The American Society of
Mechanical Engineers

A National Historic Mechanical Engineering Landmark

BLOOD HEAT EXCHANGER

Developed jointly by Harrison Radiator Division
General Motors Corporation
Lockport, New York
and Duke University Medical Center
Durham, North Carolina

Presentation Ceremony
September 9, 1980
at Capen Hall, Amherst Campus
The State University of New York at Buffalo

Coordinated by
Buffalo Section
The American Society of
Mechanical Engineers

INTRODUCTION

The design and development of a unique blood heat exchanger for use in open heart surgery was completed in 1957. It was a joint effort by engineers of Harrison Radiator Division, General Motors Corporation in Lockport, N.Y., and medical researchers from the Duke University Medical Center in Durham, N.C. The blood heat exchanger shown in Figure 1 was developed to shorten the time normally required to cool a patient prior to open heart surgery and to rewarm the patient following surgery. Prior to the time of this developmental program, the body temperature of a patient was lowered by either a refrigerated blanket or an ice pack which required from one to two hours under anesthesia before the operation could begin. It was felt that marked improvement in surgery would be possible if the time of cooling and rewarming could be shortened and the temperature level more precisely controlled. The blood heat exchanger allows the body temperature to be lowered safely in a very few minutes and carefully controlled during actual surgery. In a like manner, the heat exchanger allows rewarming of a patient to normal body temperature in 10-15 minutes, as compared to 3-4 hours formerly required. The design of the blood heat exchanger required careful consideration of certain unusual specifications and design factors not usually encountered in heat exchangers intended for an industrial application.

BACKGROUND

The development of the blood heat exchanger came about as the result of research work in the mid-1950s by Dr. Ivan W. Brown, Jr., Dr. Will C. Sealy, Dr. W. Glenn Young, and Dr. Wirt W. Smith of Duke University Medical Center on chilling of patients to subnormal temperatures during surgical operations, a process known as hypothermia. During hypothermia, oxygen and energy requirements of the body and all metabolic activity slows exponentially below its normal rate. For example, when the body temperature is lowered from 37.0 degrees C to 30 degrees C, oxygen and metabolic re-

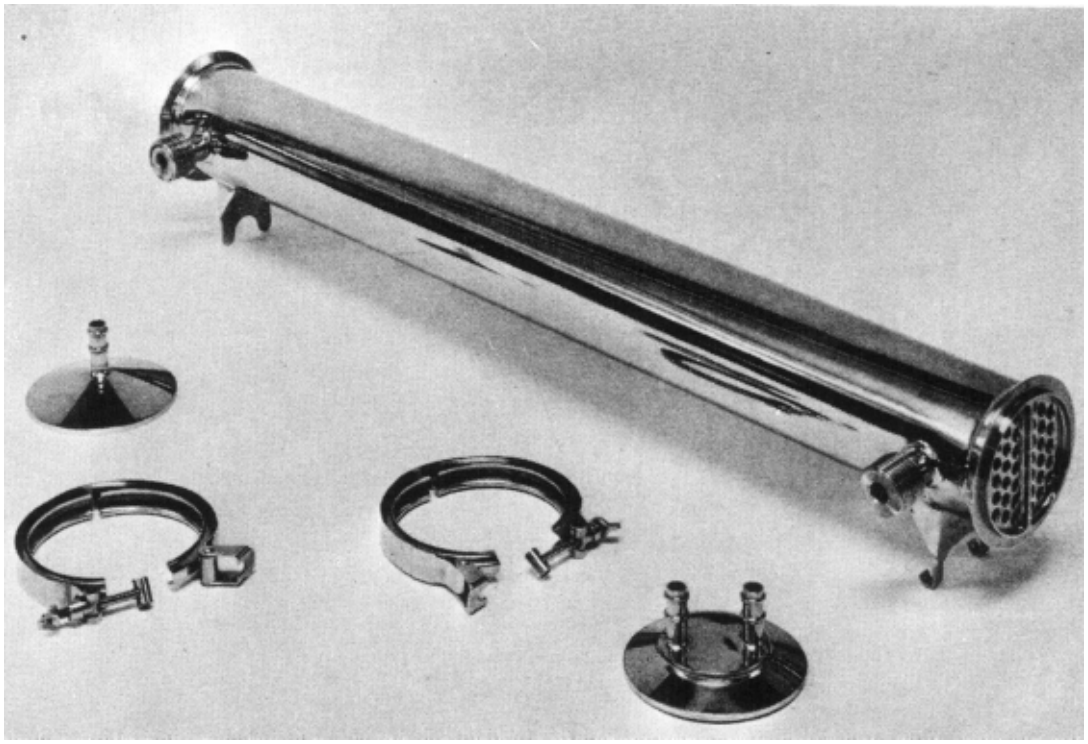

Figure 1. Production blood heat exchanger, a disassembly of a unit on the front cover.

