Printed in U.S.A.

78-WA/HT-57

an ASME publication

Determination of Specific Heat of Meat

CHIA PING WANG

Research Physicist,
Radiation Sources Group

ARI BRYNJOLFESSON

Chief
Radiation Preservation of Food Division,
Food Engineering Laboratory,
US Army Natick Research and Development Command,
Natick, Mass.

A high energy radiation has been used successfully to develop a new method of determining the specific heat of meat as a function of temperature. For beef, it is found that the specific heat has a value of 1.69 $\pm$ 0.08 $J \cdot g^{-1} \cdot {}^{\circ}C^{-1}$ (0.40 $\pm$ 0.02 $cal \cdot g^{-1} \cdot {}^{\circ}C^{-1}$) in the temperature range -60C to -40C. It then rises gradually to a value some 20 times larger near −1C, and drops to a value of 3.10 $\pm$ 0.39 $J \cdot g^{-1} \cdot {}^{\circ}C^{-1}$ to 20C. This variation follows closely the theoretical prediction.

Contributed by the Heat Transfer Division of The American Society of Mechanical Engineers for presentation at the Winter Annual Meeting, San Francisco, Calif., December 10-15, 1978. Manuscript received at ASME Headquarters August 14, 1978.

Copies will be available until September 1, 1979.

Determination of Specific Heat of Meat

CHIA PING WANG ARI BRYNJOLFESSON

ABSTRACT

A high energy radiation has been used successfully to develop a new method of determining the specific heat of meat as a function of temperature. For beef, it is found that the specific heat has a value of $1.69 \pm 0.08\ J \cdot g^{-1} \cdot {}^{o}C^{-1}$ ($0.40 \pm 0.02\ cal \cdot g^{-1} \cdot {}^{o}C^{-1}$) in the temperature range $-60^{o}C$ to $-40^{o}C$. It then rises gradually to a value some 20 times larger near $-1^{o}C$, and drops to a value of $3.10 \pm 0.39\ J \cdot g^{-1} \cdot {}^{o}C^{-1}$ ($0.74 \pm 0.09\ cal \cdot g^{-1} \cdot {}^{o}C^{-1}$) from about $-1^{o}C$ to $20^{o}C$. This variation follows closely the theoretical prediction.

NOMENCLATURE

c = Heat capacity in $J \cdot g^{-1}$
c_L = Fusion heat of frozen water in meat in J per gram of meat
c_{water} = Heat capacity of water in $J \cdot g^{-1}$
c_{ice} = Heat capacity of ice in $J \cdot g^{-1}$
c_{org} = Heat capacity of the organic component of meat in $J \cdot g^{-1}$
D = Absorbed dose in the sample in $J \cdot g^{-1}$
H(T) = Specific heat of meat in $J \cdot g^{-1}$
L = Fusion heat of ice in $J \cdot g^{-1}$
m_{ice} = The mass of ice in meat in g per g of meat
dm_{ice} = Infinitesimal change in m_{ice}
m_{org} = The mass of organic material in meat in g per g of meat
dq = The infinitesimal heat needed to melt the infinitesimal mass, dm_{ice}
Q(T) = The total heat in J to heat the sample from T to its melting point T_o
R = The universal gas constant in $J \cdot mol^{-1}$
T = Temperature in ^{o}K
dT = The infinitesimal temperature T in ^{o}K
ΔT = Finite but small temperature rise in ^{o}K
T_f = Freezing point of pure water = $273.15^{o}K$
T_o = Freezing point of water solution in the meat ^{o}K

INTRODUCTION

We report here a new method of measuring the specific heat of meat, utilizing a high energy radiation (in this case, an electron beam from a 10 MeV linear accelerator) as the heating source to heat the specimen.

When fast-moving charged particles pass through matter, they lose their energy through coulomb interactions with the atoms, giving rise to photons and electrons by processes such as atomic excitation, ionization, and bremsstrahlung. These photons and electrons in turn interact with the surrounding atoms close to the paths of the primary electrons, and their energy eventually is almost all turned into heat in the medium. The radiation absorbed dose is the energy absorbed by the medium from the radiation per unit mass of the medium (1) and this energy, therefore, should be equal to the heat developed in a unit mass of the medium due to irradiation, apart from minor fraction (< 2%) of the energy that is lost in chemical reactions.

