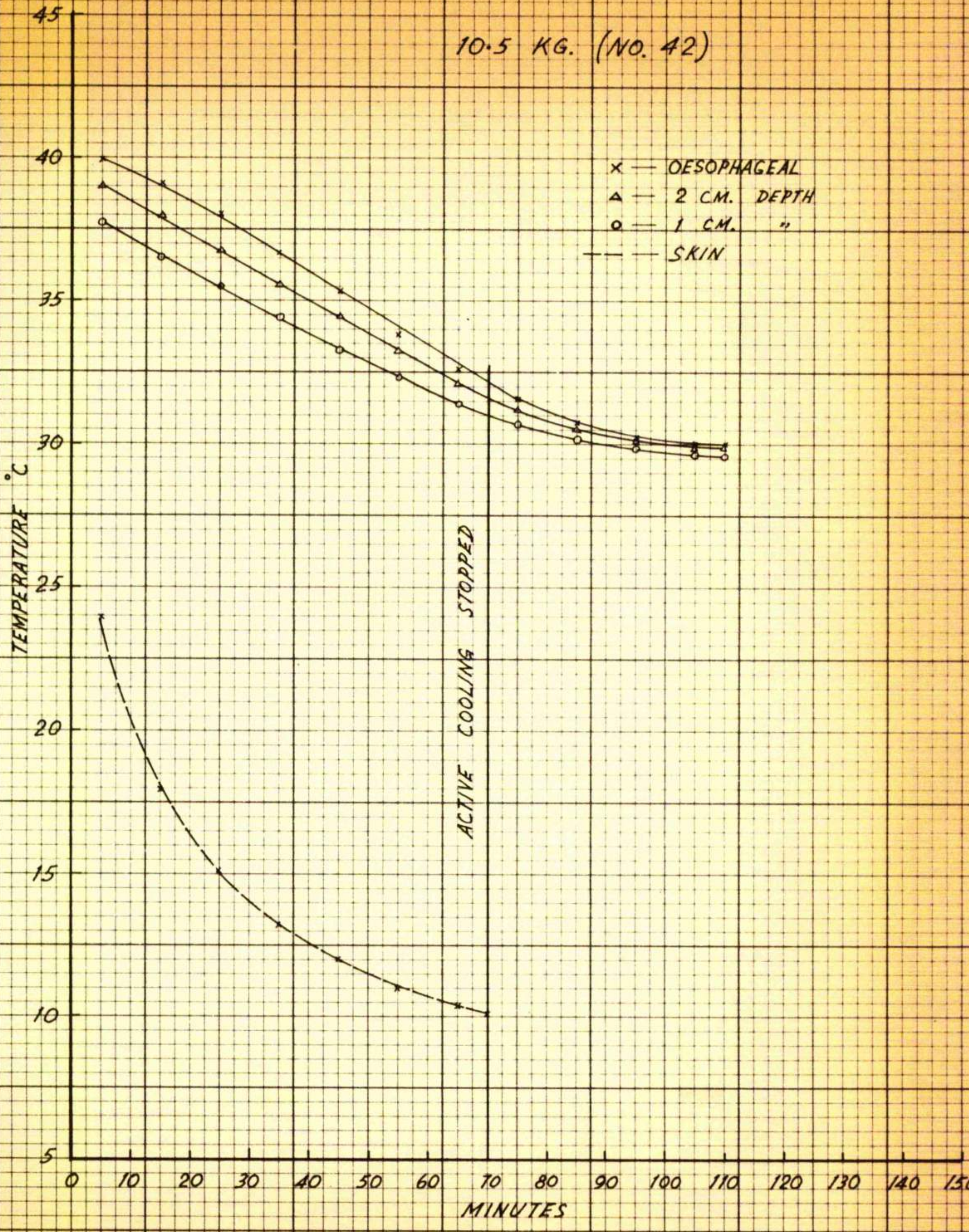


FIG. 43 TEMPERATURE DISTRIBUTION

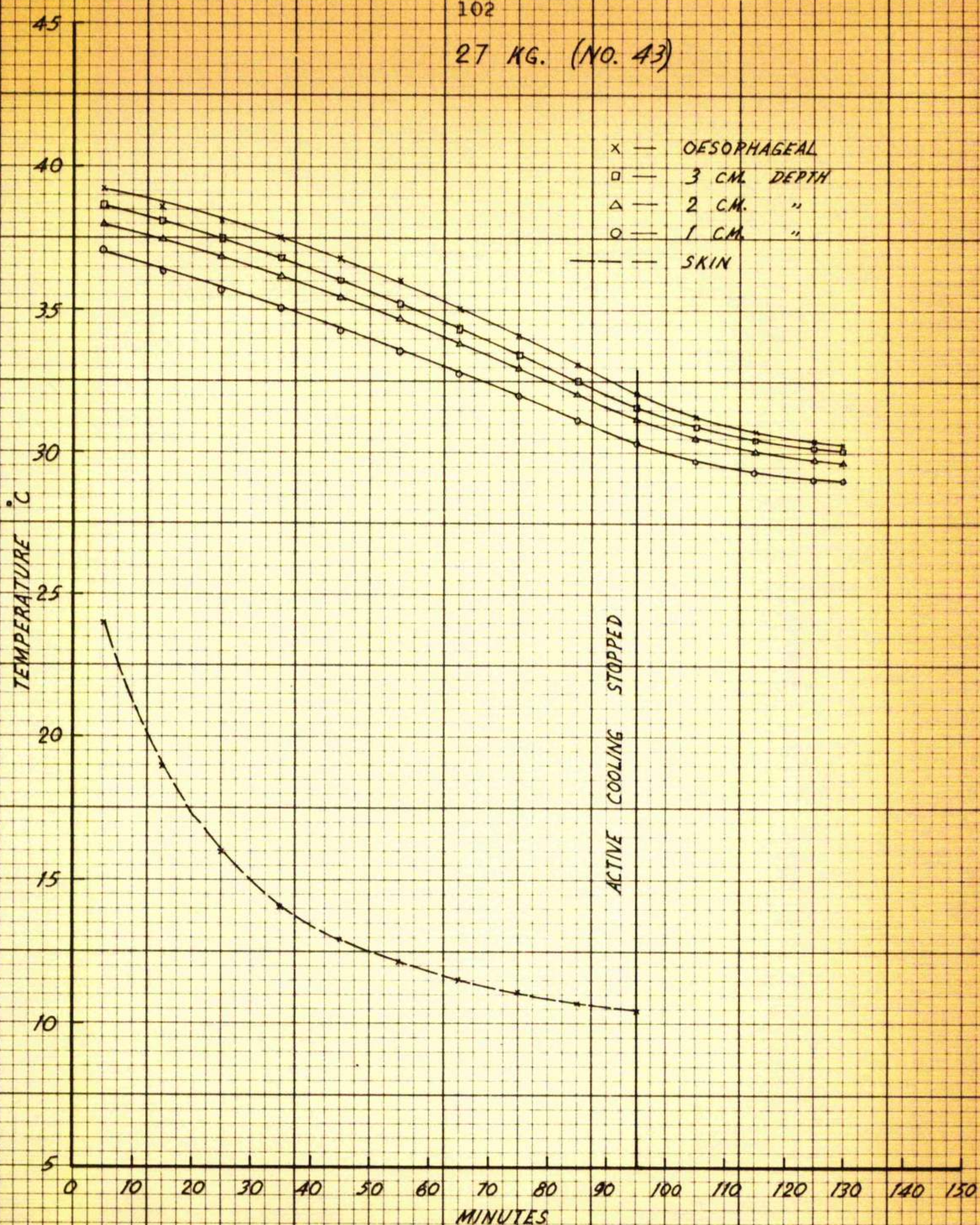


FIG. 44 TEMPERATURE DISTRIBUTION

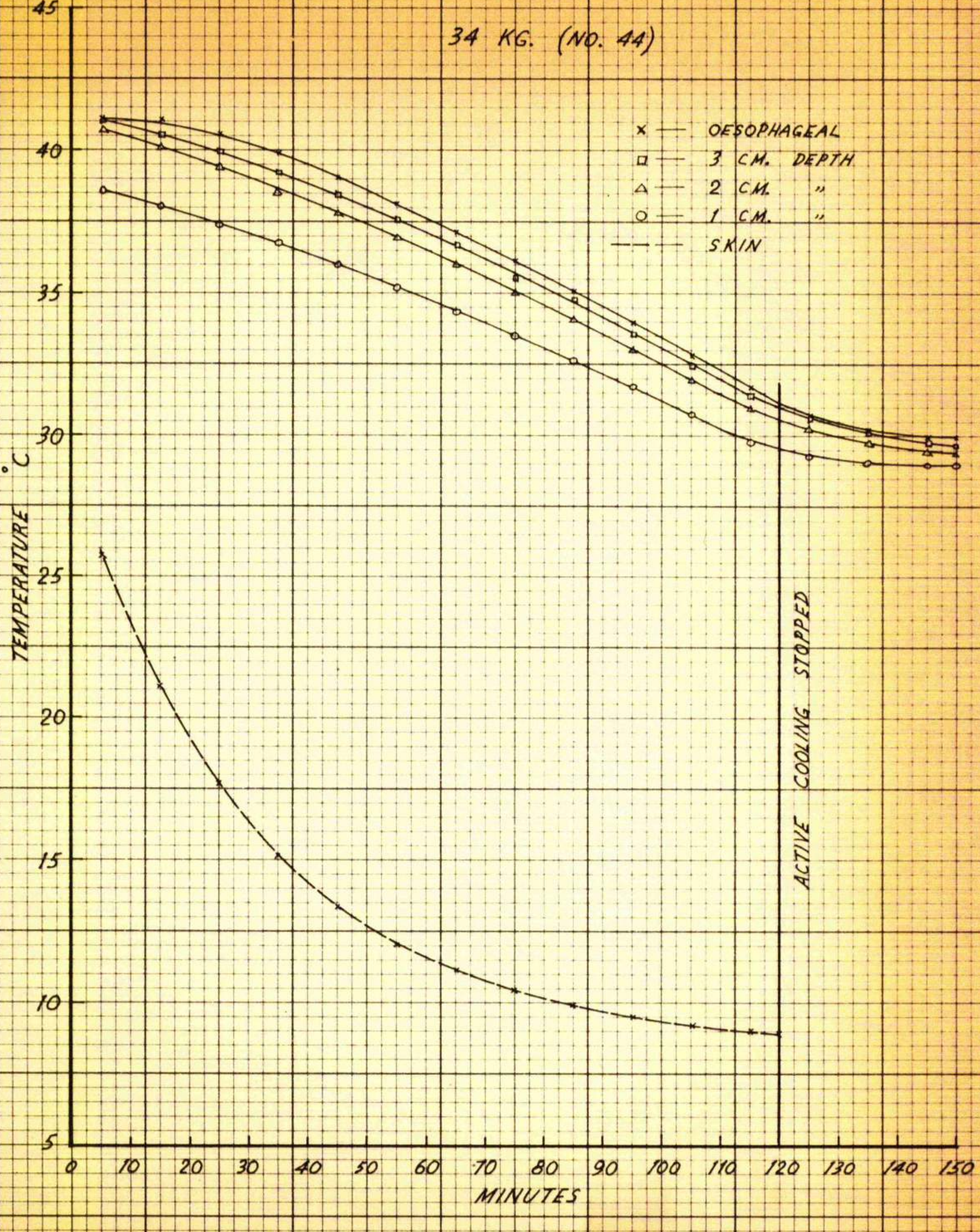


FIG. 45 TEMPERATURE DISTRIBUTION

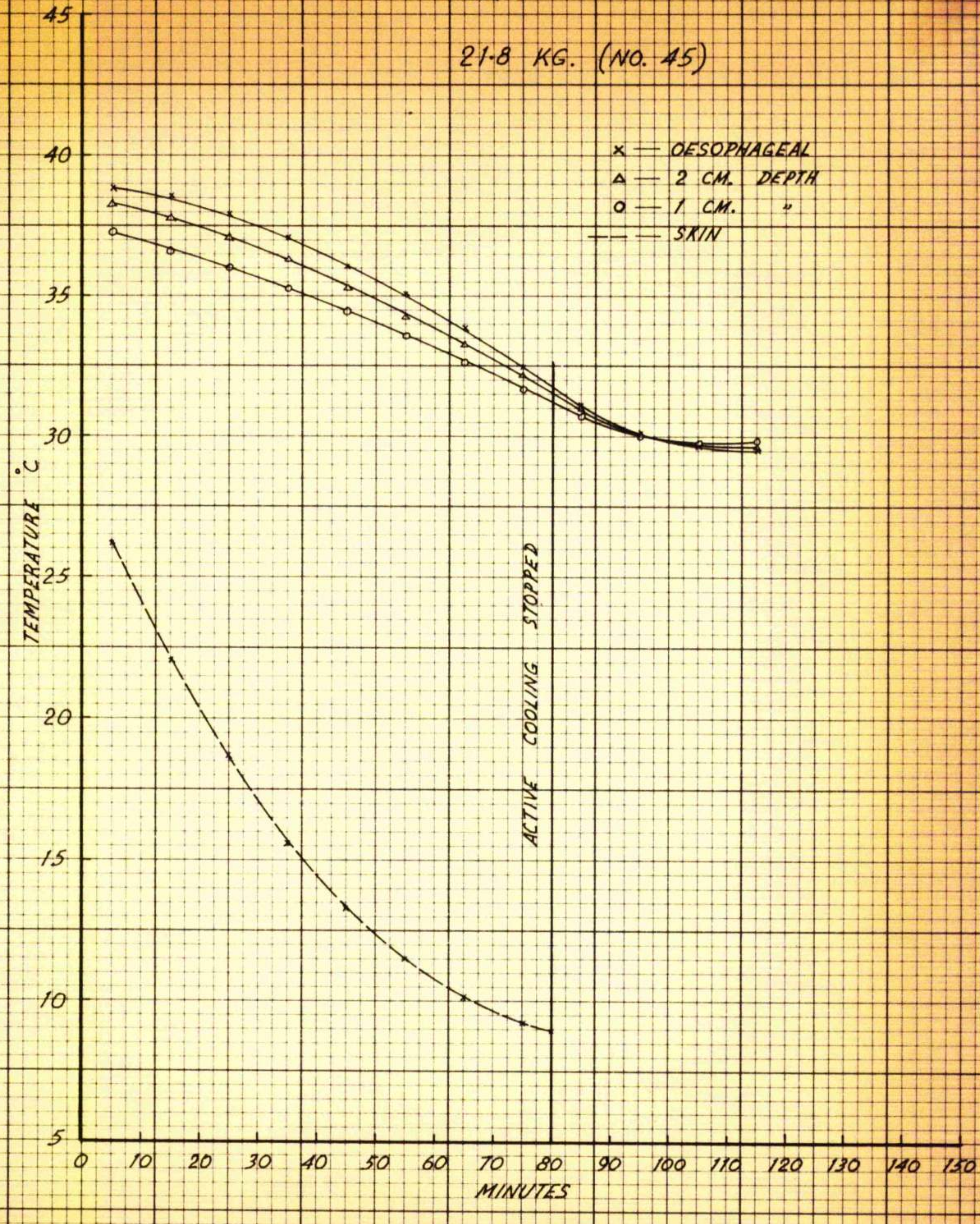


FIG. 46 TEMPERATURE DISTRIBUTION

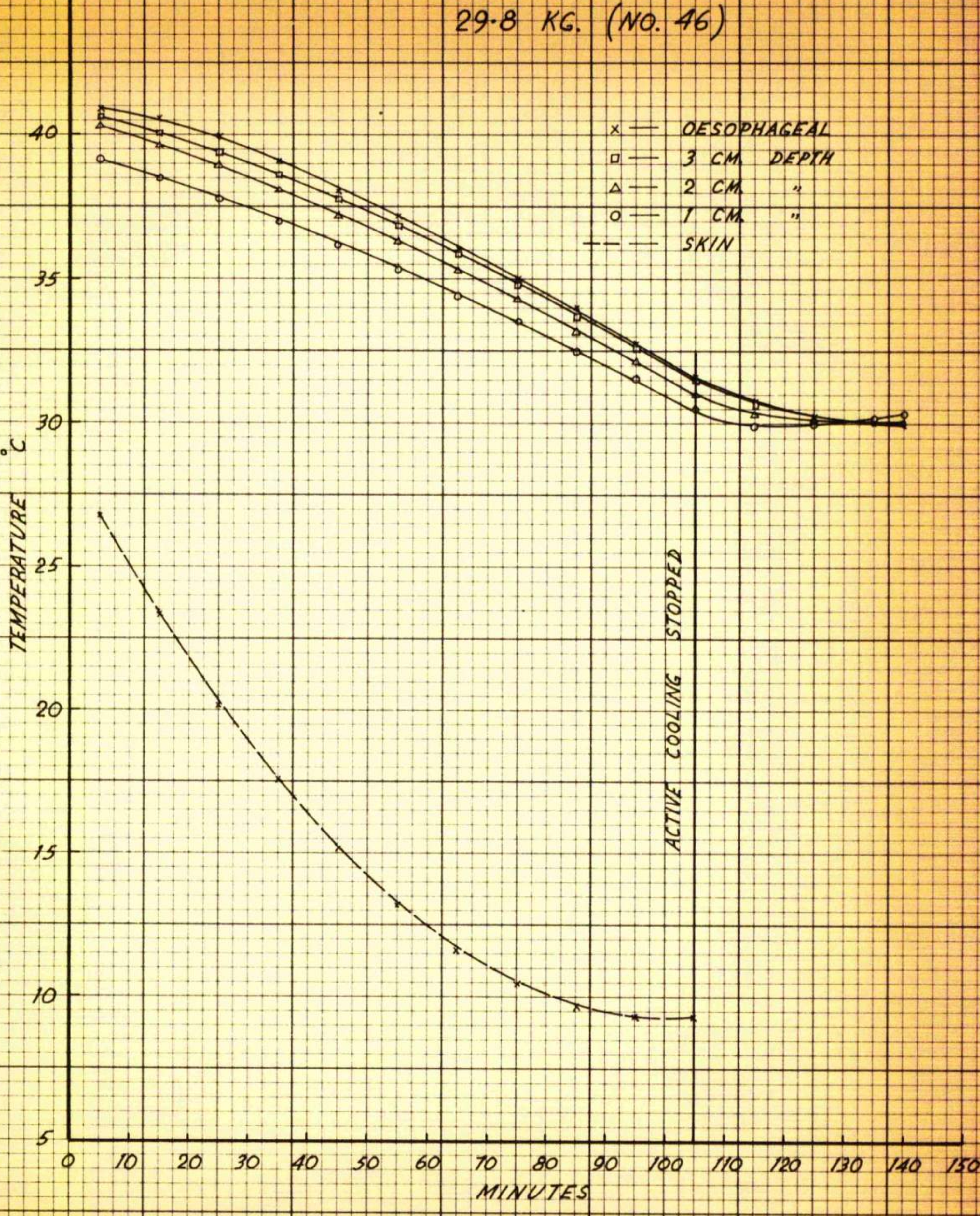


FIG. 47 TEMPERATURE DISTRIBUTION

28 KG. (NO. 47)

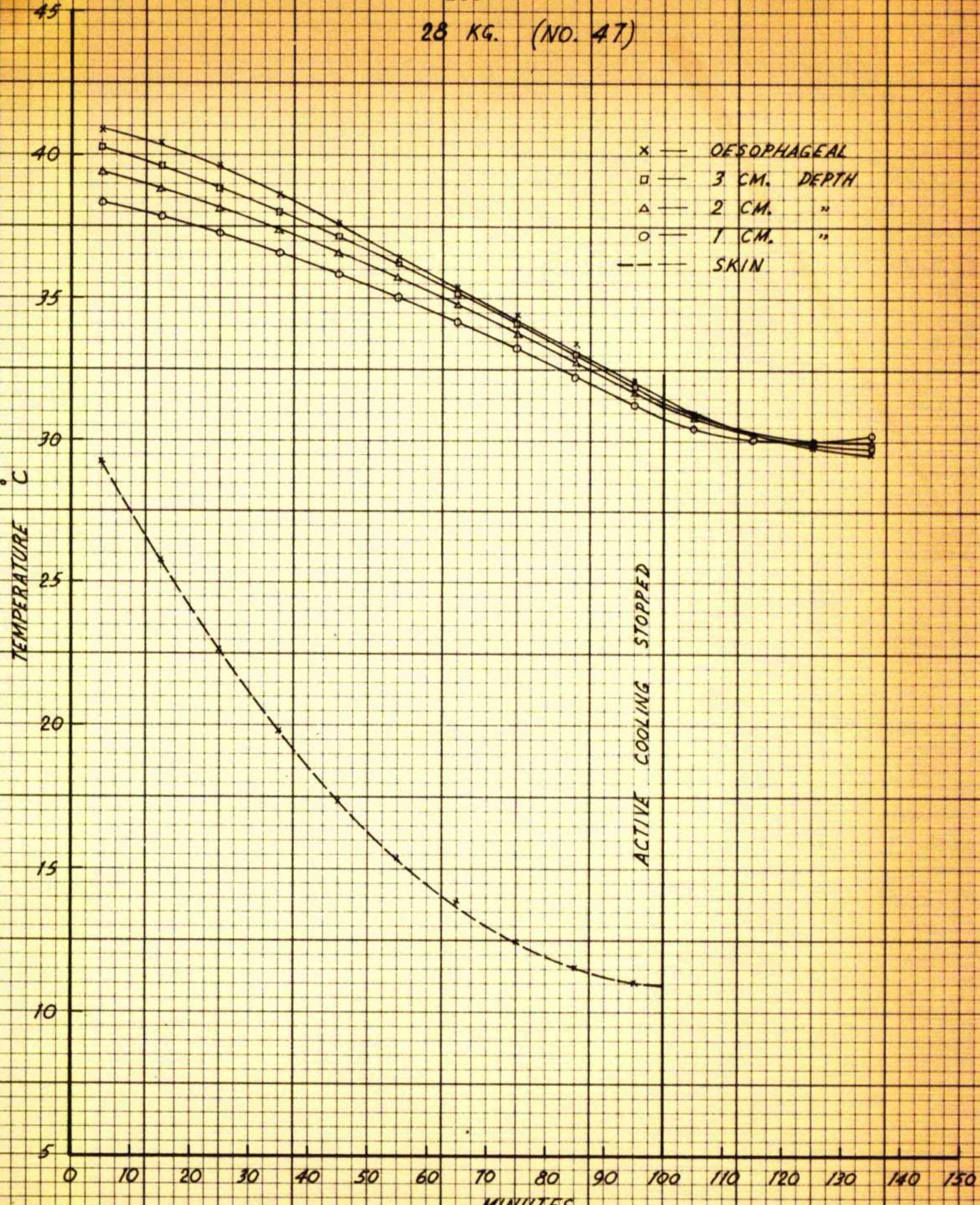