quirements are reduced by approximately 50% [1].† While researchers in subnormal cooling were having some early success, other research groups were developing heart-lung machines which would take over the pumping function of the heart and the aerating function of the lungs. With such machines, it was hoped surgeons would be able to isolate the heart and lungs for surgical procedures on the quiet non-beating heart, while the remainder of the body was perfused and oxygenated by the heart-lung machine. However, the early machines large enough to take over the entire pumping job of the heart (about 5-6 liters per minute) and gas exchanging of the lungs were costly, intricate and injurious with time of perfusion to the delicate blood at the high flow rates required. Smaller machines with lower flow rates worked well for short periods but failed to supply the total oxygen and flow needs of the body. Thus, haste was still required in the early open heart operations.

At this point, the Duke University surgeons considered combining the heart-lung machine with subnormal cooling of patients [1]. Prior methods of cooling patients by immersion in ice water, applying ice packs or using blankets containing brine circulating tubes took 1-2 hours to cool a patient. The warm-up process was similarly long and tedious. Dr. Brown felt there should be a quicker way of cooling the blood while it was being pumped through the extracorporeal circuit. Then the blood vessels within the body would act as a secondary heat exchanger, cooling the patient in a matter of minutes rather than hours. After surgery, the body would be rapidly rewarmed by the same process.

By combining extracorporeal perfusion with hypothermia, there would be less damage to the blood by the extracorporeal circuit since lower blood flows would be permissible. Furthermore since the perfusion hypothermic level could be precisely controlled, the body temperature could be safely taken to very low levels (deep hypothermia). At these body temperatures, blood flow to the entire body could be safely interrupted for periods of time to allow certain operative procedures to be accomplished that were previously considered impossible.

In 1956, Dr. Brown asked the Harrison Radiator Division of General Motors, if company engineers could design an apparatus to do this job as a public service. A cooperative development program by the Duke medical scientists and Harrison research engineers led by Mr. W.O. Emmons, Mr. D.B. Sacca and Dr. C.C. Eckles required ten months of planning and experimentation [2]. The resulting apparatus was a marvel of ingenuity.

DESIGN AND DEVELOPMENT

The intended function of the blood heat exchanger required that its overall design comply with many specifications and requirements. Particular attention was given to providing a device that would be capable of thorough cleaning, visual inspection and repeated sterilization of all blood contacting surfaces. The device had to be free of bubble trapping crevices or surfaces, simple to assemble and safe from intrusion of water or other contaminants including leaching of trace metals into the blood stream.

Blood is a suspension of very delicate living cells in a solution (plasma) composed of 60-odd proteins, complex biological molecules and enzymes. All these labile cellular and plasma constituents have strict thermal and many

†Numbers in the bracket denote references listed at the end of this article.

trauma and turbulence limits before injury. Thus, there was not only a strict and rather limiting temperature gradient to which the blood could be subjected during heat exchange, but the path of the blood through the exchanger had to be free of any undue turbulence and pressure changes. Most blood cells and many blood proteins are injured or activated when touching certain foreign surfaces. This required an inert blood surface of extremely smooth high polish. Although some dilution of the blood with physiologic Saline was permissible, the blood to prime the heart-lung machine circuit had to be supplied from the patient and from blood donors and thus kept to a minimum volume. Consequently, the heat exchanger of this extracorporeal circuit had to be relatively small with a minimal priming volume of this precious fluid. While the purpose of the heat exchanger called for relatively high efficiency, the special requirements and specifications above posed a number of unique problems in its design and development.

Another of the early design problems was the lack of certain data on the thermodynamic and physical properties of blood necessitating certain assumptions in the design calculations. The low fluid flow velocities posed a problem in that they did not lend themselves well to the design of a small compact unit.