Thus, if the temperature rise ΔT of the specimen due to this "radiation heating" is measured, and the absorbed dose D for the specimen independently determined, the specific heat c of the specimen is given by

$$c = D/\Delta T \qquad (1)$$

This radiation heating is developed in the immediate neighborhood of each primary electron path of the beam within a small fraction of a second. If the specimen is homogeneous and the irradiation uniform, we would have an "instantaneous", uniform heating in every layer of the specimen.

THE ELECTRON BEAM STRUCTURE AND BEAM SCAN

The 10 MeV electron beam from the linear accelerator consists of 60 pulses per second. Each pulse lasts for about 4.5 μs and is 500 mA in amplitude. The average current is, therefore, about 125 μA in this experiment. The diameter of the beam is 3 cm.

The beam scans 40 cm in a vertical plane at a frequency of 0.5 Hz. The samples, 3"x4 1/4"x1" in size, are mounted in the vertically hung carrier that traverses horizontally at an adjustable speed across the beam path. The scanned beam has been shown to give a dose uniformity within 2-3% at the surface of the sample (2,3).

Fig. 1 shows the depth-dose distribution in beef for 10 MeV electrons (2,3). After passing through 0.26 g cm^{-2} of the insulating and packaging materials, the electrons give an absorbed dose at the surface of the beef sample 103% of its entrance value. The absorbed dose keeps on increasing until it reaches a peak value of 122% at an equivalent depth of about 2.2 g cm^{-2}. It then drops to 112% at the other side of the sample.

There is thus an "initial" temperature distribution from layer to layer along the 1" thickness of the sample after each transversal (or irradiation pass) although in each layer the heating is uniform. This temperature distribution, however, quickly settles to a stable, average value within a few minutes after each irradiation pass as the recorded temperature of the sample shows. The temperature at the surface of the sample was recorded simultaneously with the temperature in the center layer of the sample.

In this experiment, the various parameters were so adjusted that the sample received an average absorbed dose of 10^4 Gy (1 Mrad) or 10^4 joules per kilogram in each pass.

TEMPERATURE MEASUREMENT

The temperature of the sample and the temperature rise due to radiation heating in each irradiation pass can be followed faithfully by a temperature measuring device with a small response time constant, such as a thermocouple or a thermistor, imbedded in the sample.

In this experiment we used a constantan-copper thermocouple imbedded in the meat sample, and the meat we used was blanched (70°C to 90°C) beef of about 60% water content. The sample with the imbedded (and other monitoring) thermocouples was surrounded by similar samples all frozen to about -70°C, and housed in an insulating box made of polystyrene foam (wall thickness 5 cm) during irradiation.

The thermocouple was connected to a chart recorder through a DC voltage amplifier. Thermal electromotive force (emf) could be read from the chart to an accuracy of about 5 μV and 10 μV for the two amplifier settings used in this experiment.

The heat loss (or gain) of the sample to (or from) the surrounding due to thermal radiation and conduction was found to be small and was corrected for from the cooling (heating) curves both before and after each irradiation pass.

The effect of the interaction between the electron beam and the thermocouple is believed to be negligible because of the very small mass of the junction and the leads within the sample as compared to that of the sample itself. When the beam hits the thermocouple, the noise prevented accurate measurement, but within one minute the noise had dissipated.

ABSORBED DOSE DETERMINATION

It is a routine practice of this Laboratory to check the dose corresponding to the various electronic settings of the accelerator and the conveyor system with a water calorimeter and ferrous copper dosimeters. These dose determinations agree to within the experimental accuracy of 2-3%.

EXPERIMENTAL RESULTS

Table I shows the specific heat of beef (water 60%; protein 22%; fat 15%; NaCl 0.8%; Ash 1.9%) measured at the various temperatures and that of ice and water at these temperatures (4). They are both plotted in Fig. 2 for comparison. The errors of measurements shown in Table I and Fig. 2 are the estimated errors or uncertainties of reading the emf from the recorder chart only.

It is seen from Table I and Fig. 2 that the specific heat of beef has an average value of 1.69 ± 0.08 J · g^{-1} · $^oC^{-1}$ (0.40 ± 0.02 cal· g^{-1} · $^oC^{-1}$) in the temperature range -60°C to -40°C. The measurements indicated a gradual rise to a value some 20 times larger near -1°C*, and then a sharp drop to a value of 3.10 ± 0.39 J · g^{-1} · $^oC^{-1}$ (0.74 ± 0.39 cal· g^{-1} · °C) which was practically constant from -1°C to 20°C. This variation follows closely the theoretical curve shown in the figure.