FIG. 48 TEMPERATURE DISTRIBUTION

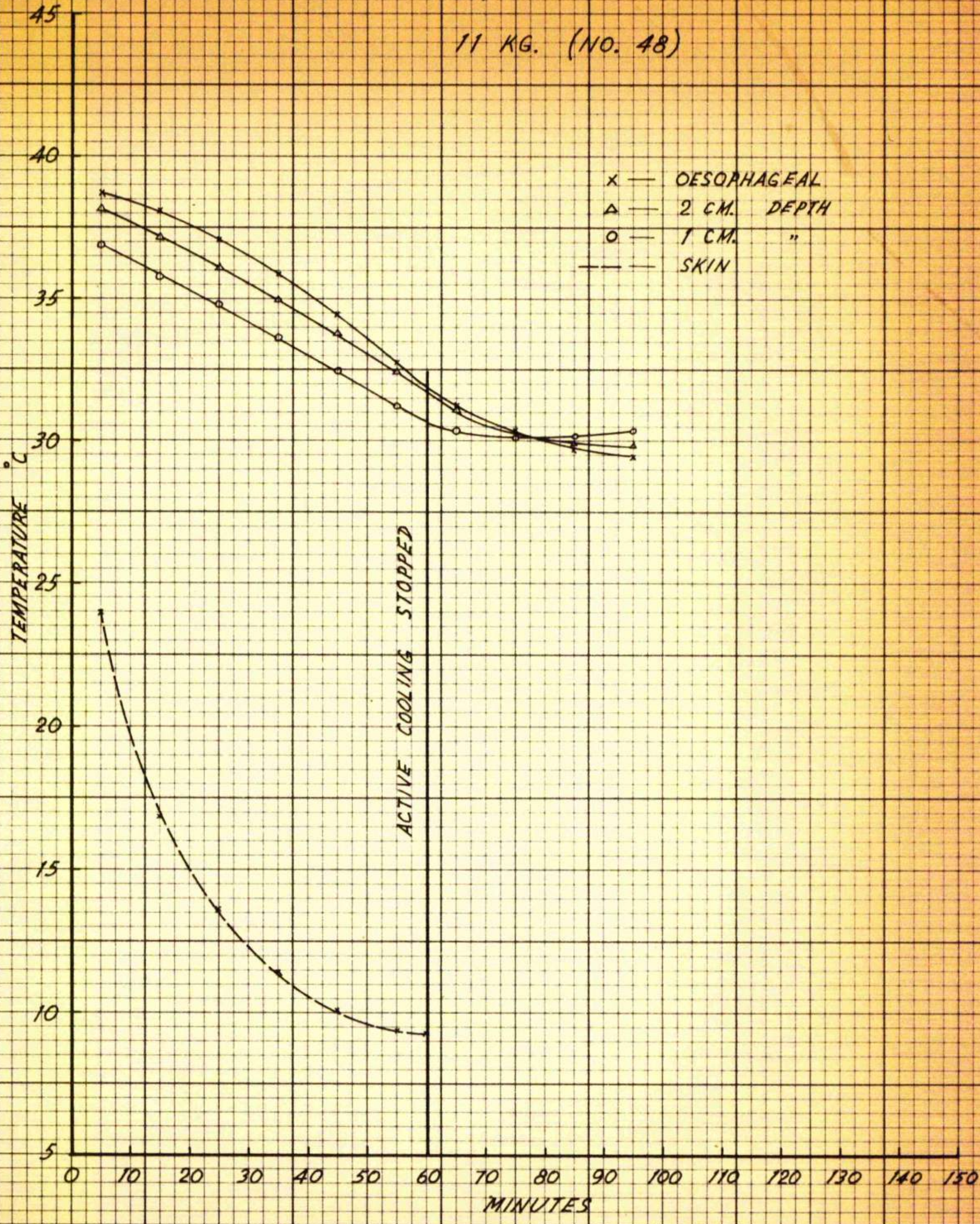


FIG. 49 TEMPERATURE DISTRIBUTION

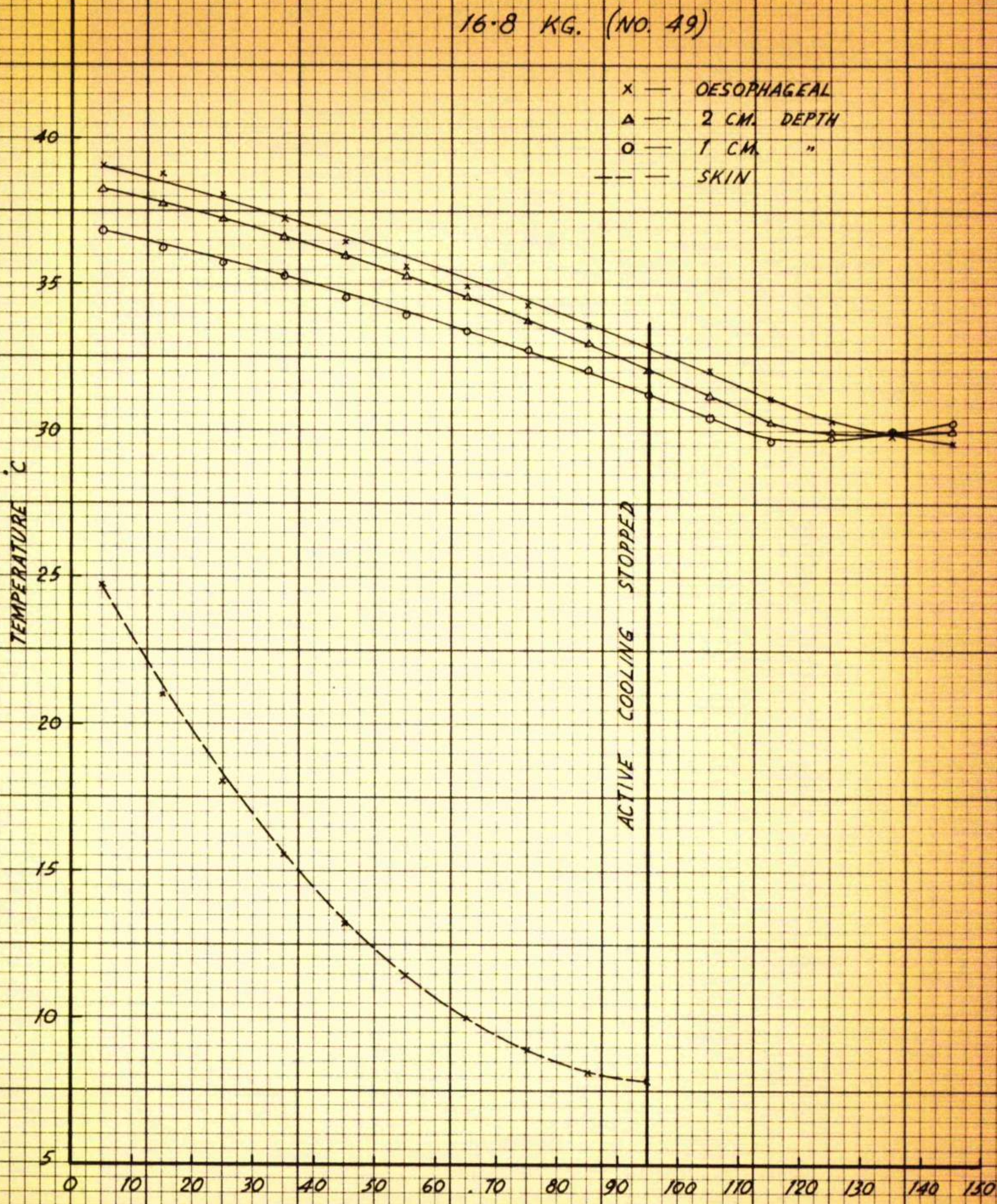


FIG. 50 TEMPERATURE DISTRIBUTION

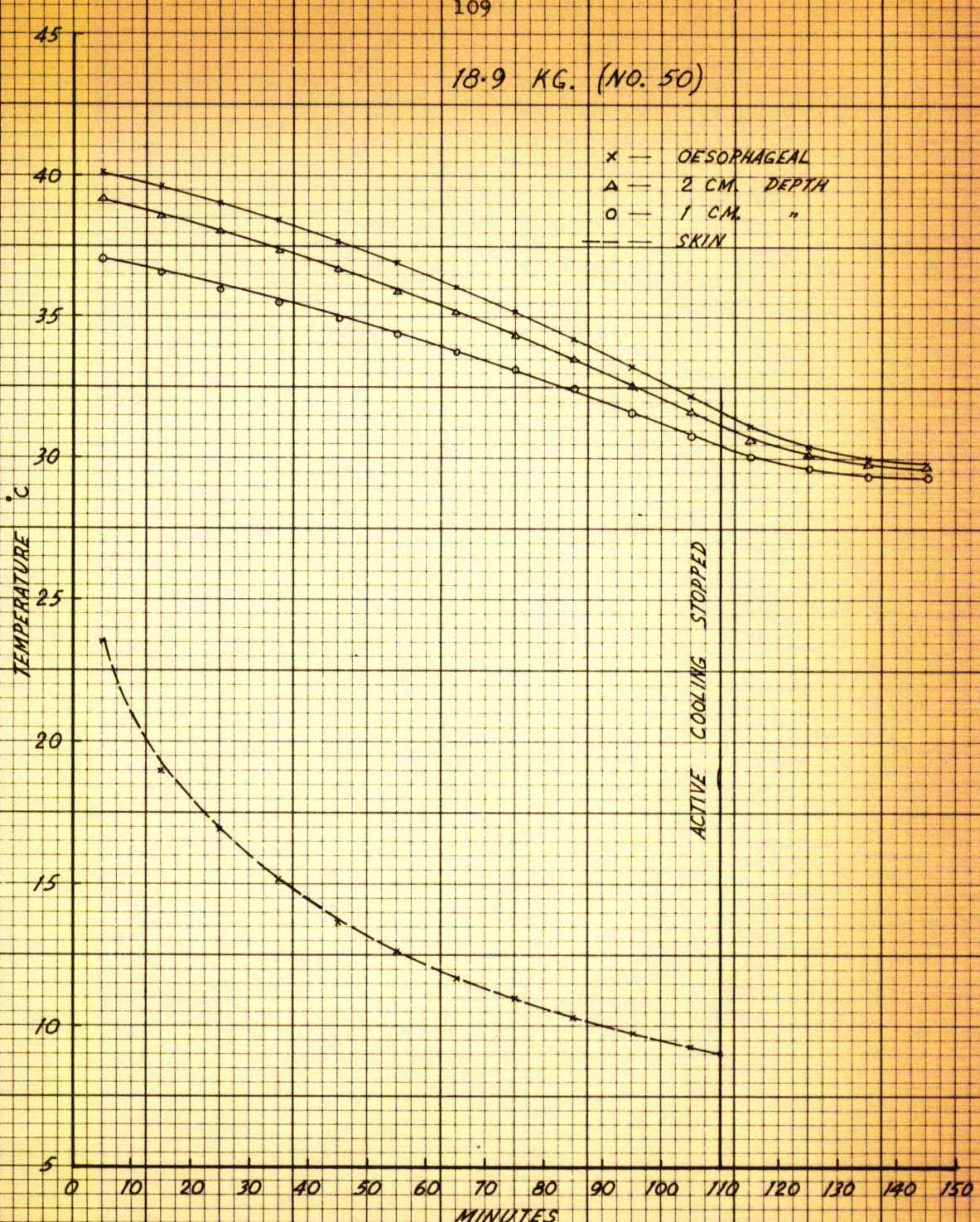


FIG. 51 TEMPERATURE DISTRIBUTION

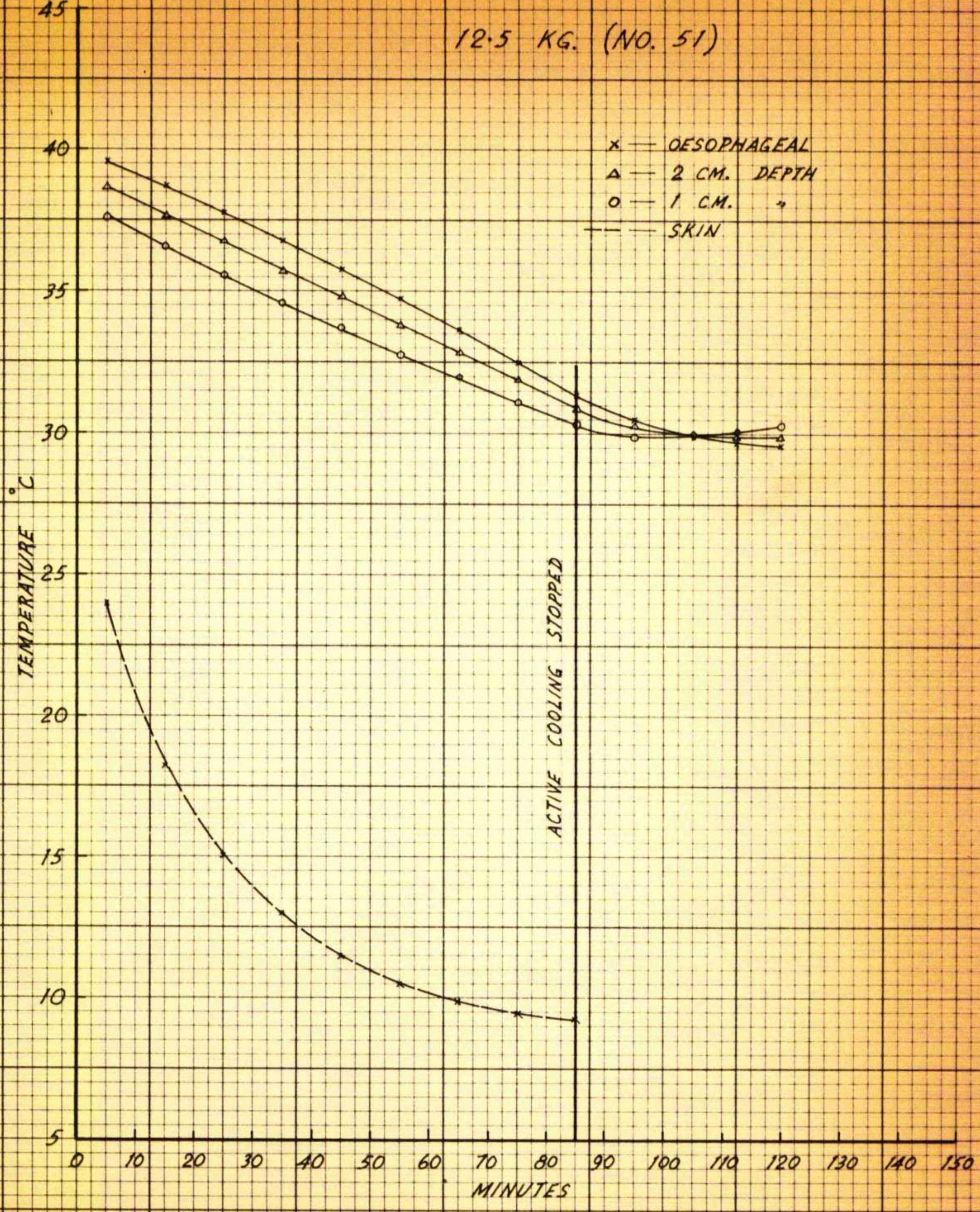


FIG. 52 TEMPERATURE DISTRIBUTION

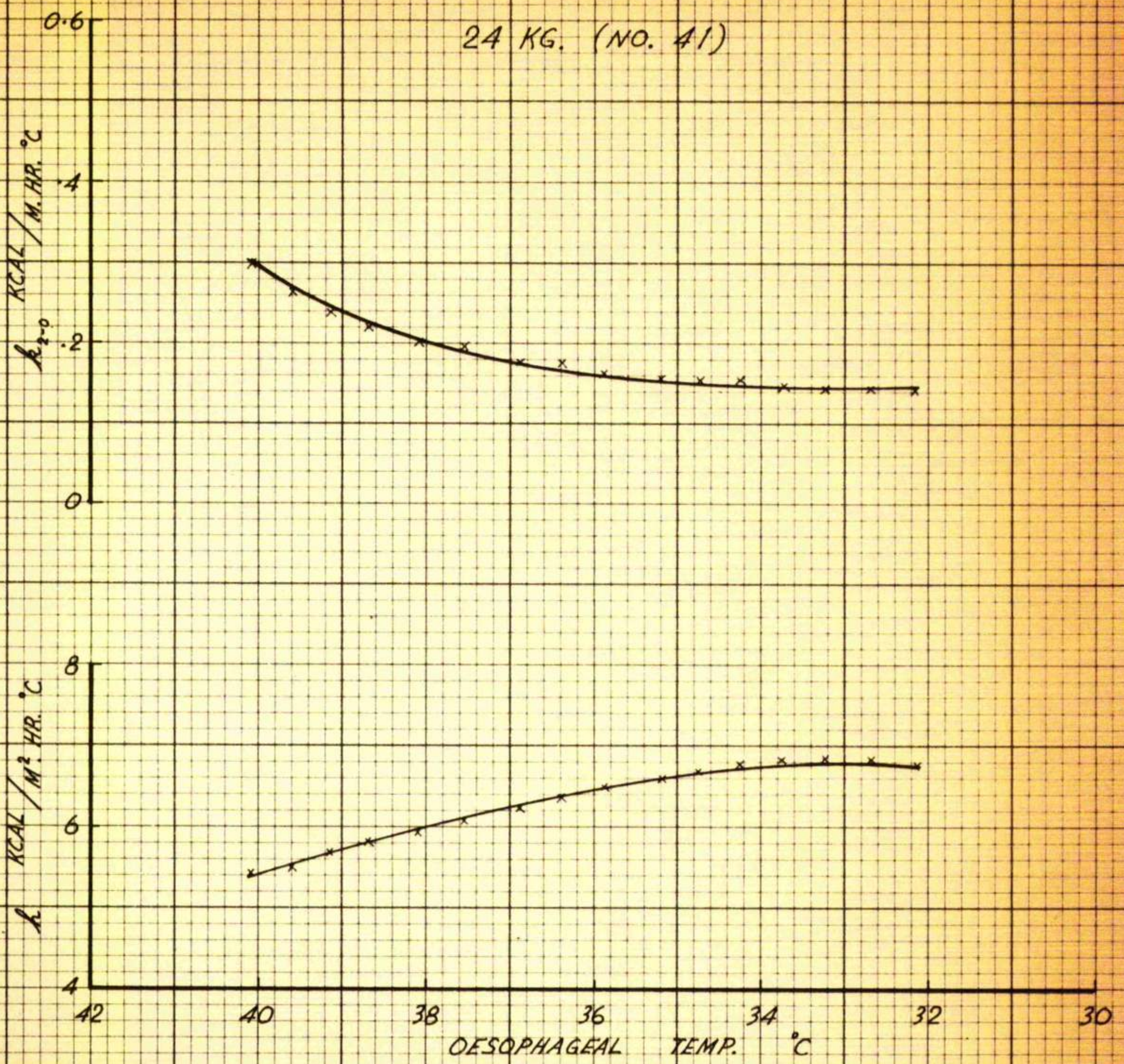


FIG. 53 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (h) OF THE DOG.