DESCRIPTION AND PERFORMANCE

Basically, the blood heat exchanger consisted of a group of slender stainless steel tubes enclosed by a specially constructed steel jacket. As blood flowed through the tubes, water was circulated outside the tubes where its inlet temperature was precisely controlled. The controlled temperature water was obtained by mixing hot and cold water through a special mixing valve where in conjunction with a thermostat the exact desired temperature was maintained. The temperature of the circulating water was automatically regulated and could be precisely controlled to either cool or warm the flowing blood. Blood was pumped from the patient through the heart-lung machine (where its oxygen supply was renewed and carbon dioxide removed) and then back to the patient by way of the heat exchanger where its temperature was either lowered or raised [3]. One type of blood heat exchanger arrangement is shown in Figure 2.

The heat exchanger was made of medically acceptable type No. 304 stainless steel throughout without the use of any other alloy as a joining agent. It consisted of an outer cylindrical jacket 387 mm long and 57 mm in diameter through which twenty-four straight thin walled tubes ran longitudinally. The ends of the tubes were welded into a header plate at each end as shown in Figure 3 and all the surfaces in contact with blood were highly polished [4].

Each end of the exchanger cylinder received a stainless steel cap. The interior of each cap was conically shaped providing sloping surfaces for flowing blood at each end of the exchanger to avoid trapping or generation of any gas bubbles. The final design utilized end caps tightened against silastic O-rings by a special clamp closure, as can be seen in Figure 1. This feature minimized the possibility of leaks and difficulties of cleaning associated with the threaded closures of the earlier prototype model shown in Figure 3.

A shell-and-tube exchanger having parallel flow of blood and water was chosen for two reasons. First, blood flow had to be vertically upward through the exchanger to eliminate the possibility of trapping of gas bubbles which