In the following Section, we show how the equation for the theoretical curve is derived.

THEORY OF THE VARIATION OF SPECIFIC HEAT OF FROZEN MEAT WITH TEMPERATURE

It is well known that 1 gram mole of substance dissolved in 1 kg of water will cause the depression of freezing point by 1.86°C. (In thermodynamics this value is shown to be $R \cdot T_f^2/(1000 \cdot L) = 1.859$ where R = 1.987 cal/mol is the gas constant, T_f = 273.15°K is the freezing point in °K, and L = 79.71 cal/g is the fusion heat.) Lowering the temperature of the 1 molar solution below its freezing point -1.86°C will cause water to freeze out from the solution and the fractional amount m_{ice} frozen out before saturation is reached will be given by

$$m_{ice} = 1 + \frac{1.86}{T}$$

where T is the temperature (always negative) in °C of the water solution.

---

* An experiment performed after this work was completed in which γ radiation for a Co-60 source was used as the heating source of the sample instead of the electrons confirms this result in the transition region indicated by the present electron experiment.

If the concentration of the solution is other than a molar, then -1.86 in Eq. (2) will have to be replaced by a value T_o

$$m_{ice} = 1 - \frac{T_o}{T} \qquad (2)$$

where T_o = -1.86 x (molar concentration) is the freezing point of the solution. This equation is valid for dilute solution only. We will nevertheless use it over an extended range as a fair approximation in the present analysis. (The exact equation requires knowledge about the value of the variation of the vapor pressure and the fusion heat with the concentration.)

For meat with 60% water content, the right hand side of Eq. (2) has to be multiplied by 0.6,

$$m_{ice} = 0.6\ (1 - \frac{T_o}{T}) \qquad (3)$$

Hence, when the temperature is changed by dT at T, the change of the weight dm_{ice} of ice is obtained by differentiating Eq. (3) with respect to T,

$$dm_{ice} = \frac{0.6\ T_o}{T^2}\ dT \qquad (4)$$

If the heat of fusion of ice is L J/g, then the heat dq needed to melt the ice, i.e., to decrease the amount of ice by ($-dm_{ice}$) gram, is $dq = -dm_{ice} \cdot L$. The corresponding contribution to the heat capacity of the meat is dq/dT, or according to Eq. (4),

$$c_L = \frac{dq}{dT} = \frac{-dm_{ice} \cdot L}{dT} = \frac{-L \cdot 0.6 \cdot T_o}{T^2}\ (J \cdot g^{-1} \cdot {}^oC^{-1}) \qquad (5)$$

valid for $T \leq T_o$; the heat of fusion is L = 79.71 $cal \cdot g^{-1}\ {}^oC^{-1}$ = 334 $J \cdot g^{-1} \cdot {}^oC^{-1}$. The specific heat of pure ice is tabulated in (4). The heat capacity of the ice in the meat can then be approximated well by

$$c_{ice} = (2.115 + 7.859 x 10^{-3} T)\ m_{ice} (J \cdot g^{-1} \cdot {}^oC^{-1}) \qquad (6)$$

for $T < 0^oC$, where m_{ice} is the amount of ice in the meat and is given by Eq. (3).

The specific heat of the unfrozen salty water phase we set as a constant and equal to 1.0 $cal \cdot g^{-1}\ {}^oC^{-1}$. (The specific heat of the unfrozen water solution may differ from that of water, and the value of 1 is in the present case only an approximation.) The heat capacity of the "salty" water phase in the meat is then:

$$c_{water} = 4.2(0.6 - m_{ice})\ (J \cdot g^{-1} \cdot {}^oC^{-1}) \qquad (7)$$

where m_{water}, the amount of unfrozen water (i.e. salty water solution) in the meat is here equal to $0.6 - m_{ice}$.

The specific heat of the organic portion of the meat is not well defined, but for the present purpose it is adequate to approximate the heat capacity of the organic fraction in the meat by:

$$c_{org} = (1.6 + 6.5 x 10^{-3} T) m_{org}\ (J \cdot g^{-1} \cdot {}^oC^{-1}) \qquad (8)$$

where m_{org} is the amount of organic materials (for instance proteins and lipids) in the meat. In our case, m_{org} = 0.4 grams per gram of meat.