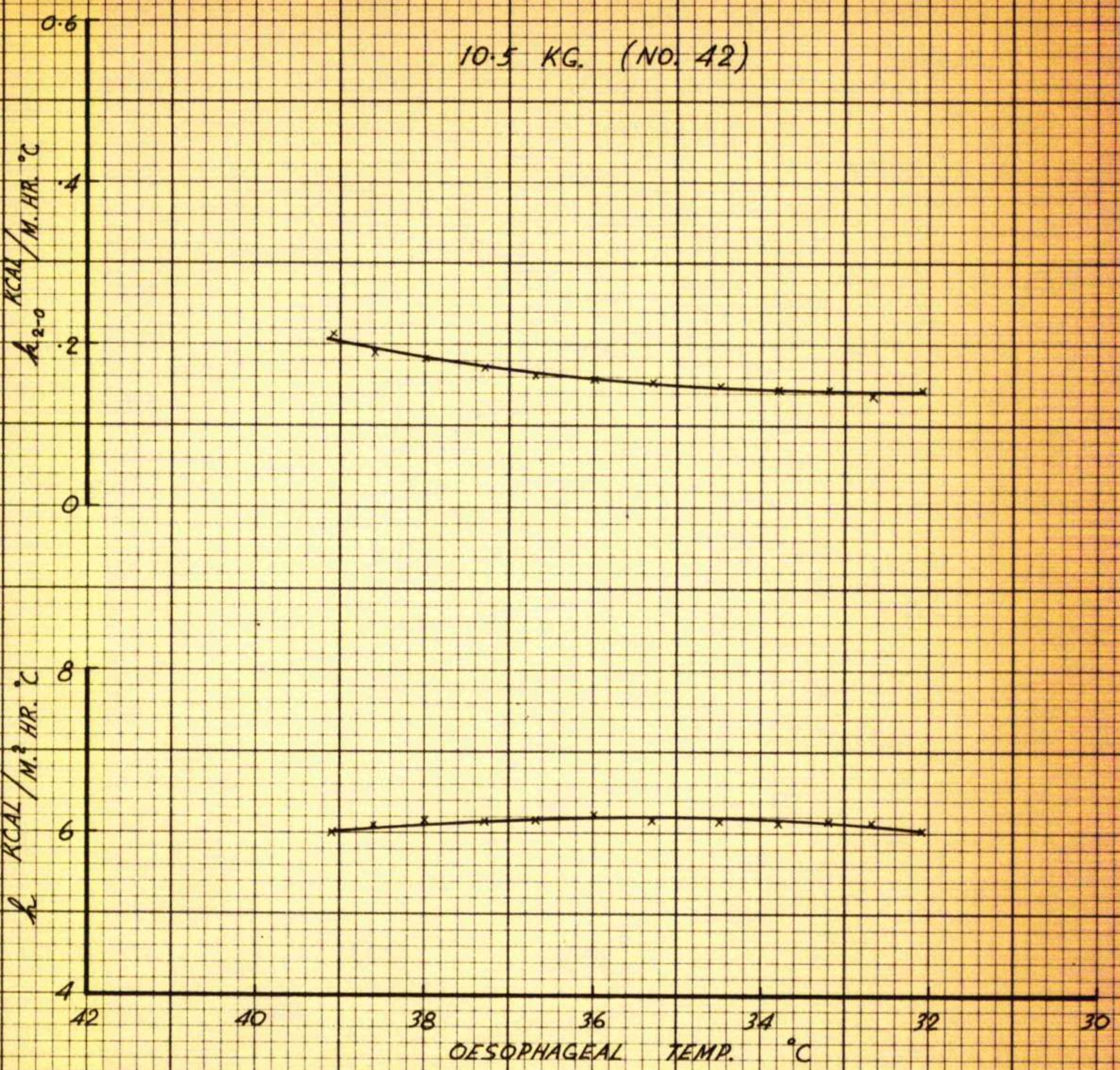


FIG. 54 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (h) OF THE DOG.

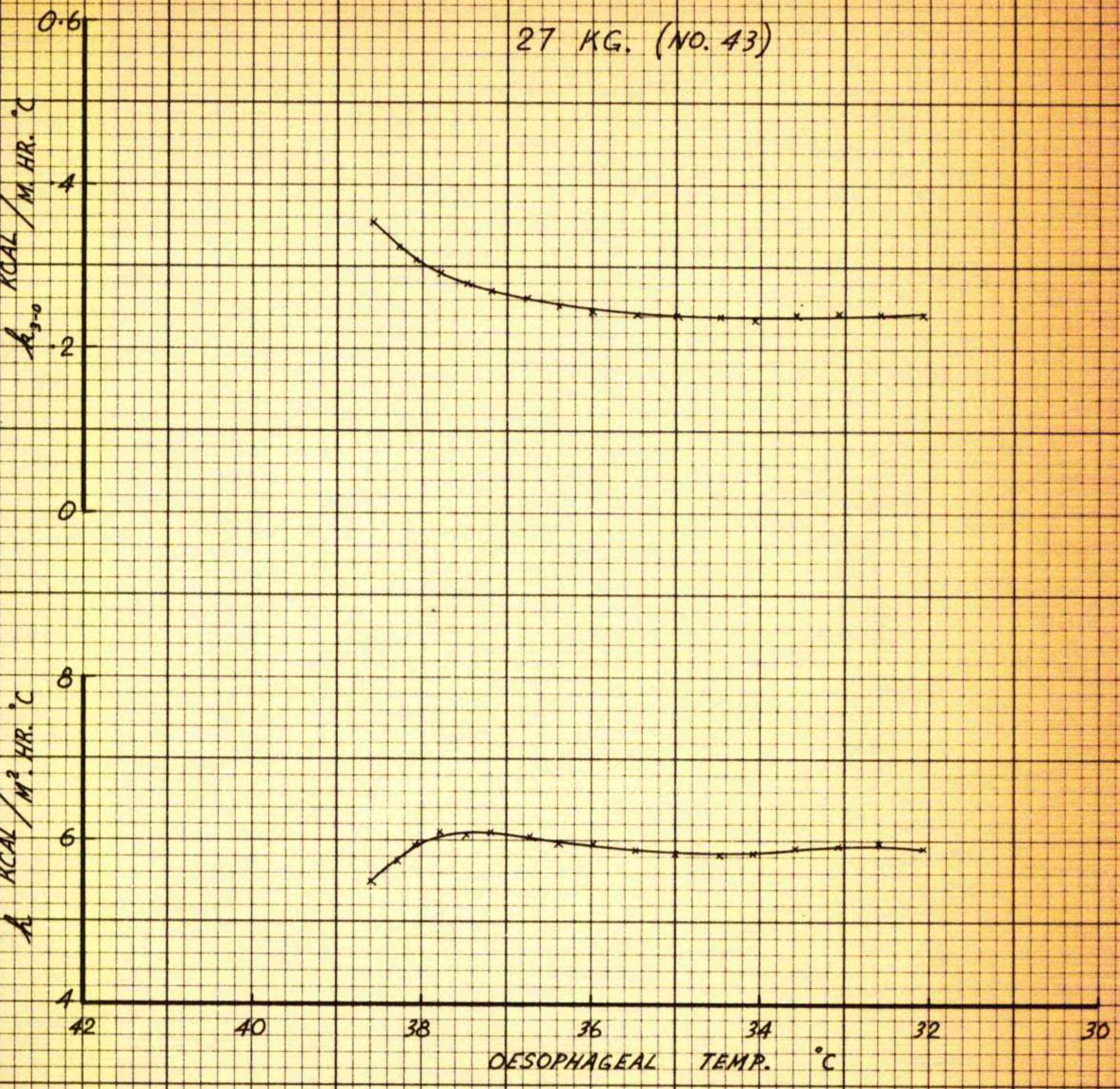


FIG. 55 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (h) OF THE DOG.

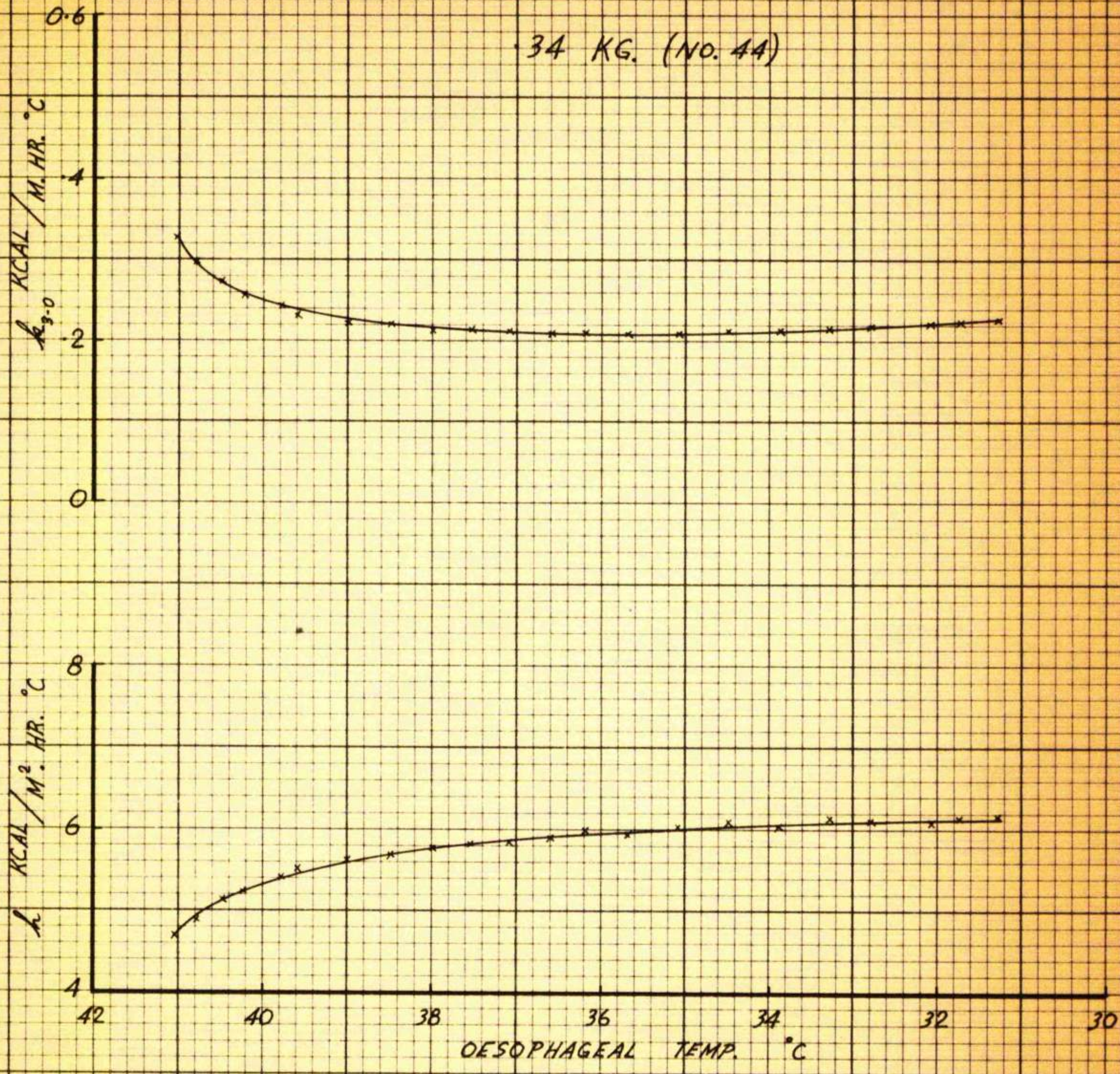


FIG. 56 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (h) OF THE DOG.

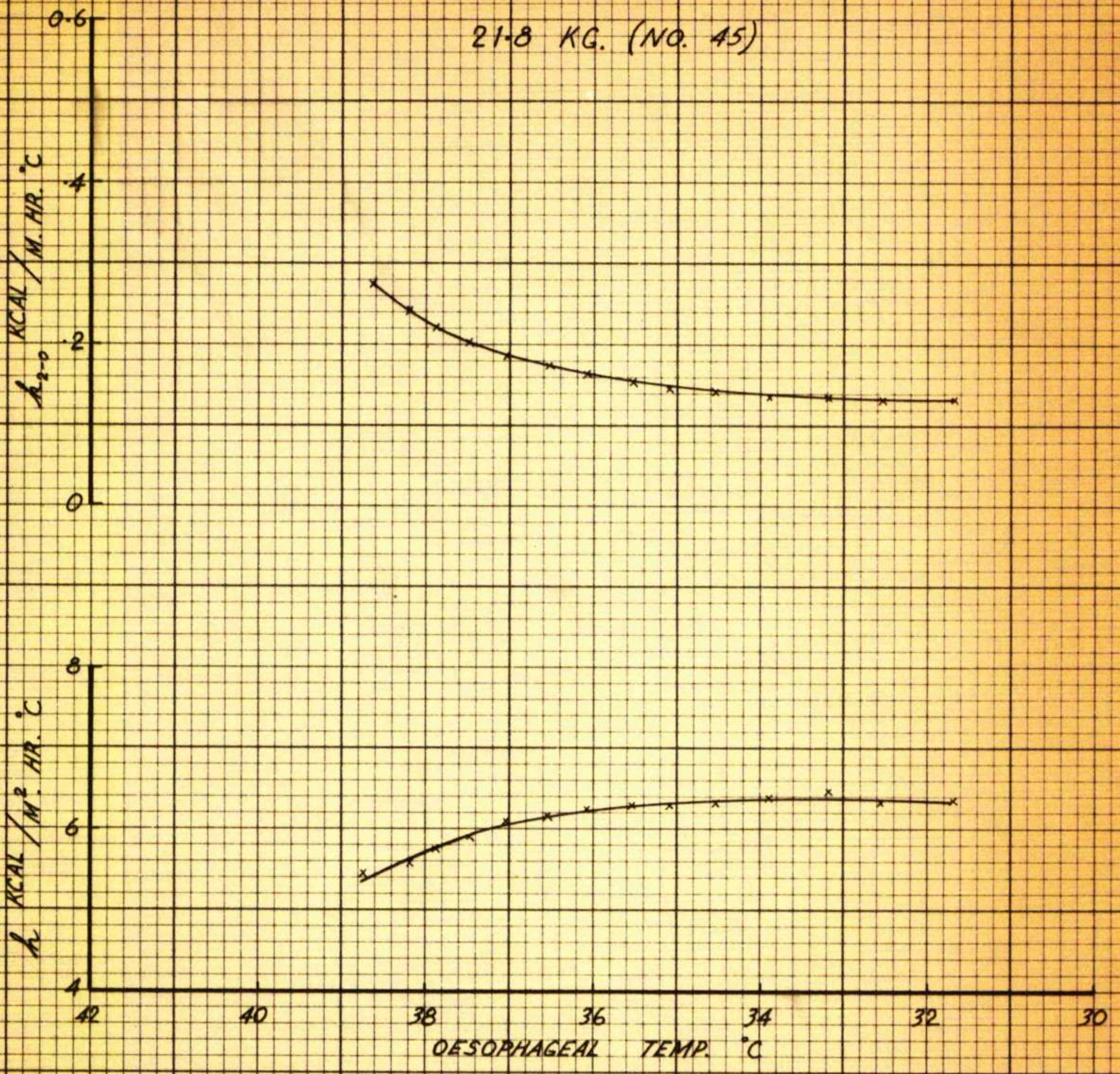


FIG. 57 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (h) OF THE DOG.