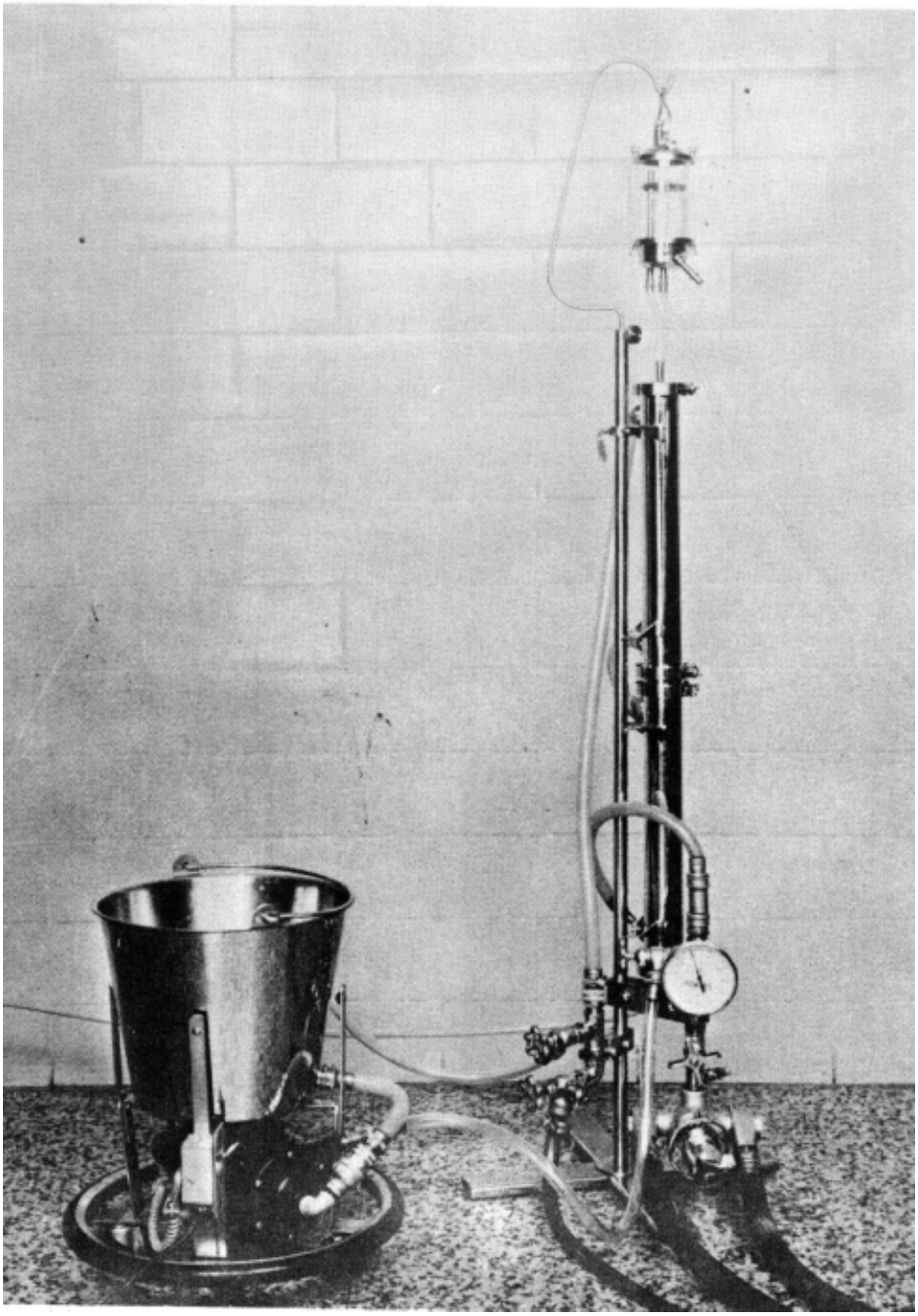

Figure 2. One type of blood heat exchanger arrangement for perfusion hypothermia. In this case, two Brown-Harrison heat exchangers are shown connected vertically for production of deep hypothermia in a large adult patient. A thermostatic mixing valve at lower right blends hot and cold tap water to produce any desired blood inflow temperature in the range 10-42 degrees C. The bucket pump unit at left circulates ice water (0 degrees C) through the exchanger jacket when lower temperatures are desired. This exchanger unit would be connected in the arterial inflow line between the heart-lung machine and the patient.

might later be released into the blood stream. Secondly, the low flow rate of water required vertically upward flow to assure that the exchanger would be filled completely with water. A single-pass construction was chosen to allow visual inspection of all blood surfaces during the careful cleaning process between usages. Baffle plates within the exchanger jacket insured thorough

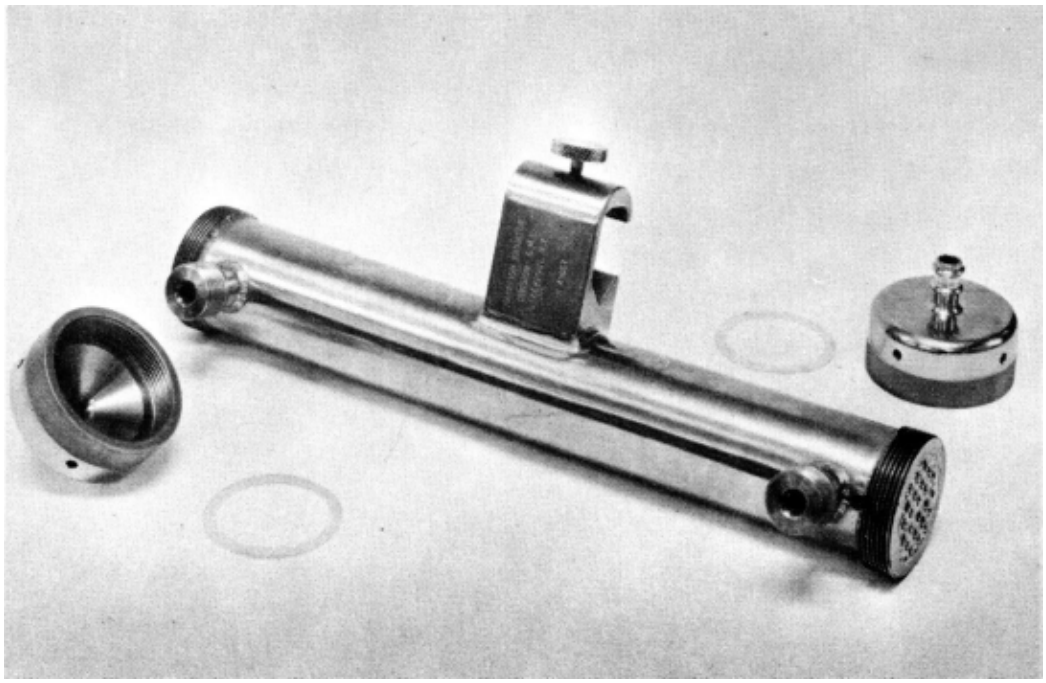

Figure 3. Prototype blood heat exchanger disassembled.