The Eq. (8) is obtained by solving the specific heat equation (Eq. 9) in the very low temperature region (-42.5°C to -56.6°C) and the temperature region above freezing (7.7°C to 15.6°C).

The specific heat H(T) of meat is then obtained by adding the different contributions given by Eqs. (5), (6), (7), and (8),

$$H(T) = c_L + c_{ice} + c_{water} + c_{org} \qquad (9)$$

The additivity of the different contributions is here used as an approximation. Interactions of physical and chemical nature may perturb this additivity rule. Inserting the numerical values into Eq. (9) we obtain

$$H(T) = \frac{-334 \cdot 0.6 \cdot T_o}{T^2} + (2.11 + 7.86 x 10^{-3} T) \cdot 0.6 \cdot (1 - \frac{T_o}{T}) + 4.2 \cdot 0.6 \frac{T_o}{T} + (1.6 + 6.5 x 10^{-3} T) \cdot 0.4 \qquad (10)$$

In this equation T_o is the initial freezing point of the meat. It can principally be predicted from analysis of the soluble materials in the water fraction of the meat. We may also determine T_o from the specific heat curve, and we found $T_o = -0.9^oC$ to give a good fit. Eq. (10) then takes the form:

$$H(T) = \frac{180}{T^2} - \frac{1.13}{T} + 1.91 + 7.3 x 10^{-3} T \qquad (11)$$

In Column 3 of Table I we list the experimentally determined values of the specific heat in beef. In Column 4 we list the corresponding values determined from Eq. (11). Fig. 2 is the graphic presentation of the same data.

We may also integrate Eq. (11) from T(<-0.9°C) to -0.9°C and we get:

$$Q(T) = 198.40 - [- \frac{180}{T} - 1.13 \ln |T| + 1.91 T + 0.00365 T^2] \qquad (12)$$

This equation, which is valid for $T < -0.9^oC$, can often be compared more easily than Eq. (11) with the experimental data.

DISCUSSION

The method of determining the specific heat of meat with a high energy radiation as the heating source has been proved to be highly successful. Several interesting results have been obtained.

For beef (which had been cooked at 70° - 90°C), it is found that the specific heat value is well approximated by Eq. (11) for temperatures from -60° to about -3°C. This equation corresponds to the expected specific heat for a mixture containing 40% organic solids and 60% water with a freezing point of -0.9°C corresponding to 0.48 molar concentration in dissolved ions. This sample of beef had about 0.8% NaCl, which if totally dissociated would result in about 0.46 molar solution in ions of Na^+ and Cl^-. About 0.4% sodium orthophosphate was also added to the meat. Some of these ions will attach to large organic molecules, and are unlikely then to separate out into the liquid phase as the water fraction freezes. A freezing point of -0.9°C for the water fraction is, therefore, close to the expected value.

TABLE I

Specific Heat of Beef and Ice and Water at Various Temperatures

Temperature (°C)	Specific Heat c ($J \cdot g^{-1} \cdot {}^{o}C^{-1}$) Ice & Water*	Beef, Experimental	Beef, Theoretical
-56.6	1.670	1.49 ± 0.08	1.57
-49.5	1.725	1.69 ± 0.08	1.64
-42.5	1.781	1.88 ± 0.08	1.73
-35.3	1.838	1.61 ± 0.09	1.83
-28.9	1.888	1.80 ± 0.09	1.95
-23.1	1.927	1.83 ± 0.10	2.13
-18.5	1.970	2.04 ± 0.12	2.31
-14.7	1.999	2.70 ± 0.15	2.71
-11.3	2.026	3.17 ± 0.25	3.34
- 8.9	2.045	4.33 ± 0.30	4.24
- 7.4	2.057	5.85 ± 0.35	5.30
- 6.4	2.065	7.35 ± 0.35	6.43
- 5.7	2.070	7.87 ± 0.35	7.61
- 5.0	2.076	8.55 ± 0.95	9.30
- 4.45	2.080	11.11 ± 2.5	11.22
- 3.96	2.084	11.63 ± 2.6	13.64
7.7	4.1935	3.12 ± 0.38	3.15
11.7	4.1869	3.00 ± 0.38	3.15
15.6	4.1825	3.20 ± 0.39	3.15

*From the least squares fits to data in Ref. (4).