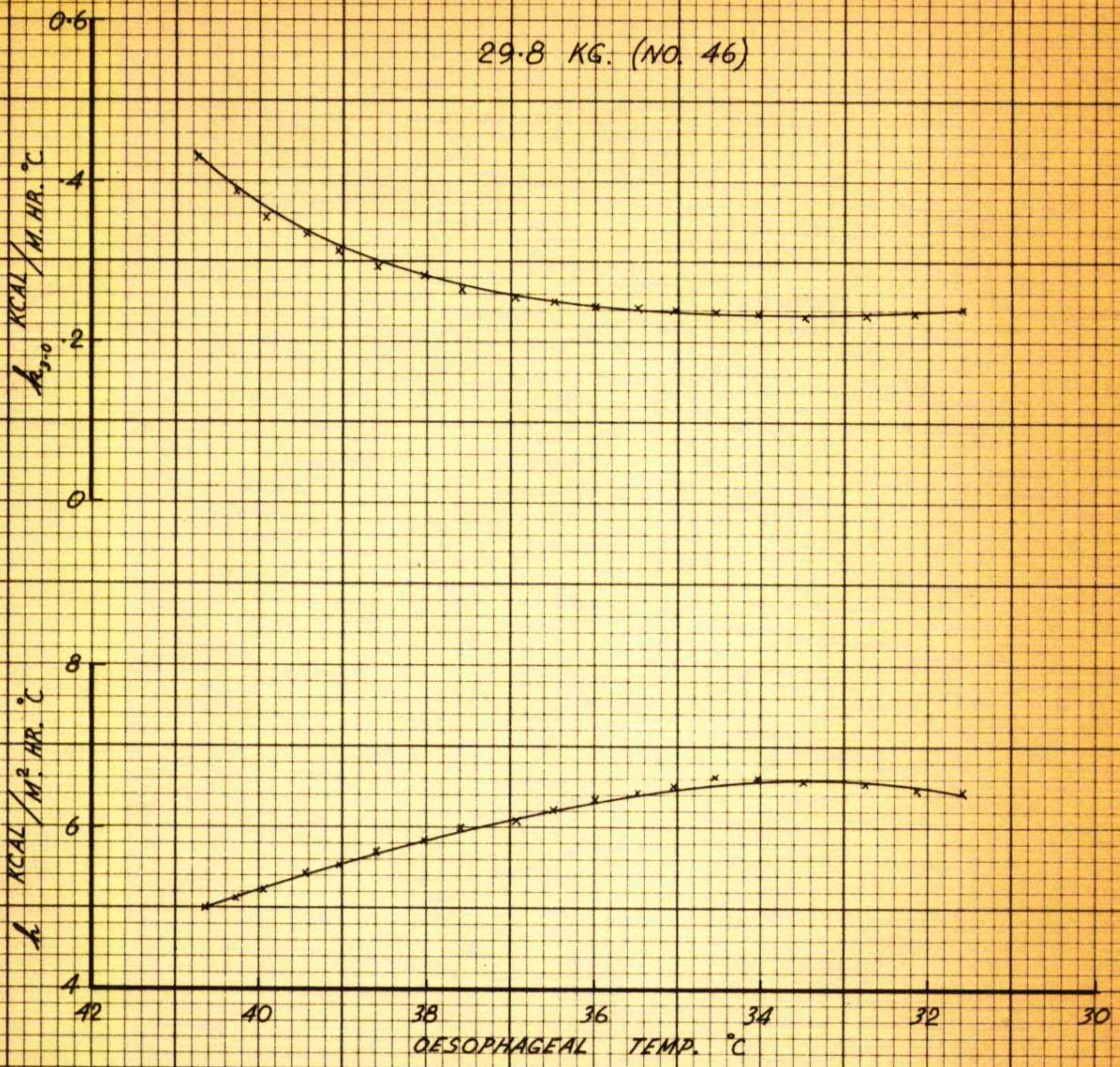


FIG. 58 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (h) OF THE DOG.

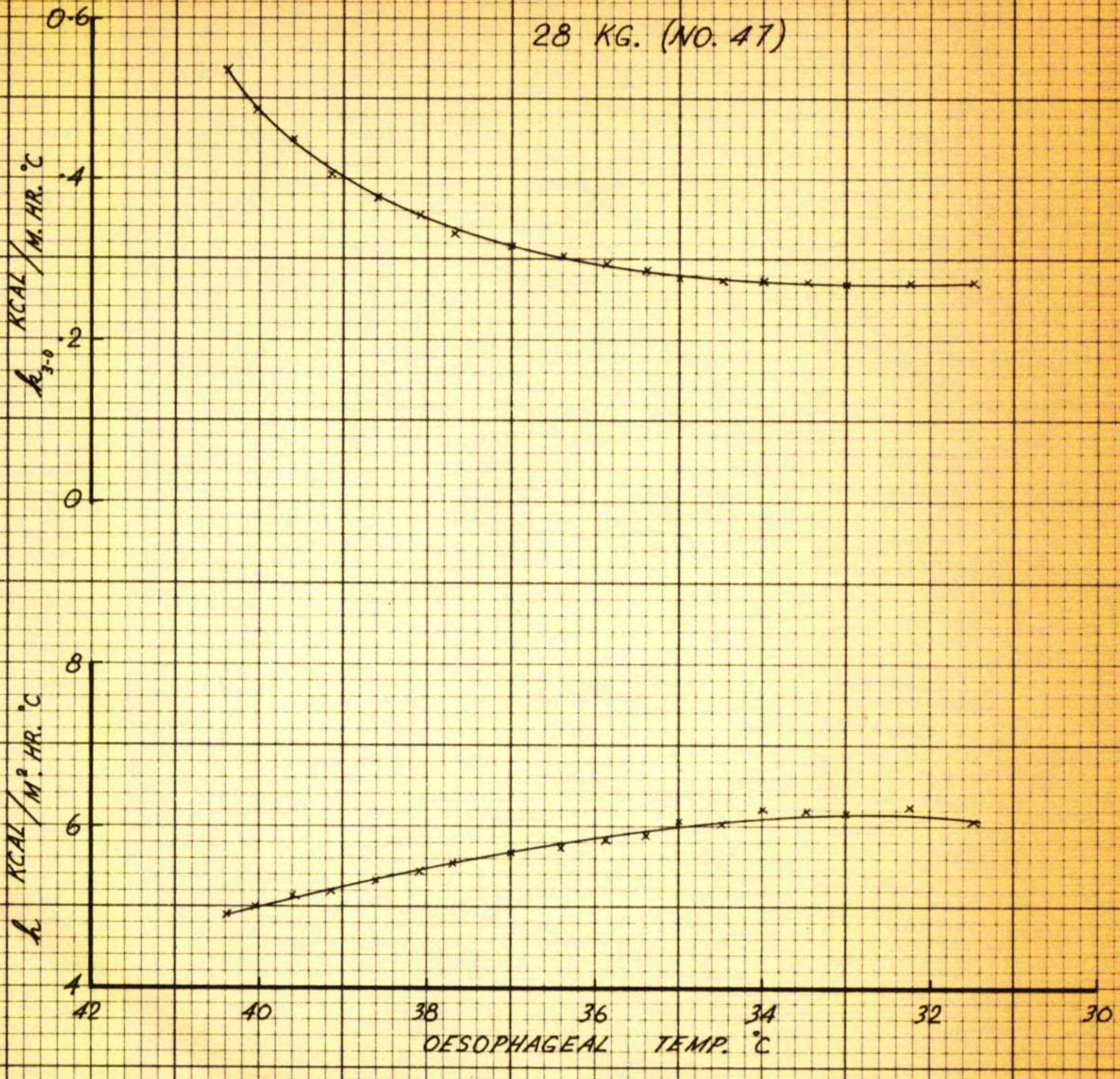


FIG. 59 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (h) OF THE DOG.

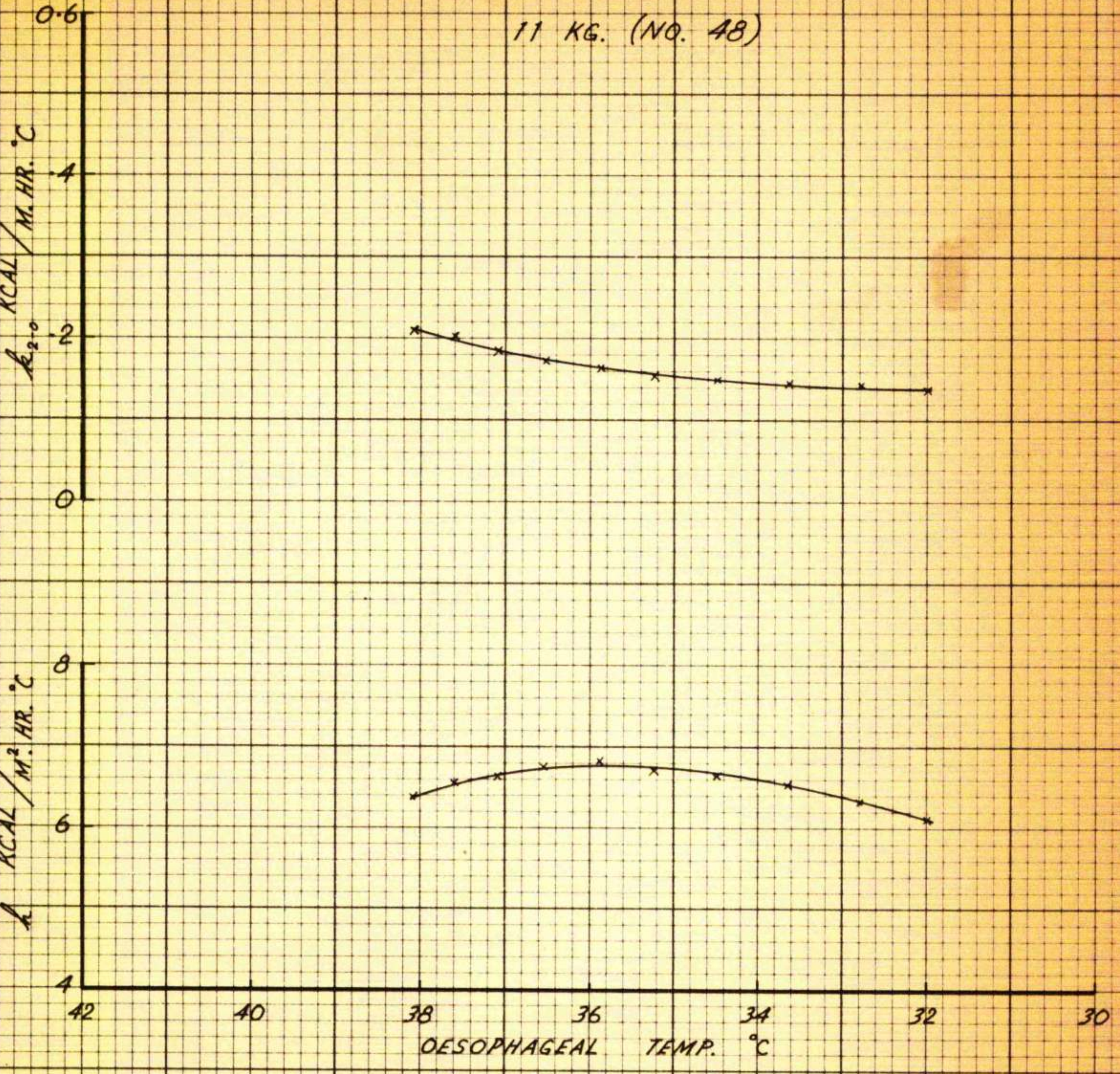


FIG. 60 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (k) OF THE DOG.

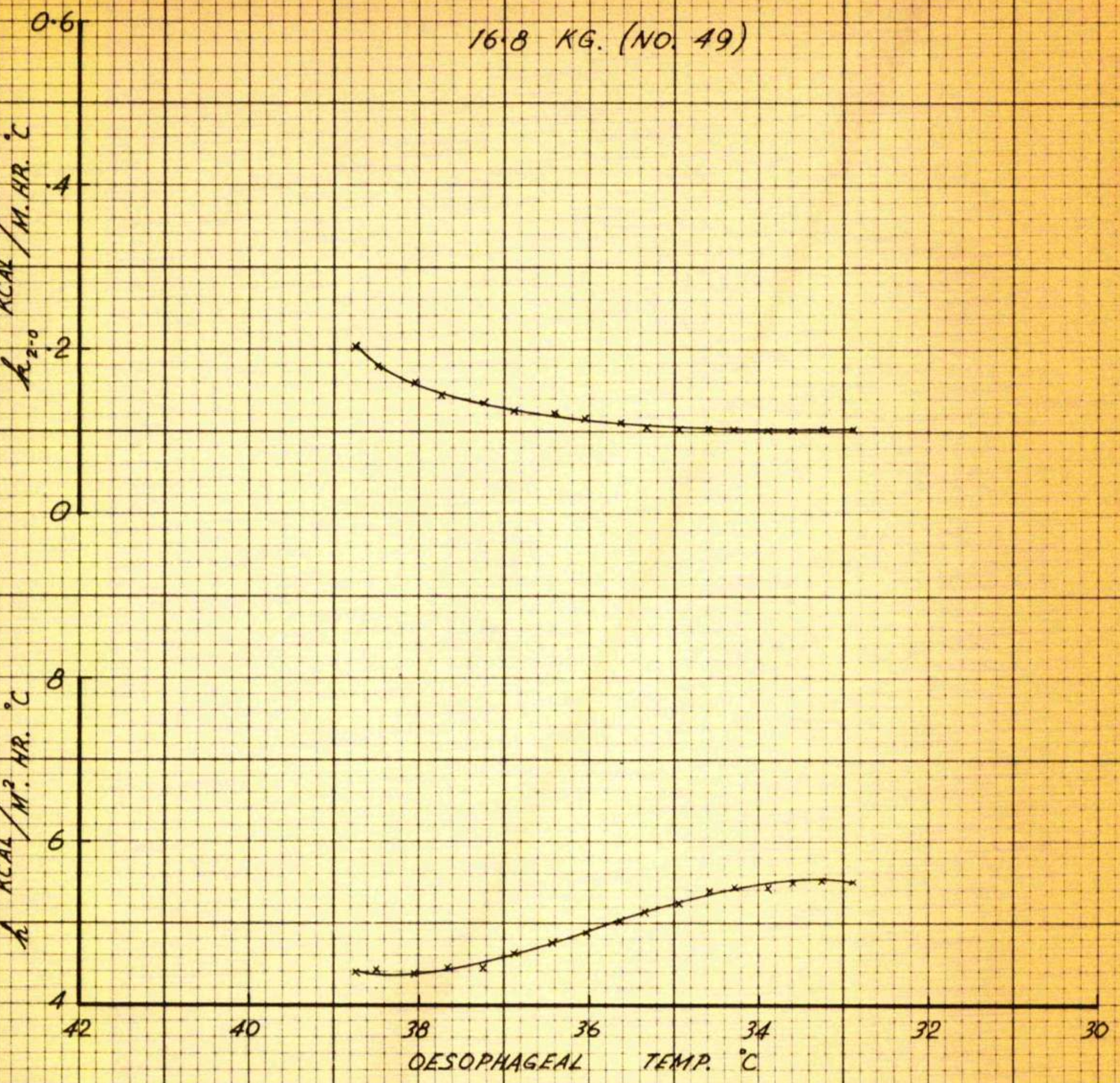


FIG. 61 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (h) OF THE DOG.

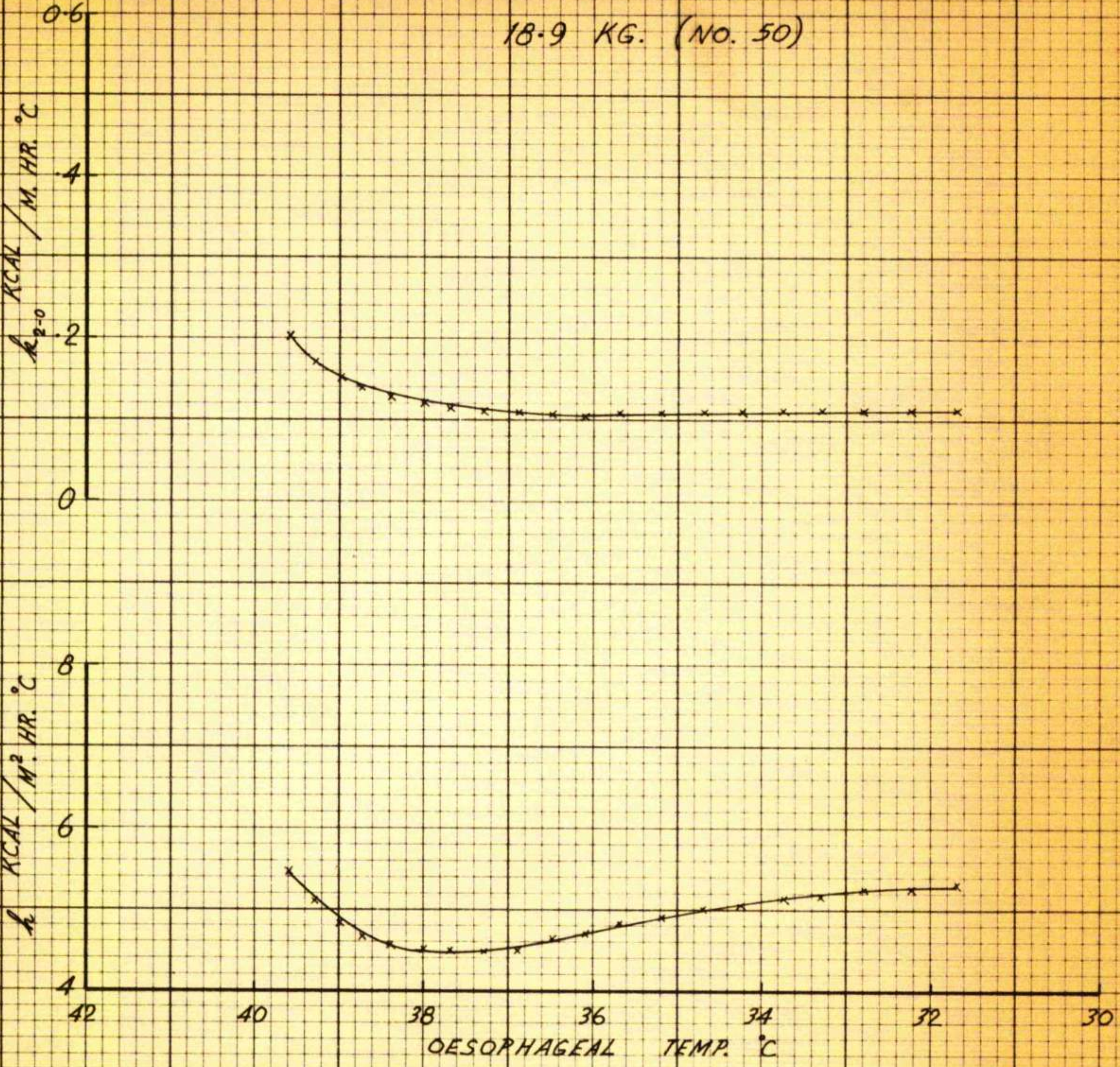


FIG. 62 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (h) OF THE DOG.