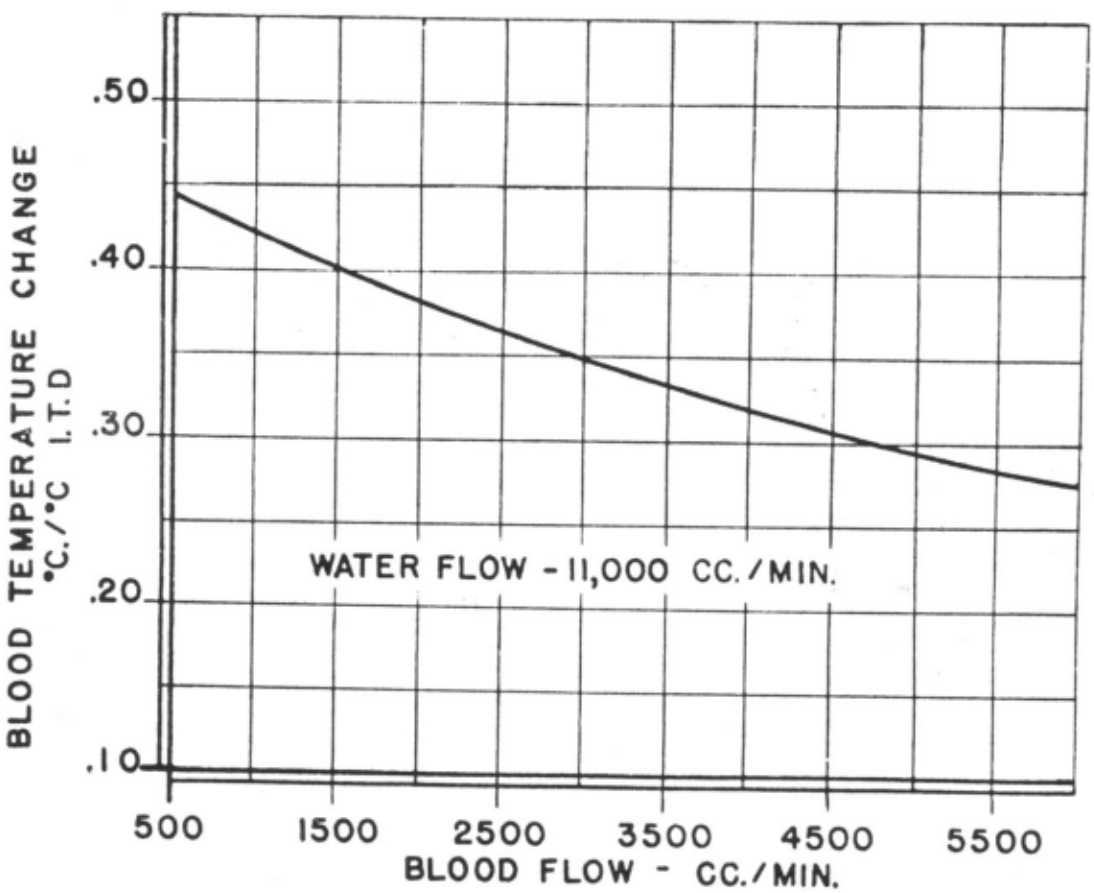

Figure 4. Graph showing blood temperature change across the heat exchanger per degree centigrade of the temperature difference between inlet blood and inlet water. If the inlet temperatures of the blood and water are known, then the temperature change that would take place in the blood between the exchanger inlet and outlet can be determined by multiplying the factor obtained on the ordinate from the curve and blood flow rate by the blood-water inlet temperature difference (I.T.D.).

circulaton of water around the tubes carrying the blood. The jacket of the exchanger was equipped with a heavy-duty hook bracket allowing the exchanger to be easily and quickly mounted or removed from a pole-type stand. This allowed freedom to tilt or shake the exchanger to aid in removing any gas bubbles that might be trapped during priming.

The final production model was 54 mm in diameter, 470 mm long including caps and had a static blood volume of 175 cc. Its mass was approximately 2.7 kg [2].

During design and development, the heat transfer characteristics of blood were predicted by calculation from available properties of blood [2]. Later tests with blood under actual surgical conditions resulted in the operating characteristics shown in Figures 4 and 5 [5, 6].