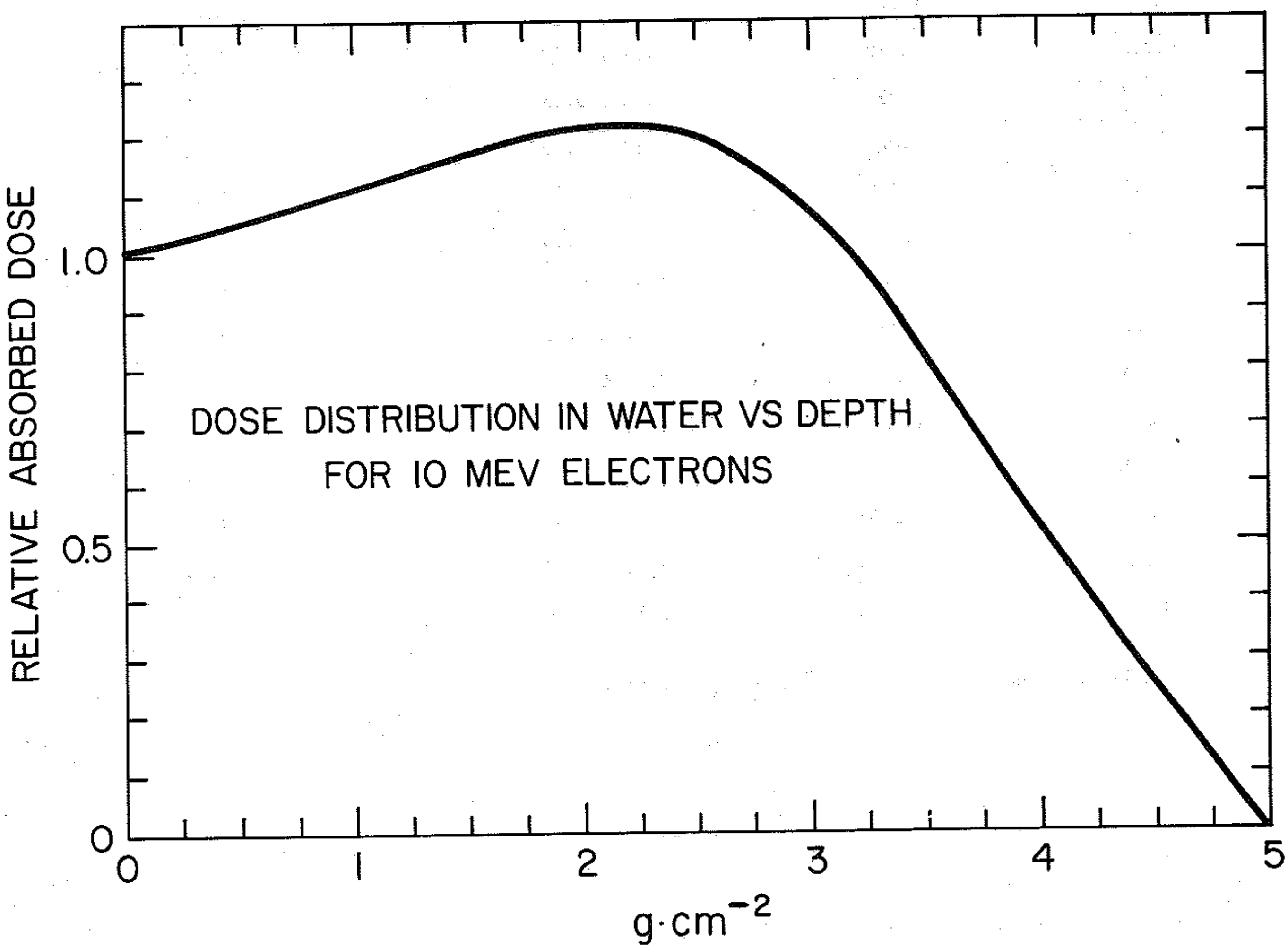

Fig. 1 - Absorbed dose distribution in beef as a function of depth for 10 MeV electrons in broad beam geometry. The absorbed dose distribution in beef expressed in water equivalent is approximately the same as that in water.

