.Heat & Temperature
Answers and Explanations

1. D

The Kelvin temperature represents the true thermodynamic temperature. The Kelvin temperature is directly proportional to the kinetic energy of the particles of a particular substance (the constant of proportionality depends on the molar heat capacity of the substance). Zero on the Kelvin scale is called absolute zero because it is the lowest possible temperature. Molecular motion ceases. The size of a Kelvin unit was developed to agree with the centigrade scale (100 gradations between the freezing and boiling points of water), so in terms of the unit magnitude: 1 K = 1°C. However, the Kelvin scale is offset 273.15.

$$T = T_c + 273.15$$

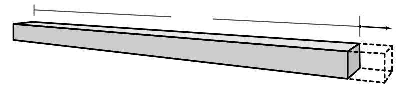
2. B

The specific heat is the heat capacity per unit mass. Specific heat tells us how many joules (or calories) are required to raise one gram of a substance one degree Celsius. The unit of heat, the calorie, is defined in terms of the specific heat of liquid water. The specific heat of water is 1 cal/g°C.

3. B

There are two things happening which will affect the pitch of the flute. Thermal expansion alters the length of the flute and the greater temperature increases the speed of sound in air.

Thermal expansion occurs when the spacial dimensions of a solid increase when it is heated. For small temperature changes, the change in length is directly proportional to the original length and the temperature change. The constant of proportionality for a particular material, the coefficient of linear expansion, α, is multiplied by the original length and temperature change to determine the change in length.



$$\Delta l = \alpha\, l_0\, \Delta T$$

Because the coefficient of linear expansion for steel given in the problem is 1.1×10^{-5} $(^{\circ}\mathrm{C})^{-1}$. A 5° increase in temperature will produce a bit more than half of 1/100 of a 1% increase in the length of the flute. Lengthening the flute lengthens the wavelength of the fundamental mode. (A flute is a pipe open at one end. $\lambda_{fund} = 4L$).

By itself the slightly longer wavelength would cause the flute to found flatter. However, despite the slightly longer wavelength the frequency is still going to be higher than before. This is because the approximately 1% increase in wave-speed in the warmer environment will increase the frequency much more than the flattening effect of the lengthening flute.

$$f = \frac{v}{\lambda_n} = \frac{n}{4L}v \quad (n = 1, 3, 5, \ldots)$$

4. A

Joule's experiment is one of the classics from the history of physics demonstrating conservation of energy. As the weight descends its gravitational potential energy is transformed into the work the paddles do on the water in which they are immersed. The work of the paddles is dissipated through friction into thermal energy. Joule demonstrated that the mechanical work of the paddles is quantitatively equivalent to heat flow.

First, we need to determine the initial potential energy of the weight.

$$U = mgh$$

$$U = (1\ \mathrm{kg})(10\ \mathrm{m/s^2})(0.8\ \mathrm{m})$$

$$U = 8\ \mathrm{J}$$

Now we determine the change in temperature brought about by the addition of 8 J thermal energy in 100 g of water.

$$Q = mc\Delta T$$

$$\Delta T = \frac{Q}{mc}$$

$$\Delta T = \frac{8\text{ J}}{(100\text{ g})(4.18\text{ J g}^{-1}\,^{\circ}\text{C}^{-1})}$$

$$\Delta T = 0.02\,^{\circ}\text{C}$$

5. C

The path has four steps: 1) heating the ice from -50°C to 0°C 2) melting the ice 3) heating the liquid water from 0°C to 100°C; and finally 4) boiling the water. The amount of heat which must be added for temperature change equals the product of the mass, specific heat and temperature change. For the phase changes, the amount of heat equals the product of the mass and the heat of transformation. Here are the computations for each of the four steps:

$$Q_{-50^{\circ}\text{C}\rightarrow 0^{\circ}\text{C}} = (100\text{ g})(.50\ \tfrac{\text{cal}}{\text{g}\,^{\circ}\text{C}})(50\ ^{\circ}\text{C}) = 2500\text{ cal}$$