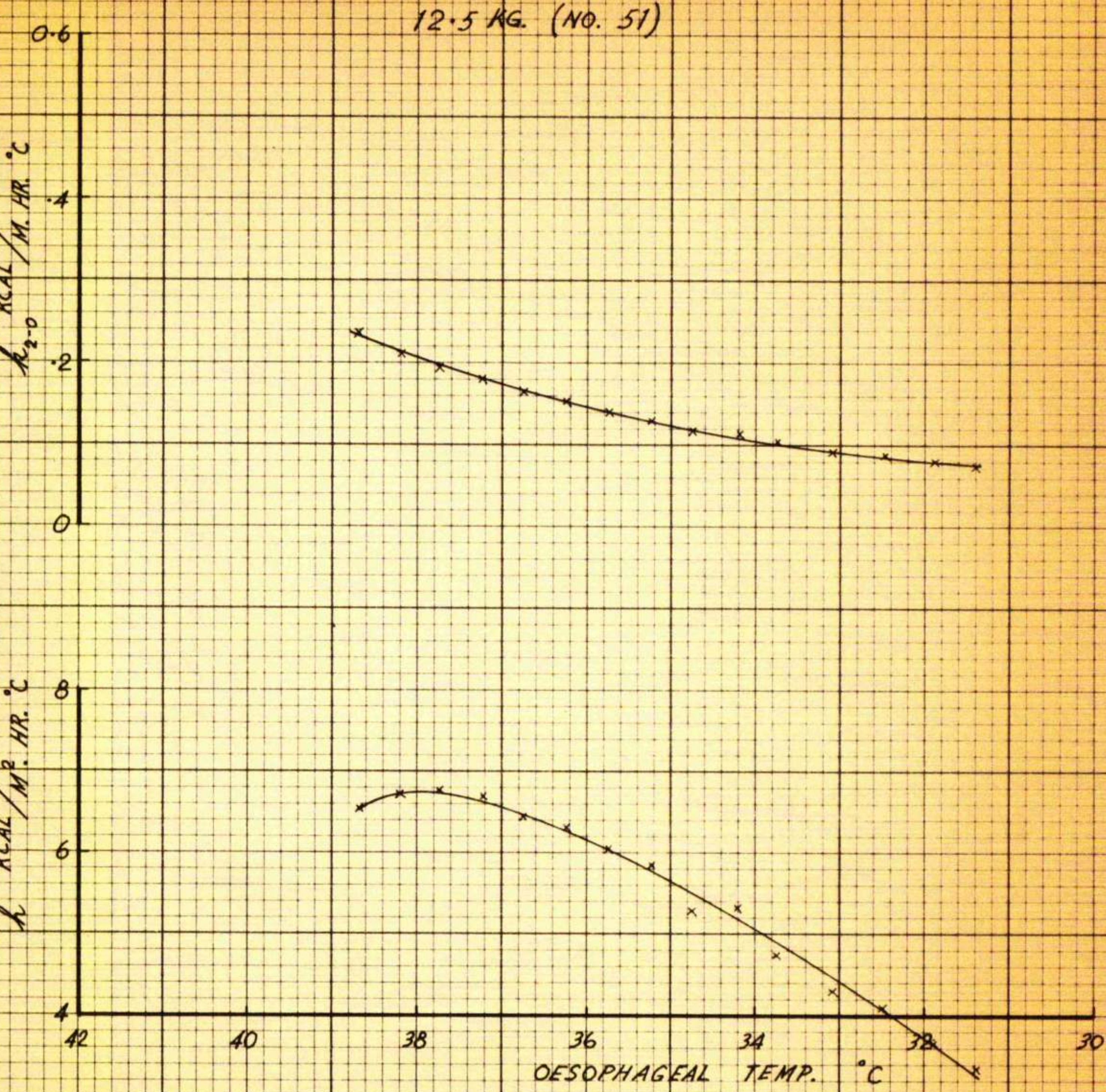


FIG. 63 THERMAL CONDUCTIVITY (k) AND CONDUCTANCE (h) OF THE DOG.

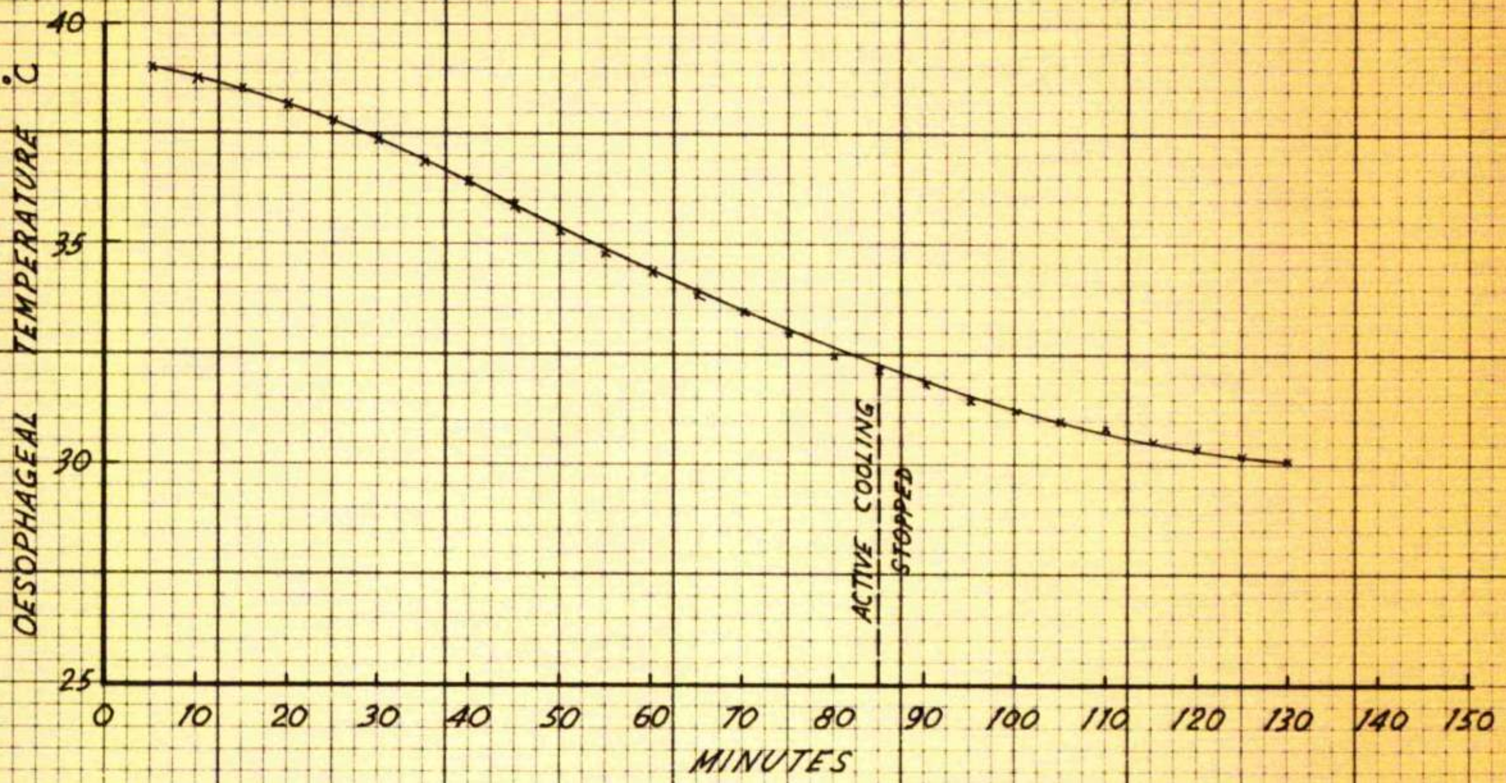


FIG. 64 GENERALISED COOLING CURVE REPRESENTING 31 DOGS OF AVERAGE WEIGHT OF 20·6 KG.

D I S C U S S I O N

Hypothermic Cabinet

Tested in experimental use, the cooling device presented has turned out to be well suited for its purpose. No serious disadvantages have been encountered. Some improvements, particularly in regard to the circulating of cold air, however, are desirable. The rate of cooling depends chiefly upon the body weight of the animal, the amount of hair shaved, and the rate of air flow and its inlet temperature. Lowering the inlet air temperature further from its present value of -10°C probably results in cold injuries of the dog, although so far in this series of experiments no damage of any kind has been recorded. The present average rate of cooling of 4.2°C/hr can be significantly increased if the capacity of the fan is increased and rendered variable, making it possible to establish a better relationship between the rate of flow and the temperature of air during the cooling phase.

The use of the nylon net stretcher as the operating table is appropriately justified by the fact that no physical handling of the animal is necessary before and after cooling.

Prediction of "After-fall"

The prediction of after-fall of the oesophageal temperature can be reliably assessed by employing the Forrester-Brown technique of surface cooling. It is seen that the cessation of cooling is independent of the instantaneous oesophageal temperature, and an average after-fall over a period of 40 minutes of 2.2°C was recorded on thirty-one dogs (Fig. 64), after that the oesophageal temperature tends to maintain at or near the desired level for a period of about an hour, when it begins to rise steadily even without re-warming, as the subject is being stabilized. An average error of 0.8% is encountered in the prediction of the oesophageal temperature in this series of experiment and represents a clinically acceptable value. Although after cooling of the subject, the after-fall persists, the only period of time when the animal as a whole is likely to lose heat is during the period of active cooling. The summation of heat extraction obtained at intervals of time is therefore the total heat loss of the dog, and this is a relevant measure for the total fall of oesophageal temperature during and after active cooling. Further development of the method, as already seen, enables the vasomotor reactions to be examined.

Pattern of Heat Extraction

The pattern of heat extraction (H kcal/hr/kg) during active cooling of the animal falls into two groups -- those which having a low rate of H (Fig. 37) and those which have a relatively high rate of H (Fig. 39) with the fall of oesophageal temperature. This is dependent on the extent to which the skin must be perfused to lose heat, since blood is the principal carrier mechanism for heat exchange. The desired final temperature is solely determined by the amount of heat which has been given up by the subject. Metabolic heat generation is allowed for in determining the value of the cabinet constant. To compare heat extraction with and without metabolic heat production results modified from Keller (1956) have been utilized. As the heat debt is equal to the heat extraction less the metabolic heat production, the former would equal exactly the latter if the dog's metabolic heat production ceased. Utilizing this in conjunction with Keller's results, Figs. 37-40 have been derived, and provide a means of comparing the amount of heat extraction of the dog.

Rate of Heat Flow

The rate of heat flow from the body during surface cooling is mainly dependent on the peripheral blood flow which in turn depends on the degree of vaso-dilatation, hence the value of the air temperature difference (t_d - t_{de}) is an indication of the state of vaso-dilatation. In the presence of full vaso-dilatation a high temperature difference is consistently maintained. The readings fall rapidly or vary at random where some vaso-constriction persists. Three cases of heat extraction in a random fashion are reported and presented in Fig. ? It can be seen that the rate of cooling of these three dogs is comparatively low, due chiefly to the fact that the peripheral blood vessels dilate only reluctantly to give up heat, this is the explanation of Lewis' "hunting" concept that vaso-constriction followed vaso-dilatation, caused by prolonged exposure of body to a cold medium. Supporting evidence by Burton & Edholm (1955) indicates that changes in the skin temperature are related to alterations in the peripheral blood flow, and to the variations of heat extraction in a random fashion. However, this state of affair does not influence the characteristics of the steady fall of the oesophageal temperature.

Muscle Temperature Gradients

Of the eleven dogs reported for muscle temperature gradient investigations, before cooling applied, there is a gradient of about 10°C between the skin and the environment, and the initial gradients among subcutaneous, muscle and oesophageal temperatures are relatively large. During the cooling process, the skin temperature falls drastically whereas the muscle and subcutaneous tissue and oesophageal temperatures tend to approach one another, steadily reducing the temperature gradients. Gradually then, the amount of heat extraction must be decreased.

However, the oesophageal temperature is still significantly higher than the others. At the end of active cooling, the skin temperature rises very rapidly to its original value, about 10°C above the ambient temperature, whereas the other temperatures continue to fall, though at different rates. Here the tempera:ture gradients among the subcutaneous, muscle and oesophagus fall into two categories -- one having a positive gradient (temperature curves not intercepting one another), the other a negative value (curves intercepting one another).

It is of interest to note in general, that the vectors of heat loss from the animal include radiation, evaporation, con:vection and conduction. However, with surface cooling, radia:tion and evaporation are of little consequence. Conduction and convection are the prime factors in heat transport from the subject to its environment during the process of active cooling. After the period of hypothermia, while the animal is being stab:ilized, radiation assumes a significant role. In the operating room, the intensive therapy unit, heating systems and lights create a re-warming environment. This may account for the fact that in dogs No. 45-9 & 51 (Figs. 46-50 & 52) negative temp:erature gradients are recorded, i.e. during the stabilization period, the oesophageal temperature which was initially the high:est of temperatures before and during cooling, is now the low:est of temperatures. It is also probable that the negative temperature gradients observed can be due to variations in the temperature of different areas of the skin of the thigh of the dog. Pennes (1948) found that in comfortable environments the temperature within the same small area of the skin of the human forearm varied an average of 0.73°C. It may be that at lower temperatures of the skin and/or environment, these differences are of a greater magnitude. Since the thermocouple used to mea-:sure the temperature of the skin of the thigh is not usually or easily located directly above the thermocouple probes which measure the subcutaneous and muscle temperatures, variations in local skin temperature can account for the apparent negative gradients.

It can be visualized that if the temperature gradients among subcutaneous, muscle and oesophagus were encouraged to increase during the period of active cooling, in spite of the reduced heat production at low temperature, an increased flow of heat from the core to the periphery for loss to the environment would be the result. However, it is anticipated that, at lowered body temperatures, a decreased heat loss is necessary to maintain thermal balance. This accounts for the collectively gradual re-:duction of the value of the thermal conductivity coefficient k with the fall of the oesophageal temperature which represents the core temperature. This leads to the conclusion that the flow of heat depends more on conductivity, the convection of heat playing a relatively minor role as a result of the reduction in blood flow at low tissue temperature.

CONCLUSION

From the foregoing experiments it is seen that the further development of the Forrester-Brown technique of surface cooling permits an effective and controlled administration of hypother-:mia. This method appears most suitable for large experimental animals including man as it eliminates, through the associated predictive technique, any possible overshoot of the after-fall of the core temperature. Further, the subject is easy to handle and be cared for, no untoward side effect having been observed during or after the period of cooling.

The heat extraction from the animal is independent of the in-:stantaneous oesophageal temperature and found to decrease grad-:ually with time. This obeys Newton's law of cooling, since the temperature difference between the skin and the environment gradually decreases as hypothermia progresses.

The presence of vaso-constriction tends to cause the rate of heat extraction to fluctuate, and correspondingly tends to re-:duce the rate of cooling of the subject. However, it does not seem to alter the very smooth pattern of the cooling curves of the oesophagus.

The muscle temperature gradients tend to decrease as hypother-:mia progresses. Also the thermal conductivity of the muscle re-:duces, this accounts for the gradual decrease of heat extraction necessary to maintain heat balance. Convective heat flow seems to play only a minor role and conduction is significantly the mechanism of heat loss in the process of surface cooling.

Potential extension of the work in the future may suitably be directed to the development of a mathematical model of the subject for heat regulation and transfer during both normothermia and hypothermia and to the establishment of a mean body temperature.

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APPENDIX I

Air Flow Measurements

Table 2

Aperture number	Length L in	Width b in	Area a in^2	h in	$\sqrt{h}$ $in^{\frac{1}{2}}$
1	7.48	0.275	2.0407	2.825	1.680
				2.821	1.677
2	7.48	0.255	1.8934	2.821	1.678
				2.819	1.676
3	7.46	0.265	1.9618	2.818	1.675
				2.810	1.674
4	7.48	0.235	1.7459	2.810	1.674
				2.823	1.679
5	7.48	0.275	2.0407	2.821	1.678
				2.821	1.678
6	7.48	0.273	2.0380	2.819	1.676
				2.818	1.675
7	7.48	0.275	2.0407	2.810	1.674
				2.818	1.675
	Total		15.5071 in^2 (0.1076 ft^2)		23.469 $in^{\frac{1}{2}}$

$$\sigma = \frac{P_1 \, T_o}{P_o \, T_1} = \frac{76 \times (273 + 15.3)}{76 \times (273 - 10.0)} = 1.089$$

k?

$$\sqrt{\sigma} = 1.043$$

$$V_m = \frac{66.2}{\sqrt{\sigma}} \left(\sqrt{h_{1a}} + \sqrt{h_{1b}} + \sqrt{h_{2a}} + \sqrt{h_{2b}} + \sqrt{h_{3a}} + \sqrt{h_{3b}} + \sqrt{h_{4a}} + \sqrt{h_{4b}} + \sqrt{h_{5a}} + \sqrt{h_{5b}} + \sqrt{h_{6a}} + \sqrt{h_{6b}} + \sqrt{h_{7a}} + \sqrt{h_{7b}} \right) \frac{k}{n} \quad \text{ft/sec}$$

$$= \frac{66.2}{\sqrt{\sigma}} \left(\sqrt{h_t} \right) \frac{k}{n}$$

$$= \frac{66.2}{1.043} \times 23.469 \times \frac{0.05}{14}$$

$$= 5.31 \text{ ft/sec}$$

$$Q = V_m \, (n \, a) = V_m \, A$$

$$= 5.31 \times 0.1076 \quad \text{ft}^3/\text{sec}$$

$$\rho = \left(0.00237 \times \frac{273 + 15.3}{273 - 10.0} \times \frac{76}{76}\right) \quad \text{lb-sec}^2/\text{ft}^4$$

not unit of density

air mass flow $M = Q \, g \, \rho$

$$= 4.773 \times 10^{-2} \quad \text{lb/sec}$$

$$= 2.17 \times 10^{-2} \quad \text{kg/sec}$$

$$M \, ds = M \times 5$$

$$= 6.505 \text{ kg/5 min}$$

according to list of symbols on p.4

ρ = density of subject

APPENDIX II

Electrical Analogue

The electrical equivalent of the transient heat transfer system of the body is the discharge of an electrical condenser in a circuit with a pure resistance. The electrical equation is

$$\frac{E_s}{E_o} = e^{-\frac{s}{RC}}$$

where E_o = potential at time zero, $E = E(s)$

R = resistance

C = electrical capacitance

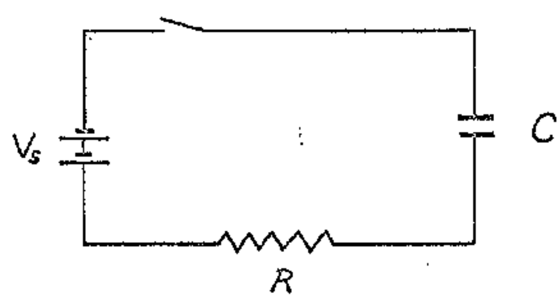
Laboratory Model:

accumulator $V_s = 12$ v. R = 400 KΩ C = 12 μF

$$RC = 400 \times 10^3 \times 12 \times 10^{-6}$$

$$= 4.8 \text{ sec}$$

Charging:



s = 10 sec

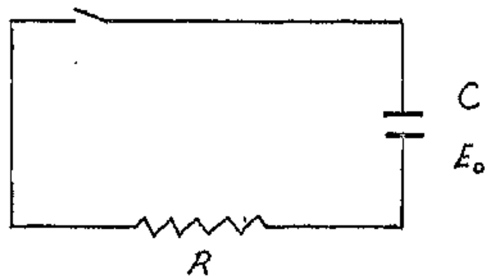
$$V_c = V_s \left(1 - e^{-\frac{s}{R\,C}}\right) \text{ v.}$$

$$= 12 \left(1 - e^{-\frac{10}{RC}}\right)$$

$$= 10.5 \text{ v.}$$

Discharging:

$$E_o = V_c = 10.5 \text{ v.}$$



$$\frac{E_s}{E_o} = e^{-\frac{s}{R\,C}} = e^{-\frac{s}{4.8}}$$

or

$$\log_e \frac{E_s}{E_o} = -\frac{s}{4.8}$$

Table 3 Electrical Analogue

s sec	R = 400 K ohm, $E_o = V_c = 10.5$ v.		R = 200 K ohm, $E_o = V_c = 11.8$ v.	
	E_s v.	E_s/E_o	E_s v.	E_s/E_o
0	10.5000	1.0000	11.8000	1.0000
0.5	9.4400	0.8990	9.6000	0.8130
1.0	8.5000	.8100	7.8000	.6610
1.5	7.6600	.7300	6.3200	.5350
2.0	6.9000	.6570	5.1300	.4350
2.5	6.2200	.5650	4.1800	.3540
3.0	5.6100	.5100	3.3800	.2860
3.5	5.0600	.4820	2.7400	.2320
4.0	4.5500	.4330	2.2200	.1880
4.5	4.1100	.3920	1.8120	.1530
5.0	3.7000	.3520	1.4620	.1240
5.5	3.3300	.3170	1.1970	.1010
6.0	3.0000	.2860	0.9700	.0820
7.0	2.4400	.2320	.6380	.0540
8.0	1.9800	.1890	.4190	.0355
9.0	1.6100	.1530	.2780	.0236
10.0	1.3100	.1250	.1830	.0155
11.0	1.0630	.1010	.1200	.0102
12.0	0.8610	.0820	.0790	.0067
13.0	0.6980	.0665	.0530	.0045
14.0	.5650	.0538	.0344	.0029
15.0	.4580	.0437	.0150	.0013
16.0	.3770	.0359		
17.0	.3040	.0289		
18.0	.2460	.0234		
20.0	.1620	.0154		
22.0	.1080	.0108		
24.0	.0710	.0068		
26.0	.0464	.0044		
28.0	.0310	.0030		
30.0	.0203	.0019		

