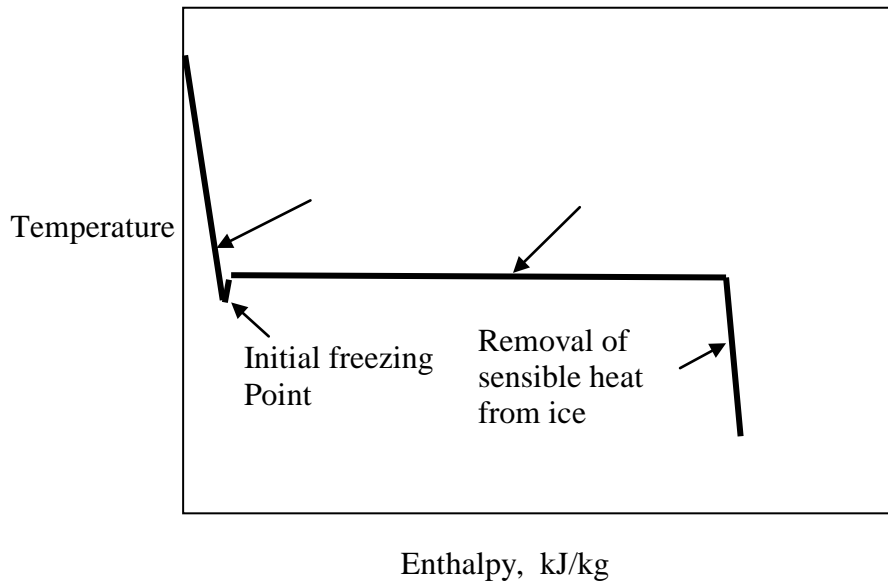## Problems Involving Phase Change - Freezing

Water

Enthalpy, kJ/kg

Calculations:
1) Removal of enthalpy to freeze a food material
2)

Removal of enthalpy to freeze a product =

 where change in enthalpy is obtained from the initial and final temperatures, see Table
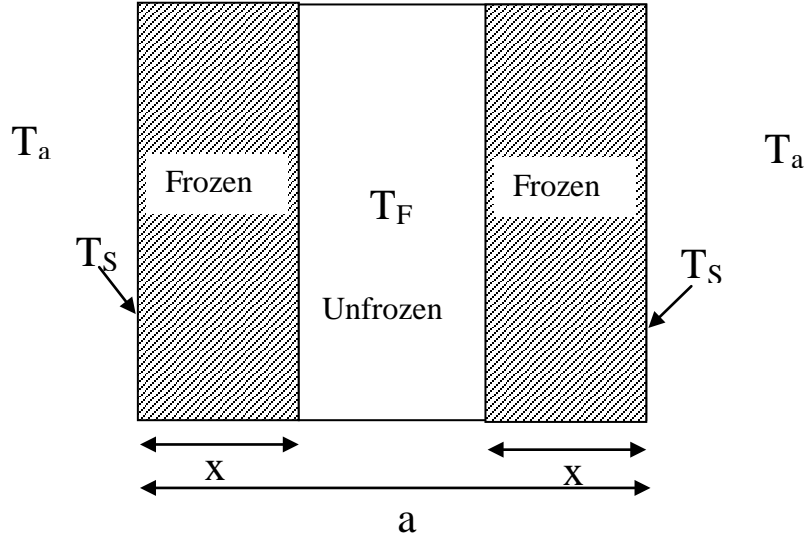
FREEZING TIME

ANALYTICAL
The physical situation is described by

$$C(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left[k(T)\frac{\partial T}{\partial r} \right] + \frac{a'k(T)}{r}\frac{\partial T}{\partial r}$$

where a' = 1 for cylinder
       a' = 2 for sphere

Plank 's Equation

from (1) and (3)

Equating (2) and (4)

Integrating x=0 to x=a/2

$$t = \frac{\rho L}{(T_f - T_a)} \left[\frac{a}{2h} + \frac{a^2}{8k} \right]$$

General form

$$t = \frac{\rho L}{(T_f - T_a)} \left[\frac{Pa}{h} + \frac{Ra^2}{k} \right]$$

	P	R
Infinite Slab	0.5	0.125
Infinite Cylinder	0.25	0.0625
Sphere	0.167	0.0417

PARAMETERS INFLUENCING FREEZING TIME
1. Initial Product Temperature
    a. Higher initial temperatures result in longer freezing time
    b.

2. Product Size or Thickness
    a. As size or thickness increases, distance for heat transfer through unfrozen
    and frozen product zones increases and freezing time must increase.
    b.

3. Surface Heat Transfer Coefficient, h
    a. As h increases, rate of heat transfer increases resulting in reduction of freezing
    time.
    b.

4. Freezing Medium Temperature
    a. As freezing medium temperature is reduced the temperature gradients
    between the surface and medium increase and freezing time is reduced.
    b. Magnitude of influence can be significant.
5. Final Product Temperature
    a. A reduction in the desired final temperature of the frozen product will extend
    the freezing time in a corresponding way
    b. Magnitude of influence does not appear to be dramatic
6. Initial Freezing Temperature of product
    a. Influence on heat transfer should be small when considering small variations in
    the initial freezing temperature.
7. Product Properties
    a. Influence in heat transfer equations is obvious
    b. Influence is magnified by influence of ice on magnitudes of properties.