$$Q_{\text{fusion}} = (100\text{ g})(80\ \tfrac{\text{cal}}{\text{g}}) = 8000\text{ cal}$$

$$Q_{0^{\circ}\text{C}\rightarrow 100^{\circ}\text{C}} = (100\text{ g})(1\ \tfrac{\text{cal}}{\text{g}\,^{\circ}\text{C}})(100\ ^{\circ}\text{C}) = 10{,}000\text{ cal}$$

$$Q_{\text{vaporization}} = (100\text{ g})(540\ \tfrac{\text{cal}}{\text{g}}) = 54{,}000\text{ cal}$$

$$\text{sum} = 74{,}500\text{ cal}$$

6. C

The triple point of a substance is the temperature and pressure at which the three phases of that substance coexist in thermodynamic equilibrium. It is a specific temperature and a specific pressure. The triple point of water is at 0.01°C (273.16K) and 611.2Pa (4.58 torr).

7. D

The rate of heat flow through the walls by conduction is proportional to the difference between the temperatures inside and outside the house.

$$\frac{Q}{t} = K A \frac{\Delta T}{\Delta x}$$

Q = heat flow
t = time
K = thermal conductivity of material
A = cross-sectional area
ΔT = temperature difference across the conductor $(T_2 - T_1)$
Δx = conductor thickness

During the day the temperature difference, ΔT, is 10°C. At night it is 20°C. Doubling the temperature difference at night results in a 100% increase in the rate of heat flow by conduction.

8. A

The space between the panes of glass in double glazed windows is very effective at reducing heat flow by conduction. Occupying the space is a gas with a very low thermal conductivity. The lower the thermal conductivity, K, the lower the rate of heat flow by conduction.

$$\frac{Q}{t} = K A \frac{\Delta T}{\Delta x}$$

Q = heat flow
t = time
K = thermal conductivity of material
A = cross-sectional area
ΔT = temperature difference across the conductor $(T_2 - T_1)$
Δx = conductor thickness

All of the other choices represent methods to decrease the rate of heat loss through infiltration, in other words, the bulk movement of air from the home.

9. C

The thermal energy stored by the wall is proportional to the mass of the wall, the specific heat of the stone, and the temperature change.

$$Q = mc\Delta T$$

$$m = \frac{Q}{c\Delta T}$$

$$m = \frac{5 \times 10^{5}\text{ kJ}}{(0.8\text{ kJ kg}^{-1}\,^{\circ}\text{C}^{-1})(20^{\circ}\text{C})}$$

$$m = 31{,}250\text{ kg}$$

10. D

Radiation is heat flow by electromagnetic waves. The rate of heat flow, $\frac{Q}{t}$, from a body by radiation is proportional to the *fourth power* of the temperature. (The rate also depends on the surface area of the body and the emissivity, ε, of the material. σ is Stefan-Boltzmann constant (5.7 × 10^{-8} W/m^2 · K^2))

$$\frac{Q}{t} = A\varepsilon\sigma T^4$$

Doubling temperature leads to a *sixteen fold* increase in the rate of emission of radiation.

$$\left(\frac{Q}{t}\right)_{new} = A\varepsilon\sigma\,(2T)^4 = 16A\varepsilon\sigma T^4$$

11. B

The heating power required will equal the rate of heat loss through the walls by conduction:

$$\frac{Q}{t} = K\,A\,\frac{\Delta T}{\Delta x}$$

$$\frac{Q}{t} = (3.1 \times 10^{-2}\ \text{W/m}\cdot{}^{\circ}\text{C})(2.4 \times 10^{1}\ \text{m}^2)\ \frac{5 \times 10^{1}\ {}^{\circ}\text{C}}{2.5 \times 10^{-1}\ \text{m}}$$

$$\frac{Q}{t} = 149\ \text{W} \sim 150\ \text{W}$$

12. D

First, let's convert the size of the furnace port into SI units, from cm^2 to m^2.