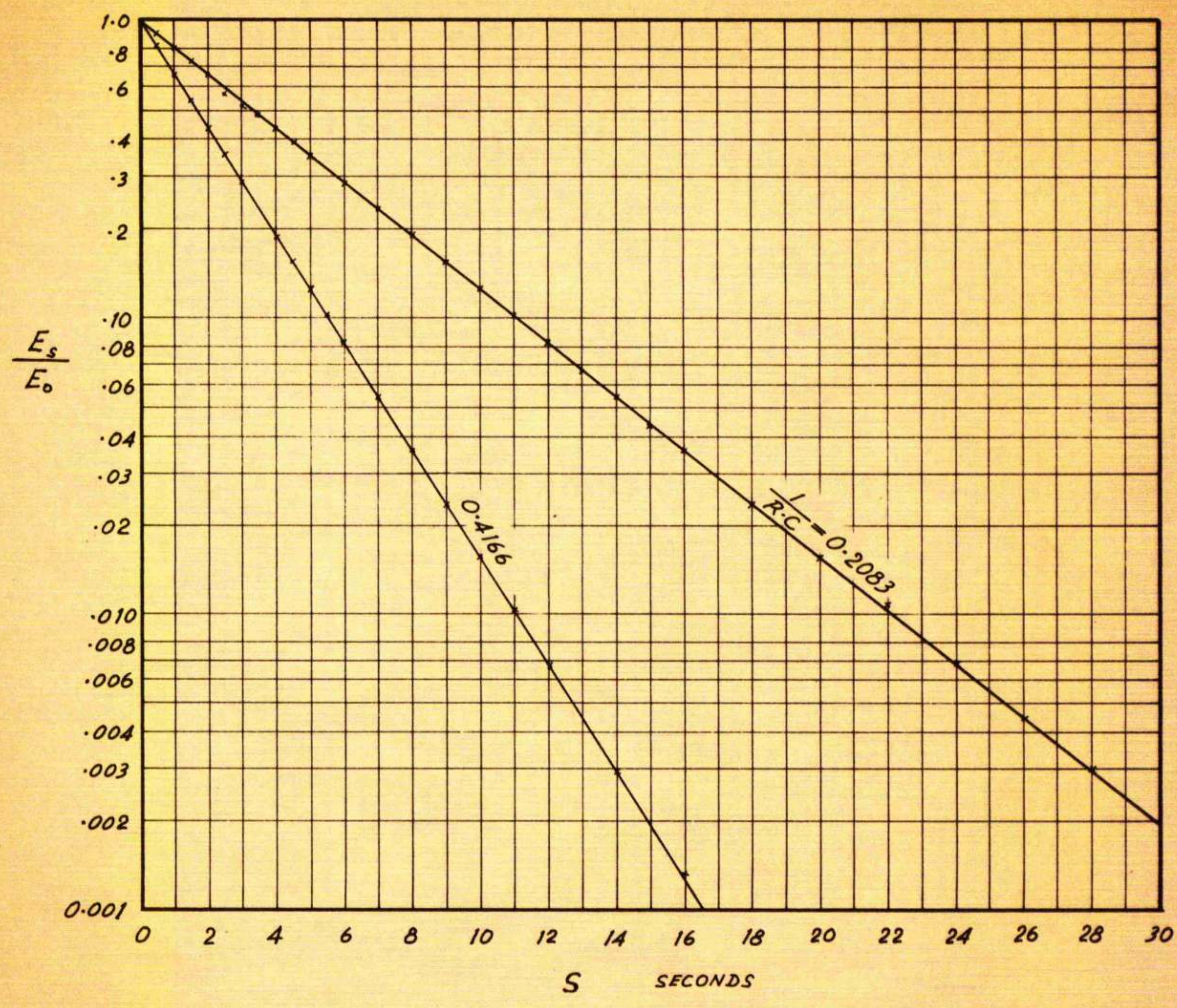


Fig. 65 Graph of $\log_e E_s/E_o$ against time s seconds, giving slope of 1/RC.

A P P E N D I X   III

Heat Transfer Equations

In radial heat flow of a cylinder, the area normal to the direction of flow increases with the radius. The heat flowing per unit length of the cylinder may be written

$$Q = 2\pi r q = -k \frac{dt}{dr} 2\pi r \qquad \text{Eq. 17}$$

where dt/dr is the temperature gradient at radius r.

From Eq. 17 above

$$Q \frac{dr}{r} = -2\pi k \, dt$$

Intergrating

$$Q \int_{r_i}^{r_s} \frac{dr}{r} = -2\pi k \int_{t_i}^{t_s} dt$$

$$Q \, \text{long}_e \frac{r_s}{r_i} = -2\pi k (t_s - t_i) \qquad \text{Eq. 18}$$

$$Q = -\frac{2\pi k (t_s - t_i)}{\log_e \frac{r_s}{r_i}} \qquad \text{Eq. 19}$$

If A_m is the mean surface area, Eq. 18 may be written

$$Q = k A_m \frac{t_i - t_s}{r_s - r_i} = -k A_m \frac{t_s - t_i}{r_s - r_i} \qquad \text{Eq. 20}$$

and let this surface be associated with a value r_m of the radius so that

$$Q = -k \, 2\pi r_m \frac{t_s - t_i}{r_s - r_i} \qquad \text{Eq. 21}$$

From Eqs. 19 & 21

$$\frac{r_m}{r_s - r_i} = \frac{1}{\log_e \frac{r_s}{r_i}}$$

or $$r_m = \frac{r_s - r_i}{\log_e \frac{r_s}{r_i}} \quad \& \quad A_m = \left(\frac{r_m}{r_s}\right)^2 A_s$$

hence $$Q = - k \, A_m \frac{t_s - t_i}{r_s - r_i}$$

also $$q = - k \frac{dt}{dr} = h \, (t_s - t_a) \qquad \text{Eq. 22}$$

i.e. the rate of conduction of heat to the surface through the tissue equals the rate of heat transfer from the surface to the environment.

$$Q = - k \, A_m \left(\frac{t_s - t_i}{r_s - r_i}\right) = - h \, A_s \, (t_a - t_s) \qquad \text{Eq. 23}$$

Heat loss by cabinet $= M \, C_p \, t_{de}$

heat gained by air $= M \, C_p \, t_d$

heat loss by dog + heat loss by cabinet = heat gained by air

i.e. $$Q + M \, C_p \, t_{de} = M \, C_p \, t_d$$

$$Q = M \, C_p \, (t_d - t_{de}) = - k \, A_m \left(\frac{t_s - t_i}{r_s - r_i}\right) = - h \, A_m \, (t_a - t_s)$$

$$= W \, C_d \, d \qquad \text{Eq. 24}$$

The rate of heat loss is not constant, so that the total heat loss over a period would be the integral of the heat loss rate, i.e. Heat loss over a period of s minutes

$$= \int_0^s Q \, ds$$

= area under the curve of Q to a base of time.

This area can be evaluated approximately by taking the summation $\sum Q \, ds$ where ds is a finite increment of time, conveniently chosen.

Hence $$\sum Q \, ds = \sum W \, C_d \, d$$

$$= \sum M \, C_p \, (t_d - t_{de}) \, ds$$

or $$W \, C_d \sum d = M \, C_p \, ds \sum (t_d - t_{de})$$

i.e. $$\sum (t_d - t_{de}) = \frac{W \, C_d \sum d}{M \, C_p \, ds}$$

$$= \frac{W \, C_d \, D}{M \, C_p \, ds} = \frac{W \, D}{K}$$

∴ Running total temperature difference = $\dfrac{\text{dog's weight x temperature depression}}{\text{cabinet constant}}$

$$K = \frac{W \, D}{\sum (t_d - t_{de})} \qquad \text{Eq. 25}$$

Table 4 Temperature Difference (t_{de} °C) between inlet and outlet air when cabinet empty

Minutes	t_{de} °C at room temperatures of 19°C	20°C	21°C	22°C	23°C	24°C
5	5.24	5.57	5.90	6.23	6.55	6.88
10	6.47	6.63	6.78	6.95	7.10	7.27
15	6.57	6.73	6.90	7.07	7.23	7.38
20	6.37	6.50	6.65	6.79	6.93	7.06
25	6.19	6.32	6.44	6.57	6.69	6.82
30	6.06	6.17	6.28	6.38	6.50	6.60
35	5.94	6.05	6.15	6.25	6.35	6.45
40	5.80	5.93	6.03	6.13	6.22	6.32
45	5.73	5.85	5.93	6.02	6.10	6.20
50	5.64	5.74	5.83	5.92	6.00	6.10
55	5.56	5.65	5.73	5.82	5.90	5.98
60	5.50	5.57	5.65	5.73	5.80	5.87
65	5.43	5.50	5.57	5.65	5.72	5.78
70	5.37	5.44	5.50	5.58	5.64	5.71
75	5.31	5.38	5.45	5.53	5.58	5.65
80	5.27	5.34	5.40	5.47	5.53	5.60
85	5.23	5.38	5.35	5.43	5.49	5.57
90	5.20	5.26	5.33	5.39	5.46	5.53
95	5.17	5.24	5.30	5.37	5.44	5.50
100	5.16	5.22	5.29	5.35	5.41	5.47
105	5.16	5.22	5.28	5.34	5.40	5.46
110	5.16	5.22	5.28	5.34	5.40	5.46
120	5.16	5.22	5.28	5.34	5.40	5.46

Table 5 Dog No. 4, W = 14.5 kg, room temp. 21°C

Minutes	Oeso. temp. °C	t_d °C	t_{de} °C	$(t_d - t_{de})$ °C
5	36.30	11.87	6.55	5.32
10	35.95	13.88	7.10	6.78
15	35.47	13.50	7.23	6.27
20	34.90	13.20	6.93	6.27
25	34.30	12.87	6.69	6.18
30	33.70	12.33	6.50	5.83
35	33.10	11.80	6.35	5.45
40	32.62	11.00	6.22	4.78
45	32.20	(active cooling stopped)		
50	31.38			
55	31.55			
60	31.38			
65	31.30			
70	31.30			

Table 6 Dog No. 5, W = 10 kg, room temp. 23°C

Minutes	Oeso. temp. °C	t_d °C	t_{de} °C	$(t_d - t_{de})$ °C
5	37.12	11.00	6.55	4.45
10	36.80	12.30	7.10	5.20
15	36.50	12.55	7.23	5.32
20	36.15	11.70	6.93	4.77
25	35.60	11.15	6.69	4.46
30	34.90	10.65	6.50	4.15
35	34.05	10.25	6.35	3.90
40	33.30	9.82	6.22	3.60
45	32.70	9.40	6.10	3.30
50	32.15	8.98	6.00	2.98
55	31.65	8.60	5.90	2.70
60	31.22			
65	30.80			
70	30.40			
75	30.14			
80	29.90			
85	29.70			
90	29.64			
95	29.64			

Table 7 Dog No. 6, W = 16 kg, room temp. 22°C

Minutes	Oeso. temp. °C	t_d °C	t_{de} °C	$(t_d - t_{de})$ °C
5	36.54	14.63	6.23	8.40
10	36.22	15.05	6.95	8.10
15	35.73	15.40	7.07	8.33
20	35.25	15.00	6.79	8.21
25	34.79	14.64	6.57	8.07
30	34.14	14.34	6.38	7.96
35	33.60	14.05	6.25	7.80
40	33.10	13.78	6.13	7.65
45	32.62	13.50	6.02	7.48
50	32.20	13.28	5.92	7.36
55	31.80	13.08	5.82	7.26
60	31.40	12.94	5.73	7.21
65	31.00			
70	30.60			
75	30.30			
80	30.15			
85	30.05			
90	30.00			
95	30.00			

Table 8 Dog No. 7, W = 21 kg, room temp. 22°C

Minutes	Oeso. temp. °C	t_d °C	t_{de} °C	$(t_d - t_{de})$ °C
5	36.60	10.20	6.23	3.97
10	36.50	12.45	6.95	5.50
15	36.34	12.62	7.07	5.55
20	36.00	12.35	6.79	5.56
25	35.64	11.90	6.57	5.33
30	35.26	11.50	6.38	5.12
35	34.85	11.14	6.25	4.89
40	34.42	10.84	6.13	4.71
45	33.93	10.60	6.02	4.58
50	33.35	10.40	5.92	4.48
55	32.80	10.19	5.82	4.37
60	32.30	9.97	5.73	4.24
65	31.84	9.75	5.65	4.10
70	31.45	9.53	5.58	3.95
75				
80				
85				
90				
95				

Table 9 Dog No. 8, W = 14.3 kg, room temp. 23°C

Minutes	Oeso. temp. °C	t_d °C	t_{de} °C	$(t_d - t_{de})$ °C
5	38.05	10.16	6.55	3.61
10	37.71	11.90	7.10	4.80
15	37.44	12.72	7.23	5.49
20	37.10	12.15	6.93	5.22
25	36.60	11.77	6.69	5.08
30	36.08	11.62	6.50	5.12
35	35.60	11.53	6.35	5.18
40	35.17	11.46	6.22	5.24
45	34.67	11.41	6.10	5.31
50	34.10	11.37	6.00	5.37
55	33.45	11.32	5.90	5.42
60	32.90	11.27	5.80	5.47
65	32.40	11.23	5.72	5.51
70	31.80			
75	31.40			
80	31.00			
85	30.70			
90	30.40			
95	30.20			
100	30.20			

Table 10 Dog No. 9, W = 26 kg, room temp. 24°C

Minutes	Oeso. temp. °C	t_d °C	(t_d - t_{de}) °C	H kcal/hr/kg
5	41.30	11.00	4.12	2.97
10	41.18	13.40	6.13	4.41
15	40.83	14.64	7.26	5.21
20	40.42	14.28	7.22	5.20
25	39.95	13.92	7.10	5.13
30	39.46	13.62	7.02	5.05
35	38.92	13.35	6.90	4.96
40	38.36	13.12	6.80	4.90
45	37.85	12.90	6.70	4.82
50	37.42	12.78	6.68	4.80
55	37.05	12.75	6.77	4.87
60	36.77	12.75	6.88	4.95
65	36.42	12.90	7.12	5.12
70	36.10	12.93	7.22	5.20
75	35.64	12.97	7.32	5.26
80	35.30	12.90	7.30	5.25
85	34.95	13.20	7.63	5.50
90	34.50	13.12	7.59	5.46
95	34.08	12.97	7.47	5.38
100	33.65	12.97	7.50	5.40
105	33.18	12.72	7.26	5.22
110	32.70	13.20	7.74	5.57
115	32.20	13.50	8.04	5.78
120	31.84	13.50	8.04	5.78
125	31.50	13.50	8.04	5.78
130	31.10			
135	30.75			
140	30.48			
145	30.20			
150	29.93			
155	29.73			
160	29.73			

Table 11 Dog No. 10, W = 37 kg, room temp. 21°C

Minutes	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$ °C	H kcal/hr/kg
5	41.44	12.56	6.66	3.37
10	41.30	15.46	8.68	4.39
15	41.20	15.60	8.70	4.41
20	41.02	15.50	8.85	4.48
25	40.70	15.40	8.96	4.53
30	40.40	15.20	8.92	4.51
35	40.05	14.92	8.77	4.43
40	39.60	14.60	8.57	4.33
45	39.18	14.36	8.43	4.27
50	38.78	14.10	8.27	4.18
55	38.34	13.83	8.10	4.10
60	37.91	13.63	7.98	4.04
65	37.46	13.50	7.93	4.01
70	37.01	13.38	7.88	3.99
75	36.60	13.28	7.83	3.96
80	36.11	13.13	7.73	3.91
85	35.46	13.08	7.73	3.91
90	34.88	13.02	7.69	3.89
95	34.22	13.00	7.70	3.89
100	33.64	13.00	7.71	3.90
105	33.10	13.00	7.72	3.90
110	32.44	13.00	7.72	3.90
115	31.88			
120	31.47			
125	31.10			
130	30.80			
135	30.56			
140	30.30			
145	30.19			
150	30.19			

Table 12 Dog No. 11, W = 20.89 kg, room temp. 22°C

Minutes	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$ °C	H kcal/hr/kg
5	38.92	11.30	5.07	4.55
10	38.72	12.70	5.75	5.15
15	38.58	13.33	6.26	5.61
20	38.25	12.80	6.01	5.39
25	37.97	12.54	5.97	5.35
30	37.66	12.50	6.12	5.49
35	37.25	11.60	5.35	4.80
40	36.90	11.00	4.87	4.36
45	36.40	11.23	5.21	4.67
50	35.86	11.80	5.88	5.27
55	35.40	11.46	5.64	5.05
60	34.89	11.66	5.93	5.31
65	34.42	11.25	5.60	5.02
70	33.85	11.05	5.47	4.90
75	33.40	11.10	5.57	5.00
80	32.88	11.00	5.53	4.96
85	32.30	11.00	5.57	5.00
90	31.83	10.10	4.71	4.22
95	31.24			
100	30.63			
105	30.26			
110	29.80			
115	29.50			
120	29.30			
125	29.30			

Table 13 Dog No. 12, W = 23.2 kg, room temp. 22°C

Minutes	Oeso. temp. °C	t_d °C	t_{de} °C	$(t_d - t_{de})$ °C
5	40.07	11.86	6.23	5.63
10	39.83	14.56	6.95	7.61
15	39.56	15.30	7.07	8.23
20	39.30	15.14	6.79	8.35
25	38.98	14.68	6.57	8.11
30	38.70	14.36	6.38	7.98
35	38.36	14.07	6.25	7.82
40	38.00	13.79	6.13	7.66
45	37.70	13.58	6.02	7.56
50	37.32	13.35	5.92	7.43
55	36.95	13.16	5.82	7.34
60	36.57	12.97	5.73	7.24
65	36.12	12.77	5.65	7.12
70	35.70	12.60	5.58	7.02
75	35.30	12.50	5.53	6.97
80	34.85	12.40	5.47	6.93
85	34.37	12.37	5.43	6.94
90	33.84	12.37	5.39	6.98
95	33.30	12.37	5.37	7.00
100	32.76	12.37	5.35	7.02
105	32.20	12.37	5.34	7.03
110	31.72			
115	31.35			
120	31.10			
125	30.86			
130	30.70			
135	30.55			
140	30.47			

Table 14   Dog No. 15,   W = 24.2 kg,   room temp. 22°C

Minutes	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C
5	38.60	11.70	5.47	5.47
10	38.50	13.20	6.25	11.72
15	38.30	14.10	7.03	18.75
20	38.00	13.60	6.81	25.56
25	37.70	13.20	6.63	32.19
30	37.30	13.00	6.62	38.81
35	36.90	12.77	6.52	45.33
40	36.50	12.63	6.50	51.83
45	36.05	12.50	6.48	58.31
50	35.60	12.40	6.48	64.79
55	35.10	12.30	6.48	71.27
60	34.58	12.20	6.47	77.74
65	34.00	12.12	6.47	84.21
70	33.50	12.00	6.48	90.69
75	32.92	11.95	6.42	97.11
80	32.32	11.90	6.47	103.58
85	31.72	11.80	6.37	109.95
90	31.27			
95	30.95			
100	30.72			
105	30.50			
110	30.42			
115	30.30			
120	30.25			
125	30.25			