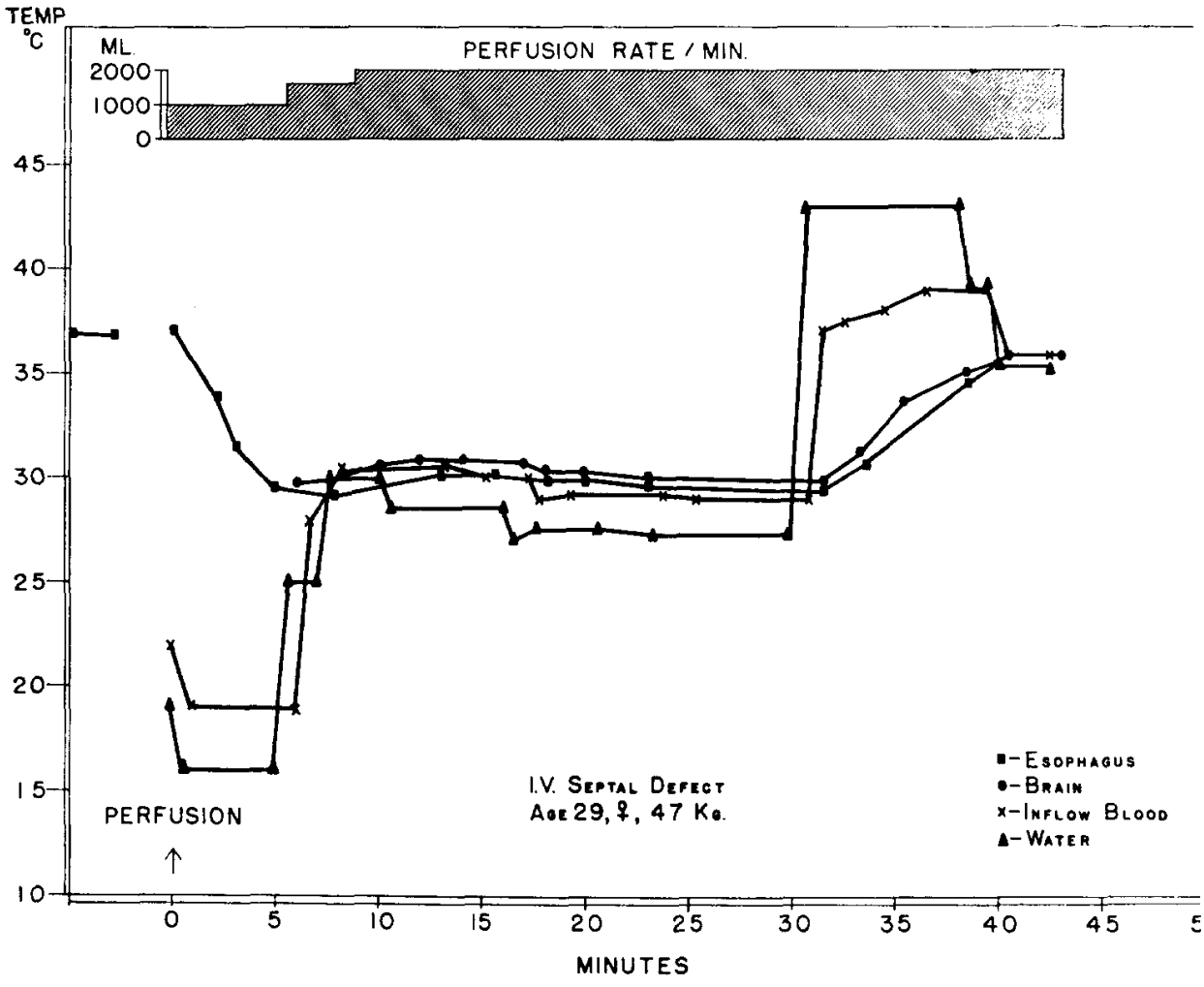

Figure 5. Graph of temperatures recorded during bypass interval in operation for interventricular septal defect. Note the rapid cooling velocity and plateau of esophageal and brain temperatures. The esophageal temperature is seen to return rapidly toward normal with the brain temperature immediately after the blood temperature was raised by the heat exchanger.

CURRENT STATUS

The application of blood heat exchangers for open heart surgery has become standard practice today. They are now employed on all heart-lung machines in the world. Either they are disposable or they are built into the disposable blood oxygenerators. In addition, their use has been expanded to deep hypothermia for certain special surgery and in some instances of cancer in isolatable regions of the body (legs, arms) to thermally enhance the anti-cancer effects of certain chemotherapy agents used to perfuse these parts in localized cancer treatment.