$$100\ \text{cm}^2 \bullet \left(\frac{1 \times 10^{-2}\ \text{m}}{\text{cm}}\right)\left(\frac{1 \times 10^{-2}\ \text{m}}{\text{cm}}\right)$$

$$= 1 \times 10^{-2}\ \text{m}^2$$

The port of the furnace is a reasonable approximation of a blackbody perfect emitter (ε = 1). The rate of heat flow by radiation is proportional to the surface area of the body, the emissivity, ε, of the material and the fourth power of the temperature.

$$\frac{Q}{t} = A\varepsilon\sigma T^4$$

Q = heat (light) emitted
t = time
A = surface area of emitter
ε = emissivity
σ = Stefan-Boltzmann constant (5.7 × 10^{-8} W/m^2 · K^2)
T = emitter absolute temperature

Solving for the temperature of our glass blower's furnace is a good exercise in operations of scientific notation and mental math.

$$\frac{Q}{t} = A\varepsilon\sigma T^4$$

$$2.4 \times 10^{3}\ \text{J/s} = (10^{-2}\ \text{m}^2)(1)(6 \times 10^{-8}\ \text{W/m}^2\cdot\text{K}^2)\ T^4$$

$$T^4 = \frac{2.4 \times 10^{3}}{6 \times 10^{-10}}$$

$$T^4 = 4 \times 10^{12}$$

$$T = 1.4 \times 10^{3}\ \text{K}$$

Taking the 4th root of 4 × 10^{12} is the same as taking the square root of the square root. Also, simplifying the Stefan-Boltzmann constant to make our math easier landed us a little lower than the answer choice. When you do mental math and simplify numbers, keep track of the direction the error is going to propagate. This will help you feel comfortable with your answer choice and may help you distinguish the correct answer if you land between two choices. This usually won't be a problem, though, because numerical answer choices on the MCAT are almost always spaced far apart. The MCAT encourages mental math.

13. D

Because the specific heat of water is close to mind expressed on a per gram basis, let's convert our flow rate from L/hr to ml/s. Remember 1 ml$_{H2O}$ = 1 g$_{H2O}$, so this will also be g/s.

$$\left(\frac{35\ \text{L}}{\text{hr}}\right)\left(\frac{\text{hr}}{3600\ \text{s}}\right)\left(\frac{1000\ \text{ml}}{\text{L}}\right) \approx \frac{10\ \text{ml}}{\text{s}} = \frac{10\ \text{g}}{\text{s}}$$

10g of water is flowing through the system per second, leaving 15°C warmer. Because the specific heat of water is 1 cal g^{-1} $°C^{-1}$, it's very good if you see 10g of water increasing 15°C and say, 'that's 150 calories', and because 1 cal = 4.18 J, you know then that's about 600 J, so the power output of the solar water heater is 600 J/s or about 600 W.

$$\left(\frac{10\text{ g}}{\text{s}}\right)\left(\frac{4.18\text{ J}}{\text{g °C}}\right)\left(15\text{ °C}\right) \approx 600\text{ W}$$

14. B

The coefficient of linear expansion, α, is multiplied by the original length and temperature change to determine the change in length.

$$\Delta l = \alpha\, l_0\, \Delta T$$

$$\Delta l = (1.7 \times 10^{-5})(5\text{ m})(40\text{ °C})$$

$$= 3.4 \times 10^{-3}\text{ m}$$

15. C

In the passage collector efficiency is defined as the ratio of the usable energy output to the incident solar radiation. 100% efficiency would only occur if *both* choices 'B' and 'A' are true, ie. the absorptance of the collector is 100% and energy losses from the collector are zero.

16. B

The stagnation temperature is the temperature at which all absorbed energy is lost to the surroundings. The glass plate and casement would decrease the rate of conduction losses from the collector plate to the environment for a given temperature difference much as a double-glazed window decreases conduction losses from a heated building to the outside air. Therefore, our water heater system would require a higher collector temperature for the rate of energy loss to equal the rate of absorption if the collector were covered with a glass plate and casement.

17. B

The rate of heat loss from the system by conduction to the surroundings increases with temperature. At the stagnation temperature, the rate of heat loss has grown to equal the rate of absorption. It is the maximum temperature for the collector for given insolation and ambient wind conditions.