Table 15 Dog No. 19, W = 18.5 kg, room temp. 23°C

Minutes	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C
5	38.40	10.10	3.55	3.55
10	38.33	12.30	5.20	8.75
15	38.15	12.75	5.52	14.27
20	37.85	12.20	5.27	20.54
25	37.50	11.70	5.01	25.55
30	37.15	11.32	4.82	30.37
35	36.80	11.20	4.85	35.22
40	36.35	11.00	4.78	40.00
45	35.90	11.00	4.90	44.90
50	35.40	10.92	4.92	49.82
55	34.90	10.80	4.90	54.72
60	34.40	10.75	4.95	59.67
65	33.90	10.70	4.98	64.75
70	33.30	10.65	5.01	69.76
75	32.80	10.65	5.07	74.83
80	32.20	10.65	5.12	79.95
85	31.65	10.65	5.16	85.11
90	31.10			
95	30.60			
100	30.30			
105	30.10			
110	29.94			
115	29.85			
120	29.78			
125	29.75			
130	29.75			

Table 16 Dog No. 20, W = 11.5 kg, room temp. 23°C

Minutes	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C
5	38.70	10.05	3.50	3.50
10	38.40	11.50	4.40	7.90
15	38.00	12.30	5.07	12.97
20	37.55	11.90	4.97	17.94
25	36.95	11.50	4.81	22.75
30	36.36	11.10	4.60	27.35
35	35.73	10.80	4.45	31.80
40	35.20	10.45	4.23	36.03
45	34.52	10.10	4.00	40.03
50	33.90	9.72	3.72	43.75
55	33.30	9.30	3.40	47.15
60	32.70	8.90	3.10	50.25
65	32.10	8.75	3.03	53.28
70	31.50	8.25	2.61	55.99
75	31.13			
80	30.90			
85	30.70			
90	30.60			
95	30.50			
100	30.36			
105	30.30			
110	30.30			

Table 17 Dog No. 23, W = 8.7 kg, room temp. 22°C

Minutes	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C
5	37.60	9.90	3.67	3.67
10	37.30	11.22	4.27	7.94
15	36.92	11.55	4.48	12.42
20	36.50	11.30	4.51	16.93
25	35.95	10.92	4.35	21.28
30	35.20	10.50	4.12	25.40
35	34.35	10.13	3.88	29.28
40	33.50	9.60	3.47	32.75
45	32.50	8.95	2.92	35.67
50	31.40	7.31	1.39	37.06
55	30.65			
60	30.20			
65	30.00			
70	29.90			
75	29.80			
80	29.80			

Table 18 Dog No. 24, W = 29.5 kg, room temp. 22°C

Mins.	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg
5	38.90	12.90	6.67	6.67	4.33
10	38.80	14.60	7.65	14.32	4.85
15	38.66	15.10	8.03	22.35	5.10
20	38.50	14.60	7.81	30.16	4.96
25	38.27	14.30	7.73	37.89	4.90
30	38.00	14.06	7.68	45.57	4.87
35	37.72	13.93	7.68	53.25	4.87
40	37.50	13.90	7.77	61.02	4.93
45	37.15	13.86	7.84	68.86	4.97
50	36.82	13.80	7.88	76.74	5.00
55	36.47	13.80	7.98	84.72	5.06
60	36.00	13.90	8.17	92.89	5.18
65	35.52	13.95	8.30	101.19	5.26
70	35.00	13.40	7.82	109.01	4.96
75	34.48	12.40	6.87	115.88	4.36
80	33.80	13.20	7.73	123.61	4.90
85	33.13	12.10	6.67	130.28	4.30
90	32.47	11.80	6.41	136.69	4.07
95	31.70	12.79	7.42	144.11	4.71
100	31.10				
105	30.68				
110	30.40				
115	30.20				
120	30.10				
125	30.00				
130	29.95				
135	29.95				
140	29.95				

Table 19 Dog No. 25, W = 13.4 kg, room temp. 24°C

Minutes	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C
5	38.30	9.00	2.12	2.12
10	38.17	10.50	3.23	5.35
15	37.92	11.35	3.97	9.32
20	37.66	11.10	4.04	13.36
25	37.36	10.97	4.15	17.41
30	37.10	10.82	4.22	21.65
35	36.70	10.67	4.22	25.85
40	36.20	10.50	4.18	30.03
45	35.60	10.35	4.15	34.18
50	35.15	10.18	4.08	38.26
55	34.65	10.00	4.02	42.28
60	34.10	9.84	3.97	46.25
65	33.50	9.65	3.87	50.12
70	32.85	9.44	3.73	53.85
75	32.30	9.30	3.65	57.50
80	31.88	9.10	3.50	61.00
85	31.50			
90	31.30			
95	31.00			
100	30.80			
105	30.54			
110	30.34			
115	30.14			
120	30.00			
125	29.85			
130	29.75			
135	29.70			
140	29.70			

Table 20 Dog No. 26, W = 35.4 kg, room temp. 23°C

Minutes	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C
5	36.92	11.50	4.95	4.95
10	36.70	13.63	6.53	11.48
15	36.40	14.50	7.27	18.75
20	36.16	14.40	7.47	26.22
25	35.92	14.33	7.64	33.86
30	35.70	14.25	7.65	41.51
35	35.50	14.18	7.83	49.34
40	35.30	14.10	7.88	57.22
45	35.00	13.97	7.87	65.09
50	34.70	13.85	7.85	72.94
55	34.40	13.60	7.70	80.64
60	34.10	13.40	7.60	88.24
65	33.80	13.23	7.51	95.75
70	33.50	13.12	7.48	103.23
75	33.10	13.12	7.54	110.77
80	32.70	13.12	7.59	118.36
85	32.20	13.12	7.63	125.99
90	31.80	13.12	7.66	133.65
95	31.40			
100	31.00			
105	30.60			
110	30.25			
115	29.90			
120	29.75			
125	29.65			
130	29.60			
135	29.60			

Table 21 Dog No. 27, W = 13.45 kg, room temp. 23°C

Minutes	Oeso, temp. °C	t_d °C	$(t_d - t_{de})$°C	$\sum(t_d - t_{de})$°C
5	37.40	8.05	1.50	1.50
10	37.00	11.00	3.90	5.40
15	36.65	13.20	5.97	11.37
20	36.25	12.70	5.77	17.14
25	35.90	12.30	5.61	22.75
30	35.53	11.80	5.30	28.05
35	35.00	11.30	4.95	33.00
40	34.40	10.80	4.58	37.58
45	33.75	10.23	4.13	41.71
50	33.19	9.70	3.70	45.41
55	32.60	9.17	3.27	48.68
60	32.10	8.76	2.96	51.64
65	31.60	8.40	2.68	54.32
70	31.14			
75	30.60			
80	30.26			
85	30.08			
90	29.92			
95	29.82			
100	29.78			
105	29.75			
110	29.75			

Table 22 Dog No. 35, W = 28.6 kg, room temp. 22°C

Mins.	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$°C	$\sum(t_d - t_{de})$°C	H kcal/hr/kg
5	41.00	14.80	8.57	8.57	5.60
10	40.80	16.05	9.10	17.67	5.95
15	40.55	16.65	9.58	27.25	6.27
20	40.20	16.19	9.40	36.65	6.15
25	39.80	15.74	9.17	45.82	6.00
30	39.33	15.38	9.00	54.82	5.88
35	38.80	15.03	8.78	63.60	5.75
40	38.33	14.77	8.64	72.24	5.65
45	37.75	14.47	8.45	81.69	5.53
50	37.25	14.22	8.30	89.99	5.43
55	36.73	13.93	8.11	98.10	5.31
60	36.20	13.73	8.00	106.10	5.23
65	35.75	13.55	7.90	114.00	5.17
70	35.25	13.38	7.80	121.80	5.10
75	34.80	13.18	7.65	129.45	5.00
80	34.25	13.02	7.55	137.00	4.93
85	33.70	12.86	7.43	144.43	4.86
90	33.10	12.72	7.33	151.76	4.80
95	32.55	12.58	7.21	158.97	4.72
100	31.95	12.45	7.10	166.07	4.64
105	31.40	12.37	7.03	173.10	4.60
110	30.90				
115	30.60				
120	30.30				
125	30.20				
130	30.15				
135	30.15				

Table 23 Dog No. 36, W = 15.5 kg, room temp. 22°C

Mins.	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg
5	39.00	11.59	5.36	5.36	6.49
10	38.80	12.96	6.01	11.37	7.36
15	38.50	13.54	6.47	17.84	7.82
20	38.00	13.00	6.21	23.05	7.50
25	37.60	12.65	6.08	29.13	7.34
30	37.10	12.26	5.88	35.01	7.10
35	36.50	11.91	5.66	40.67	6.84
40	35.90	11.59	5.45	46.12	6.60
45	35.35	11.30	5.28	51.40	6.38
50	34.70	11.03	5.11	56.52	6.17
55	34.00	10.76	4.94	61.46	5.96
60	33.20	10.48	4.75	66.21	5.74
65	32.40	10.25	4.60	70.81	5.55
70	31.60	9.97	4.39	75.20	5.30
75	31.10				
80	30.60				
85	30.20				
90	29.90				
95	29.70				
100	29.60				
105	29.60				

Table 24 Dog No. 37, W = 23.3 kg, room temp. 24°C

Mins.	Oeso. temp. °C	t_d °C	$(t_d - t_{de})$°C	$\sum(t_d - t_{de})$°C	H kcal/hr/kg
5	38.70	12.51	5.63	5.63	4.53
10	38.65	14.37	7.10	12.73	5.71
15	38.60	15.72	8.34	21.17	6.70
20	38.30	15.11	8.05	29.22	6.47
25	37.95	14.69	7.87	37.09	6.32
30	37.70	14.23	7.63	44.72	6.13
35	37.25	13.88	7.43	52.15	5.97
40	36.90	13.54	7.22	59.37	5.80
45	36.50	13.23	7.03	66.40	5.65
50	36.05	12.88	6.78	73.18	5.45
55	35.55	12.58	6.60	79.78	5.30
60	34.95	12.34	6.47	86.25	5.20
65	34.30	12.06	6.28	92.53	5.05
70	33.70	11.87	6.16	98.69	4.95
75	33.00	11.69	6.04	105.73	4.85
80	32.20	11.57	5.97	111.70	4.80
85	31.70				
90	31.20				
95	30.75				
100	30.40				
105	30.20				
110	29.95				
115	29.90				
120	29.90				

Table 25 Dog No. 41, W = 24 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	40.55	7.25	7.25	5.65	28.20
10	40.40	8.30	15.55	6.47	26.00
15	40.10	9.17	24.72	7.16	24.00
20	39.60	8.87	33.59	6.92	22.20
25	39.15	8.64	42.23	6.74	20.40
30	38.70	8.38	50.61	6.54	18.80
35	38.10	8.10	58.71	6.32	17.30
40	37.56	7.91	66.62	6.17	16.00
45	36.90	7.76	73.38	6.06	14.90
50	36.40	7.56	80.94	5.90	13.80
55	35.90	7.43	88.37	5.79	12.90
60	35.20	7.29	95.66	5.69	12.10
65	34.74	7.18	102.84	5.60	11.50
70	34.27	7.05	109.89	5.50	10.80
75	33.75	6.95	116.84	5.42	10.40
80	33.25	6.83	123.67	5.33	10.00
85	32.70	6.73	130.40	5.25	9.70
90	32.15	6.60	137.00	5.15	9.50
95	31.70				
100	31.30				
105	30.90				
110	30.60				
115	30.30				
120	30.20				
125	30.10				
130	30.10				

surface area A_s = 0.933 m^2 , room temp. 22°C

Depths 1 cm °C	2 cm °C	h kcal/m^2/hr/°C	k kcal/m/hr/°C
39.2	40.0	3.55	0.286
38.8	39.6	4.31	0.305
38.4	39.2	5.42	0.299
38.1	38.7	5.53	0.266
37.7	38.2	5.70	0.240
37.3	37.7	5.83	0.220
36.9	37.3	5.95	0.201
36.5	36.8	6.10	0.188
36.1	36.3	6.25	0.179
35.7	35.8	6.38	0.178
35.2	35.3	6.50	0.163
34.8	34.9	6.60	0.158
34.3	34.4	6.70	0.155
33.9	33.9	6.78	0.155
33.4	33.5	6.83	0.149
32.9	33.0	6.85	0.146
32.5	32.5	6.84	0.146
32.0	32.1	6.78	0.145
31.5	31.7		
31.0	31.2		
30.6	30.8		
30.3	30.5		
30.0	30.3		
29.8	30.1		
29.7	30.0		
29.7	29.9		
29.7	29.8		
29.8	29.8		

Table 26 Dog No. 42, W = 10.5 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	39.90	2.87	2.87	5.12	24.0
10	39.50	3.95	6.82	7.04	20.3
15	39.10	4.83	11.65	8.61	18.0
20	38.60	4.61	16.26	8.21	16.3
25	38.00	4.48	20.74	7.99	15.3
30	37.30	4.32	25.06	7.71	14.4
35	36.70	4.15	30.21	7.40	13.4
40	36.00	4.07	34.28	7.25	12.7
45	35.30	3.93	38.21	7.01	12.2
50	34.50	3.83	42.04	6.83	11.7
55	33.80	3.73	45.77	6.65	11.2
60	33.20	3.67	49.44	6.54	10.8
65	32.70	3.60	53.04	6.42	10.5
70	32.10	3.52	56.56	6.27	10.3
75	31.60				
80	31.10				
85	30.60				
90	30.30				
95	30.20				
100	30.15				
105	30.10				
110	30.10				

surface area A_s = 0.537 m^2,   room temp. 22°C

Depths 1 cm °C	2 cm °C	h kcal/m^2/hr/°C	k kcal/hr/m/°C
37.7	39.0	4.10	0.134
37.1	38.4	4.60	.152
36.5	37.9	6.00	.212
36.0	37.3	6.10	.191
35.5	36.7	6.17	.183
35.0	36.1	6.16	.173
34.4	35.6	6.17	.163
33.8	35.0	6.23	.159
33.3	34.5	6.16	.154
32.8	33.8	6.15	.151
32.3	33.3	6.13	.147
31.9	32.8	6.15	.145
31.4	32.2	6.13	.138
31.1	31.6	6.04	.144
30.8	31.2		
30.5	30.8		
30.2	30.6		
30.0	30.4		
29.9	30.2		
29.8	30.0		
29.7	30.0		
29.6	29.9		

Table 27 Dog No. 43, W = 27 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	39.20	3.95	3.95	2.74	24.0
10	38.85	7.40	11.35	5.13	21.2
15	38.60	8.57	19.92	5.95	19.0
20	38.30	8.47	28.39	5.88	17.2
25	38.10	8.36	36.75	5.80	16.0
30	37.80	8.20	44.95	5.68	14.9
35	37.50	7.95	52.90	5.51	14.2
40	37.20	7.78	60.68	5.40	13.6
45	36.75	7.55	68.23	5.23	13.1
50	36.40	7.30	75.53	5.06	12.7
55	36.00	7.15	82.68	4.96	12.3
60	35.50	7.00	89.68	4.85	12.0
65	35.00	6.88	96.56	4.77	11.7
70	34.50	6.76	103.32	4.68	11.5
75	34.10	6.72	110.04	4.66	11.2
80	33.60	6.72	116.76	4.66	11.0
85	33.10	6.71	123.47	4.65	10.9
90	32.60	6.64	130.11	4.61	10.7
95	32.10	6.56	136.67	4.55	10.5
100	31.60				
105	31.25				
110	30.90				
115	30.75				
120	30.50				
125	30.35				
130	30.30				
135	30.30				

surface area A_s = 1.01 m^2, room temp. 23°C

Depths 1 cm °C	2 cm °C	3 cm °C	h kcal/m²/hr/°C	k kcal/m/hr/°C
37.0	37.9	38.6	2.16	0.215
36.7	37.7	38.3	4.40	.344
36.3	37.4	38.0	5.50	.355
36.0	37.2	37.8	5.77	.327
35.7	36.8	37.5	5.96	.309
35.3	36.5	37.1	6.10	.293
35.0	36.1	36.8	6.09	.281
34.7	35.8	36.3	6.11	.272
34.3	35.4	36.0	6.05	.262
33.9	35.0	35.5	5.95	.255
33.5	34.7	35.2	5.95	.248
33.2	34.2	34.8	5.90	.244
32.8	33.8	34.3	5.87	.242
32.4	33.4	33.8	5.82	.240
32.0	33.0	33.4	5.86	.238
31.7	32.5	32.9	5.93	.244
31.2	32.0	32.5	5.94	.246
30.8	31.6	32.2	5.95	.245
30.4	31.2	31.5	5.92	.244
29.9	30.8	31.2		
29.7	30.5	30.9		
29.5	30.2	30.7		
29.3	30.0	30.5		
29.2	29.9	30.3		
29.1	29.8	30.2		
29.1	29.7	30.1		

Table 28 Dog No. 44, W = 34 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	41.07	10.10	10.10	5.56	25.8
10	41.06	9.70	19.80	5.34	23.4
15	41.05	9.31	29.11	5.07	21.2
20	40.80	9.20	38.31	5.00	19.5
25	40.50	9.09	47.40	4.94	17.8
30	40.25	8.86	56.26	4.82	16.5
35	39.80	8.67	64.93	4.72	15.3
40	39.60	8.55	73.48	4.65	14.3
45	39.00	8.40	81.88	4.57	13.5
50	38.50	8.27	90.15	4.50	12.8
55	38.00	8.16	98.31	4.44	12.2
60	37.55	8.05	106.36	4.38	11.8
65	37.10	8.00	114.36	4.35	11.4
70	36.60	7.88	122.24	4.29	11.0
75	36.20	7.88	130.12	4.29	10.7
80	35.70	7.74	137.86	4.21	10.4
85	35.10	7.72	145.58	4.20	10.1
90	34.50	7.70	153.38	4.19	9.9
95	33.90	7.58	161.96	4.12	9.7
100	33.30	7.60	169.56	4.14	9.5
105	32.80	7.53	177.06	4.10	9.4
110	32.10	7.50	184.56	4.08	9.3
115	31.75	7.50	192.06	4.08	9.2
120	31.30	7.50	199.56	4.08	9.1
125	30.80				
130	30.50				
135	30.25				
140	30.10				
145	30.00				
150	30.00				

surface area A_s = 1.175 m^2,   room temp. 22°C

Depths 1 cm °C	2 cm °C	3 cm °C	h kcal/m^2/hr/°C	k kcal/m/hr/°C
38.6	40.7	41.0	4.50	0.453
38.3	40.4	40.8	4.62	.381
38.0	40.0	40.5	4.71	.330
37.7	39.8	40.2	4.91	.299
37.4	39.4	39.9	5.14	.276
37.0	39.0	39.5	5.26	.259
36.8	38.6	39.2	5.41	.244
36.3	38.2	38.8	5.53	.234
36.0	37.8	38.5	5.64	.226
35.6	37.3	38.0	5.71	.221
35.2	37.0	37.6	5.79	.215
34.8	36.5	37.1	5.82	.214
34.4	36.0	36.7	5.87	.212
34.0	35.5	36.2	5.91	.211
33.5	35.0	35.7	6.00	.212
33.1	34.6	35.2	5.96	.211
32.7	34.1	34.8	6.05	.211
32.2	33.6	34.2	6.10	.214
31.8	33.0	33.6	6.06	.214
31.3	32.5	33.1	6.15	.217
30.7	32.0	32.5	6.12	.220
30.3	31.5	32.0	6.11	.222
29.8	31.0	31.5	6.14	.226
29.5	30.6	31.1	6.18	.229
29.3	30.3	30.7		
29.2	30.0	30.4		
29.1	29.8	30.2		
29.0	29.6	29.9		
29.0	29.5	29.8		
29.0	29.4	29.7		