Although the original Brown-Harrison heat exchanger has been superseded by lower cost disposable models, it remains the standard to which all others are compared. There remains a number of the original models still in use throughout the world.

REFERENCES

1Ratcliff, J.D., "Frozen Sleep: New Frontier in Surgery", *Readers Digest,* September 1958, p. 93.

2Emmons, W.O., and Sacca, D.B., "The Design and Development of a Blood Heat Exchanger for Open Heart Surgery", *General Motors Engineering Journal,* July - September 1958, p. 39.

3"Blood Heat Exchanger",*Mechanical Engineering,* March 1958, pp. 102-103.

4Brown, I.W., Smith, W.W., and Emmons, W.O., "An Efficient Blood Heat Exchanger for Use with Extracorporeal Circulation", *Surgery,* Volume 44, No. 2, 1958, pp. 372-375.

5Brown, I. W., Smith, W.W., Young, W.G. and Sealy, W.C., "Experimental and Clinical Studies of Controlled Hypothermia Rapidly produced and Corrected by a Blood Heat Exchanger During Extracorporeal Circulation", *Journal of Thoracic Surgery,* Vol. 36, 1958, pp. 497-505.

6Brown, I.W. "Hypothermia Combined with Extracorporeal Circulation" Chapter 28, pp. 708-746, *Gibbons Surgery of the Chest,* First Edition, W.B. Saunders, Philadelphia, 1962.

WORDING ON THE ASME PLAQUE

This is the first commercial human blood heat exchanger. Developed in 1957, it permitted a patient's body temperature to be safely and rapidly lowered during open heart surgery to any desired and precisely controlled hypothermic level, then during the conclusion of the operation rapidly rewarmed to normal. Prior to this, hypothermic surgery required hours of pre-operative hard to control external emersion cooling and post-operative rewarming.

Its design was a cooperative development between researchers at the Duke University Medical Center lead by Dr. Ivan W. Brown, Jr. and research engineers of the Harrison Radiator Division of the General Motors Corporation lead by Mr. W.O. Emmons.

THE AMERICAN SOCIETY OF
MECHANICAL ENGINEERS — 1980

ACKNOWLEDGEMENTS

The Buffalo Section of The American Society of Mechanical Engineers gratefully acknowledges the efforts of all who cooperated on the landmark dedication of the Blood Heat Exchanger.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS

Dr. Donald N. Zwiep, Past President
Dr. Charles E. Jones, President
Dr. Richard A. Kenyon, Vice President, Region III
Daniel T. Koening, Chairman, History and Heritage, Region III
Dr. Rogers B. Finch, Executive Director and Secretary

THE ASME NATIONAL HISTORY AND HERITAGE COMMITTEE

Prof. J.J. Ermenc, Chairman
Dr. R. Carson Dalzell, Secretary
Prof. R.S. Hartenberg
Dr. J. Paul Hartman
Robert M. Vogel, Smithsonian Institute
Carron Garvin-Donohue, ASME Staff Liaison
Jill Birghenthal, Administrator

THE ASME BUFFALO SECTION

Dr. Ramesh K. Shah, Chairman
Richard S. Meyer, P.E., Vice-Chairman
Dr. Peter S. Pawlik, Program Chairman
Dr. Hiroshi Morihara, Secretary
Raymond E. Eldridge, Treasurer
Dr. Paul M. Culkowski, Past Chairman
Gerard L. Conroy, P.E., History and Heritage
Robert R. Erickson, Professional Development
Robert J. Hagen, Publicity/Public Affairs
Frederick V. Oddi, Honors and Awards
Dr. Ravinder Prakash, Newsletter
Dr. Herbert Reismann, P.E., Career Guidance
Robert Wantuck, Roster

STATE UNIVERSITY OF NEW YORK AT BUFFALO

Saktisdas Roy, Director, University Libraries
James Webster, Director, Science and Engineering Library

The material for this booklet was compiled and written by Robert J. Flower and Dr. Ramesh K. Shah of Harrison Radiator Division of GMC. Dr. Ivan W. Brown, Jr., M.D., of Watson Clinic, Lakeland, FL, Dr. W.G. Young, Jr., M.D., of Duke University, and D.B. Sacca of Harrison Radiator provided information on history and current status of the blood heat exchanger. James Webster of State University of New York at Buffalo (SUNYAB) was very helpful in organizing the dedication ceremony at the SUNYAB Amherst Campus.