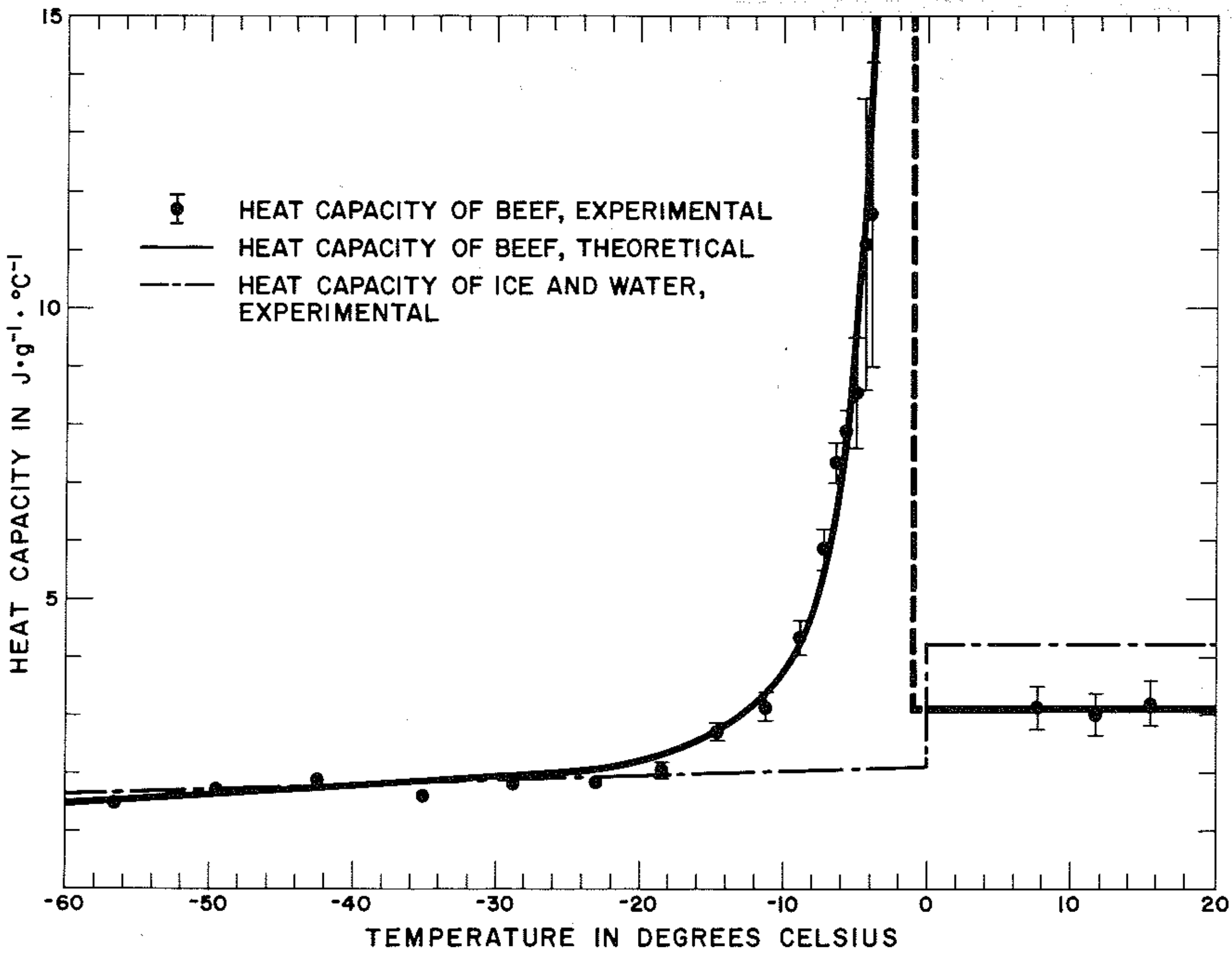

Fig. 2 - Variation of heat capacity of beef per gram with temperature. The heat capacity of ice and water per gram is also shown for comparison. The theoretical curve is the plot of Eq. (11).

REFERENCES

1 For further detail, see for example, Attick, Frank H., Roesch, William C., and Tochilin, Eugene, ed., Radiation Dosimetry, 2nd ed., Academic Press, 1966.

2 Brynjolfsson, A., "Three-Dimensional Dose Distribution in Samples Irradiated by Electron Beams", Proceedings, Radiation Research, International Conference at US Army Natick Laboratories, 1963, pp. 116-129.

3 Rees, C. W., and Caspersen, J. M., "Electron Irradiation in the Sterilization of Meat", Proceedings of the First International Congress on Engineering and Food, 1976.

4 Weast, Robert C., ed., Handbook of Chemistry and Physics, 58th ed., The Chemical Rubber Co., 1977-1978.