Table 29 Dog No. 45, W = 21.8 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	38.80	7.50	7.50	6.45	26.3
10	38.70	8.10	15.60	7.01	24.2
15	38.65	8.21	23.81	7.05	22.2
20	38.20	7.95	31.76	6.82	20.4
25	37.90	7.75	39.51	6.66	18.8
30	37.50	7.52	47.03	6.46	17.2
35	37.05	7.34	54.37	6.30	15.7
40	36.55	7.08	61.45	6.08	14.5
45	36.10	6.86	68.31	5.89	13.5
50	35.55	6.64	74.95	5.70	12.5
55	35.10	6.41	81.36	5.50	11.7
60	34.55	6.22	87.58	5.34	11.0
65	33.90	6.06	93.64	5.20	10.3
70	33.20	5.88	99.52	5.05	9.9
75	32.55	5.77	105.29	4.96	9.5
80	31.70	5.71	111.00	4.90	9.2
85	31.20				
90	30.75				
95	30.30				
100	30.00				
105	29.70				
110	29.60				
115	29.60				

surface area A_s = 0.875 m^2, room temp. 22°C

Depths 1 cm °C	2 cm °C	h kcal/m^2/hr/°C	k kcal/m/hr/°C
37.3	38.3	4.41	0.335
37.0	38.0	5.10	.316
36.7	37.8	5.45	.277
36.4	37.5	5.59	.245
36.0	37.2	5.77	.222
35.7	36.8	5.92	.203
35.3	36.3	6.11	.188
35.0	35.8	6.18	.176
34.5	35.3	6.26	.165
34.1	34.9	6.31	.156
33.6	34.3	6.32	.149
33.2	33.9	6.35	.143
32.7	33.3	6.40	.138
32.3	32.8	6.51	.135
31.8	32.2	6.35	.134
31.3	31.6	6.37	.134
30.8	31.0		
30.3	30.5		
30.0	30.2		
29.8	30.0		
29.8	29.8		
29.9	29.8		
29.9	29.8		

Table 30 Dog No. 46, W = 29.8 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	40.80	6.90	6.90	4.33	26.8
10	40.70	9.20	16.10	5.78	25.0
15	40.65	9.85	25.95	6.04	23.4
20	40.30	9.62	35.57	5.90	21.8
25	39.95	9.39	44.96	5.76	20.3
30	39.45	9.26	54.22	5.68	18.9
35	39.05	9.05	63.27	5.55	17.7
40	38.60	8.89	72.16	5.45	16.4
45	38.05	8.72	80.88	5.35	15.3
50	37.60	8.55	89.43	5.24	14.2
55	36.95	8.40	97.83	5.15	13.3
60	36.50	8.28	106.11	5.08	12.6
65	36.00	8.15	115.26	5.00	11.8
70	35.50	8.07	123.33	4.95	11.3
75	35.05	8.00	131.33	4.90	10.7
80	34.55	7.90	139.23	4.85	10.3
85	34.05	7.75	146.98	4.75	9.9
90	33.50	7.64	154.62	4.68	9.6
95	32.75	7.53	162.15	4.62	9.5
100	32.15	7.45	169.60	4.57	9.5
105	31.60	7.40	177.00	4.54	9.4
110	31.20				
115	30.80				
120	30.50				
125	30.25				
130	30.05				
135	30.00				
140	30.00				

surface area A_s = 1.077 m^2, room temp. 23°C

Depths 1 cm °C	2 cm °C	3 cm °C	h kcal/m^2/hr/°C	k kcal/m/hr/°C
39.1	40.2	40.6	3.25	0.372
38.8	40.0	40.3	4.57	.448
38.5	39.6	40.0	5.00	.430
38.1	39.3	39.8	5.13	.388
37.7	38.9	39.4	5.25	.357
37.4	38.5	39.0	5.43	.334
37.0	38.0	38.6	5.55	.314
36.5	37.7	38.2	5.71	.295
36.2	37.2	37.8	5.85	.281
35.7	36.8	37.3	6.00	.268
35.3	36.3	36.9	6.10	.258
34.8	35.8	36.4	8.00	.252
34.4	35.3	35.9	6.35	.246
34.0	34.8	35.4	6.43	.243
33.6	34.3	34.8	6.53	.240
33.0	33.7	34.3	6.61	.239
32.6	33.2	33.7	6.60	.237
32.2	32.7	33.2	6.59	.234
31.6	32.2	32.7	6.56	.235
31.0	31.6	32.1	6.49	.239
30.4	31.0	31.5	6.45	.243
30.0	30.3	30.5		
29.9	30.4	30.7		
29.9	30.3	30.5		
30.0	30.2	30.4		
30.1	30.2	30.3		
30.2	30.2	30.2		
30.3	30.2	30.2		

Table 31 Dog No. 47, W = 28 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	40.80	7.88	7.88	5.27	29.3
10	40.70	9.10	16.98	6.09	27.5
15	40.40	9.72	26.70	6.50	25.8
20	40.05	9.50	36.20	6.35	24.3
25	39.60	9.31	45.51	6.22	22.8
30	39.15	9.05	54.56	6.04	21.3
35	38.60	8.83	63.39	5.90	19.9
40	38.10	8.67	72.06	5.80	18.7
45	37.70	8.46	80.52	5.66	17.5
50	37.00	8.32	88.84	5.56	16.4
55	36.40	8.15	96.99	5.44	15.5
60	35.90	7.97	104.96	5.33	14.7
65	35.40	7.87	112.83	5.26	14.0
70	35.00	7.78	120.61	5.20	13.1
75	34.50	7.63	128.24	5.10	12.8
80	34.00	7.60	135.84	5.08	12.1
85	33.50	7.45	143.39	4.98	11.7
90	33.00	7.32	151.71	4.89	11.4
95	32.25	7.25	158.06	4.84	11.3
100	31.50	7.14	166.20	4.77	11.2
105	31.00				
110	30.70				
115	30.20				
120	30.00				
125	29.80				
130	29.70				
135	29.70				

surface area A_s = 1.035 m^2,   room temp. 22°C

Depths 1 cm °C	2 cm °C	3 cm °C	h kcal/m^2/hr/°C	k kcal/m/hr/°C
38.3	39.4	40.2	3.63	0.560
38.0	39.2	39.9	4.40	.570
37.8	38.8	39.6	4.90	.537
37.5	38.5	39.4	5.00	.488
37.3	38.2	38.8	5.13	.452
36.9	37.8	38.5	5.21	.408
36.6	37.4	38.1	5.33	.378
36.3	37.0	37.7	5.46	.355
35.8	36.6	37.3	5.56	.332
35.5	36.2	36.8	5.69	.316
35.0	35.8	36.3	5.76	.304
34.7	35.3	35.8	5.82	.294
34.2	34.8	35.2	5.91	.288
33.7	34.2	34.8	6.08	.278
33.3	33.8	34.3	6.02	.275
32.8	33.3	33.7	6.21	.273
32.3	32.8	33.1	6.20	.273
31.8	32.3	32.5	6.17	.270
31.3	31.8	32.0	6.27	.272
31.0	31.3	31.5	6.09	.273
30.5	30.9	31.0		
30.2	30.6	30.7		
30.1	30.2	30.3		
30.0	30.1	30.1		
30.0	30.0	30.0		
30.1	30.0	29.8		
30.3	30.0	29.8		

Table 32 Dog No. 48, W = 11 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	38.70	4.34	4.34	7.38	24.1
10	38.40	5.02	9.36	8.55	19.2
15	38.10	5.11	14.47	8.70	17.0
20	37.60	4.92	19.39	8.37	15.2
25	37.10	4.71	24.10	8.02	13.8
30	36.55	4.52	28.62	7.70	12.5
35	35.90	4.38	33.00	7.45	11.6
40	35.25	4.18	37.18	7.12	10.9
45	34.50	4.02	42.20	6.83	10.3
50	33.65	3.88	46.08	6.60	9.9
55	32.80	3.69	49.77	6.28	9.6
60	32.00	3.53	53.30	6.01	9.5
65	31.30				
70	30.80				
75	30.40				
80	30.05				
85	29.80				
90	29.60				
95	29.50				
100	29.50				

surface area $A_s = 0.555\ m^2$, room temp. 23°C

Depths 1 cm °C	2 cm °C	h kcal/hr/m^2/°C	k kcal/hr/m/°C
36.9	38.2	4.29	0.259
36.4	37.7	5.80	.228
35.8	37.2	6.39	.211
35.3	36.7	6.58	.203
34.8	36.1	6.67	.187
34.2	35.6	6.78	.173
33.7	35.0	6.83	.165
33.1	34.4	6.72	.157
32.5	33.8	6.67	.151
31.9	33.2	6.56	.146
31.3	32.5	6.34	.142
30.7	31.8	6.11	.139
30.4	31.2		
30.3	30.6		
30.3	30.3		
30.3	30.1		
30.3	30.0		
30.3	30.0		
30.5	29.9		

Table 33 Dog No. 49, W = 16.8 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	39.00	3.67	3.67	4.08	24.8
10	38.90	4.75	8.42	5.29	22.7
15	38.77	5.35	13.77	5.96	21.1
20	38.50	5.11	18.88	5.70	19.6
25	38.08	4.83	23.71	5.38	18.2
30	37.66	4.70	28.41	5.23	16.8
35	37.27	4.50	32.91	5.01	15.7
40	36.90	4.43	37.34	4.93	14.4
45	36.42	4.38	41.72	4.88	13.4
50	36.03	4.31	46.03	4.81	12.5
55	35.62	4.24	50.27	4.73	11.6
60	35.34	4.19	54.46	4.67	10.8
65	34.94	4.15	58.61	4.63	10.2
70	34.60	4.12	62.73	4.60	9.5
75	34.30	4.04	66.77	4.51	9.0
80	33.90	3.98	70.75	4.44	8.7
85	33.60	3.94	74.69	4.40	8.3
90	33.28	3.94	78.63	4.40	8.2
95	32.90	3.90	82.53	4.35	8.1
100	32.50				
105	32.14				
110	31.66				
115	31.15				
120	30.70				
125	30.28				
130	30.00				
135	29.83				
140	29.70				
145	29.70				

surface area A_s = 0.736 m^2, room temp. 22°C

Depths 1 cm °C	2 cm °C	h kcal/m^2/hr/°C	k kcal/m/hr/°C
36.8	38.3	2.67	0.175
36.5	38.0	3.70	.198
36.3	37.8	4.40	.202
36.0	37.5	4.42	.180
35.8	37.3	4.38	.160
35.5	36.9	4.48	.147
35.3	36.7	4.47	.135
35.0	36.3	4.64	.128
34.7	36.0	4.78	.122
34.3	35.7	4.90	.117
34.0	35.3	5.02	.113
33.7	35.0	5.15	.109
33.4	34.6	5.26	.107
33.1	34.2	5.40	.105
32.8	33.8	5.45	.103
32.5	33.3	5.45	.102
32.1	33.0	5.51	.101
31.7	32.5	5.54	.103
31.3	32.1	5.51	.103
30.8	31.7		
30.5	31.3		
30.0	30.8		
29.7	30.3		
29.7	30.1		
29.8	30.0		
29.9	30.0		
30.1	30.0		
30.2	30.0		
30.3	30.1		

Table 34 Dog No. 50, W = 18.9 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	40.05	6.67	6.67	6.60	23.5
10	39.85	6.70	13.37	6.63	20.6
15	39.60	6.78	20.15	6.71	19.1
20	39.30	6.06	26.21	6.00	18.0
25	39.00	5.53	31.74	5.48	17.0
30	38.75	5.22	36.96	5.16	16.2
35	38.40	4.91	41.87	4.86	15.3
40	38.00	4.72	46.59	4.66	14.5
45	37.70	4.56	51.15	4.51	13.8
50	37.30	4.45	55.60	4.41	13.3
55	36.90	4.38	59.98	4.33	12.8
60	36.50	4.37	64.35	4.32	12.3
65	36.10	4.38	68.73	4.33	11.8
70	35.70	4.42	73.15	4.37	11.5
75	35.20	4.42	77.57	4.37	11.2
80	34.70	4.42	81.99	4.38	10.8
85	34.25	4.43	86.42	4.37	10.5
90	33.75	4.41	90.83	4.36	10.2
95	33.30	4.38	95.21	4.33	9.9
100	32.80	4.40	99.61	4.35	9.7
105	32.25	4.36	104.97	4.31	9.4
110	31.70	4.36	109.33	4.31	9.2
115	31.20				
120	30.75				
125	30.40				
130	30.20				
135	30.00				
140	29.85				
145	29.80				
150	29.80				

surface area A_s = 0.795 m^2,   room temp. 22°C

Depths 1 cm °C	2 cm °C	h kcal/m²/hr/°C	k kcal/m/hr/°C
37.1	39.2	4.68	0.250
36.9	38.9	5.15	.322
36.6	38.6	5.48	.202
36.3	38.4	5.10	.172
36.0	38.0	4.83	.153
35.8	37.8	4.69	.140
35.5	37.3	4.58	.129
35.2	37.0	4.53	.121
34.9	36.7	4.51	.115
34.7	36.3	4.50	.113
34.4	35.9	4.52	.110
34.1	35.6	4.63	.109
33.8	35.2	4.72	.108
33.5	34.8	4.85	.110
33.2	34.3	4.92	.111
32.8	33.9	5.01	.112
32.5	33.5	5.08	.112
32.2	33.0	5.14	.112
31.7	32.6	5.19	.112
31.4	32.2	5.26	.113
30.8	31.7	5.29	.113
30.5	31.2	5.33	.114
30.1	30.7		
29.9	30.4		
29.7	30.2		
29.5	30.0		
29.4	29.8		
29.3	29.7		
29.3	29.7		

Table 35 Dog No. 51, W = 12.5 kg,

Mins.	Oeso. temp. °C	$(t_d - t_{de})$ °C	$\sum(t_d - t_{de})$ °C	H kcal/hr/kg	Skin temp. °C
5	39.50	1.05	1.05	1.57	24.0
10	39.20	4.70	5.75	7.03	20.4
15	38.70	5.97	11.72	8.93	18.8
20	38.20	5.77	17.49	8.63	16.5
25	37.75	5.51	23.00	8.25	15.1
30	37.25	5.20	28.20	7.78	14.0
35	36.75	4.90	33.10	7.33	13.1
40	36.25	4.58	37.68	6.85	12.3
45	35.75	4.25	41.93	6.36	11.7
50	35.25	4.00	45.93	5.98	11.1
55	34.75	3.60	49.53	5.39	10.6
60	34.20	3.50	53.03	5.24	10.2
65	33.65	3.08	57.11	4.61	10.0
70	33.10	2.76	59.87	4.13	9.8
75	32.50	2.62	62.49	3.92	9.6
80	31.90	2.32	65.81	3.47	9.5
85	31.40	2.11	67.92	3.16	9.4
90	30.85				
95	30.50				
100	30.20				
105	29.90				
110	29.70				
115	29.70				
120	29.70				

surface area A_s = 0.605 m^2, room temp. 23°C

Depths 1 cm °C	2 cm °C	h kcal/m^2/hr/°C	k kcal/m/hr/°C
37.6	38.6	0.96	0.060
37.1	38.1	4.76	.205
36.6	37.7	6.55	.238
36.0	37.2	6.72	.212
35.5	36.7	6.78	.195
35.0	36.2	6.70	.180
34.6	35.7	6.55	.165
34.2	35.2	6.34	.153
33.7	34.8	6.07	.140
33.2	34.3	5.86	.131
32.8	33.8	5.30	.119
32.2	33.3	5.35	.116
32.0	32.8	4.76	.103
31.5	32.4	4.32	.094
31.1	31.9	4.12	.090
30.7	31.4	3.67	.081
30.3	30.9	3.37	.075
30.0	30.5		
29.9	30.3		
29.9	30.1		
29.9	30.0		
30.0	30.0		
30.1	29.9		
30.2	29.9		

APPENDIX IV

Evaluation of Cabinet Constant

Dog No. 10

Weight of dog	$W = 37$ kg
Initial oesophageal temperature	$= 41.44$ °C
Required oesophageal temperature	$= 30.00$ °C
Desired temperature depression	$D = 41.44 - 30.00$
	$= 11.44$ °C
from Table 11	$\sum(t_d - t_{de}) = 178.22$ °C

Applying Eq. 25

$$K = \frac{W\,D}{\sum(t_d - t_{de})} = \frac{37 \times 11.44}{178.22}$$

$$= 2.38 \text{ kg at 5-minute intervals}$$

Table 36

Dog No.	K
4	2.43
5	1.59
6	1.20
7	2.09
8	1.75
9	1.75
10	2.38
11	1.87
12	1.38

Hence the mean value of constant K for the cabinet calibrated at 5-minute intervals is taken as $K = 1.83$

Evaluation of Specific Heat of the dog

$$\text{Cabinet constant } K = \frac{W\ D}{\sum(t_d - t_{de})} = \frac{M\ C_p\ ds}{C_d}$$

$$1.83 = \frac{6.505 \times 0.2397}{C_d}$$

$$C_d = 0.852 \ \ \text{kcal/kg/}^{\circ}\text{C}$$

This is the overall specfic heat of the intaot and perfused animal.

APPENDIX V

Prediction of Total Heat Extraction

In all cases the required final oesophageal temperature is to be kept at 30.00 °C.

Knowing the initial oesophageal temperature, hence the temperature depression D, and the constant K, the precooling calculation can thus be evaluated:

$$\sum(t_d - t_{de}) = \frac{W\,D}{K} \ ^\circ C$$

Typical calculation

Dog No. 26 (35.4 kg)

Initial oesophageal temperature $= 36.92\ ^\circ C$

Desired temperature depression $D = 36.92 - 30.00$

$= 6.92\ ^\circ C$

Precooling calculation $\sum(t_d - t_{de}) = \frac{W\,D}{K} = \frac{35.4 \times 6.92}{1.83}$

$= 133.8\ ^\circ C$

i.e. when the sum of temperature differences taken at 5-minute intervals reaches a total of 133.8 °C, active cooling is stopped.

For dog No. 26, the actual oesophageal temperature attained is 29.60 °C

$$\text{Hence} \quad \text{error} = \frac{30.00 - 29.60}{30} = 1.33\ \%$$

APPENDIX VI

Evaluation of Thermal Conductivity (k) & Conductance (h) of Muscles

$$Q = H\,W = M\,C_p\,(t_d - t_{de}) = -\,k\,A_m\,\left(\frac{t_s - t_i}{r_s - r_i}\right) = -\,h\,A_s\,(t_a - t_s)$$

$$r_m = \frac{r_s - r_i}{\log_e \frac{r_s}{r_i}} \qquad A_m = \left(\frac{r_m}{r_s}\right)^2 A_s$$

Typical calculation

Dog No. 47 (28 kg) Surface area $A_s = 1.035\ m^2$

Depth of maximum needle penetration = 3 cm

$r_s = 10$ cm $r_i = 7$ cm

$$r_m = \frac{10 - 7}{\log_e \frac{10}{7}} = 8.4\ \text{cm} \qquad A_m = \left(\frac{8.4}{10}\right)^2 A_s = 0.7\ A_s$$

At 20 minutes after cooling started, the instantaneous heat extraction $Q = H\,W = 6.35 \times 28$ kcal/hr

Conductivity $k = \dfrac{H\,W\,(r_s - r_i)}{A_m\,(t_i - t_s)}$

$$k_{3-0} = \frac{6.35 \times 28}{0.7 \times 1.035}\,\frac{(10 - 7)}{100}\,\frac{1}{(39.4 - 24.3)}$$

$$= 0.488\ \text{kcal/m/hr/}^\circ\text{C}$$

Conductance $h = \dfrac{H\,W}{A_s\,(t_s - t_a)} = \dfrac{6.35 \times 28}{1.035\,(24.3 + 10)}$

$$= 5.00\ \text{kcal/m}^2\text{/hr/}^\circ\text{C}$$

These are the instantaneous values of k and h of the dog.