University of New Mexico
Mechanical Engineering
Spring 2012 PhD qualifying examination
Heat Transfer

Closed book. Formula sheet and calculator are allowed, but not cell phones, computers or any other wireless device.
Time allowed: 150 minutes.

Part 1: General knowledge questions (25 points)

1. The physical significance of the Biot number is
   (a) the ratio of elapsed time to time required to reach steady-state.
   (b) the ratio of conductive resistance on one side of the interface to convective resistance on the other.
   (c) the ratio of convective resistance on one side of the interface to conductive resistance on the other.

   Answer:

2. For large Biot numbers in steady-state problems, the temperature distribution is
   (a) uniform, but time dependant.
   (b) uniform and not time dependant.
   (c) time dependant, not necessarily uniform.

   Answer:

3. In radiant heat transfer, the emissivity is a number which represents
   (a) the capacity of a real surface to emit thermal radiation relative to an ideal surface.
   (b) the capacity of a surface to reflect photons from a nearby emitter.
   (c) the capacity of a surface to emit visible radiation.

   Answer:

4. In radiant heat transfer, a blackbody surface is
   (a) a surface which absorbs all photons in the visible spectrum.
   (b) a surface which reflects all photons in the visible spectrum.
   (c) a surface which absorbs all photons in the thermal spectrum.

   Answer:

5. Sometimes, increasing the thickness of insulation on a pipe actually increases the heat loss. This is because:
   (a) sometimes the insulation materials is a bad insulator.
   (b) there is more heat loss because the insulation heats up when in contact with the pipe.
   (c) while the conductive resistance increases, the convective resistance is reduced.

   Answer:

6. When an incandescent light is turned off, the filament loses heat primarily by
   (a) conduction.
   (b) convection.
   (c) radiation.

   Answer:

7. A long cylinder is heat-treated by immersing it in an oil bath. For the purposes of calculating transient behavior, the relevant characteristic dimension is the
   (a) radius.
   (b) diameter.
   (c) length.

   Answer:

8. Dimensional analysis in heat transfer is useful because?
   (a) it allows us to perform experiments with the smallest parameter space.
   (b) it makes certain correlations look much more elegant.
   (c) it eliminates the confusion of converting between units.

   Answer:

9. The Fourier number represents
   (a) the number of terms necessary in a transient heat conduction solution by Fourier series.
   (b) the dimensionless time scale resulting from the shape and properties of the solid object being cooled.
   (c) the dimensionless time scale resulting from the convection process around the solid object being cooled.

   Answer:

10. Electronic components in a space vehicle must be cooled by some cooling device. In turn, the device rejects heat to the outside by
    (a) radiation.
    (b) convection.
    (c) both convection and radiation.

    Answer:

Part 2: Problems (25 points per question)

Attempt all problems in this section, clearly stating any assumptions and simplifications used in your solution.

Problem 1

In the vulcanization of tires, the carcass is placed into a jig and steam at 150°C is admitted suddenly to both sides. The tire thickness is 2.5 cm, initial temperature is 21°C, the convection coefficient h is 150 W/m^2·K, the density ρ is 240 kg/m^3, the specific heat capacity c is 1650 J/kg·K, and the conductivity k is 0.16 W/m·K. What is the time required for the center of the rubber to reach 132°C?

Problem 2

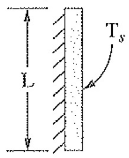
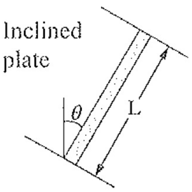
A beer can 160 mm long and 75 mm in diameter is initially at 30°C, and is to be cooled in a refrigerator to 2°C. In the interest of maximizing the cooling rate, should the can be laid horizontally or vertically in the compartment? As a first approximation, neglect heat transfer from the ends.

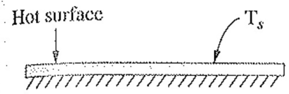
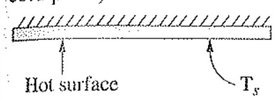
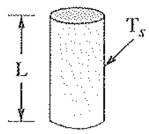
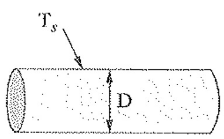
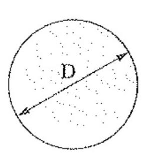
Problem 3

Solar irradiation of 1100 W/m^2 is incident on a large flat horizontal metal roof on a day when air flowing over the roof causes a heat transfer coefficient of 25 $W/m^2{\cdot}K$. The outside air temperature is 27°C, the metal surface absorptivity for solar radiation is 0.6, the metal surface emissivity is 0.2. The sky temperature is 70 K. If the roof is well insulated from below, calculate the steady-state temperature of the roof.

Properties of air at 1 atm pressure

Temp. T, °C	Density ρ, kg/m³	Specific Heat c_p, J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m²/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m²/s	Prandtl Number Pr
−150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
−100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-5}	5.837×10^{-6}	0.7263
−50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
−40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
−30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
−20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
−10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935
350	0.5664	1056	0.04721	7.892×10^{-5}	3.101×10^{-5}	5.475×10^{-5}	0.6937
400	0.5243	1069	0.05015	8.951×10^{-5}	3.261×10^{-5}	6.219×10^{-5}	0.6948
450	0.4880	1081	0.05298	1.004×10^{-4}	3.415×10^{-5}	6.997×10^{-5}	0.6965
500	0.4565	1093	0.05572	1.117×10^{-4}	3.563×10^{-5}	7.806×10^{-5}	0.6986
600	0.4042	1115	0.06093	1.352×10^{-4}	3.846×10^{-5}	9.515×10^{-5}	0.7037
700	0.3627	1135	0.06581	1.598×10^{-4}	4.111×10^{-5}	1.133×10^{-4}	0.7092
800	0.3289	1153	0.07037	1.855×10^{-4}	4.362×10^{-5}	1.326×10^{-4}	0.7149
900	0.3008	1169	0.07465	2.122×10^{-4}	4.600×10^{-5}	1.529×10^{-4}	0.7206
1000	0.2772	1184	0.07868	2.398×10^{-4}	4.826×10^{-5}	1.741×10^{-4}	0.7260
1500	0.1990	1234	0.09599	3.908×10^{-4}	5.817×10^{-5}	2.922×10^{-4}	0.7478
2000	0.1553	1264	0.11113	5.664×10^{-4}	6.630×10^{-5}	4.270×10^{-4}	0.7539

Geometry	*Characteristic length*, L_c	*Range of* Ra	Nu
Vertical plate  	L	10^4–0^9 10^9–10^{13} Entire range	$Nu = 0.59\ Ra^{1/4}$ $Nu = 0.1\ Ra^{1/3}$ $Nu = \left\{0.825 + \frac{0.387\ Ra^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right\}^2$ (complex but more accurate)
Inclined plate  	L		Use vertical plate equations as a first degree of approximation Replace g by $g \cos \theta$ for $Ra < 10^9$

Geometry	*Characteristic length*, L_c	*Range of* Ra	Nu
Horizontal plate (surface area A_s and perimeter P) (a) Upper surface of a hot plate (or lower surface of a cold plate) 	$\frac{A_s}{P}$	10^4–10^7 10^7–10^{11}	$Nu = 0.54\ Ra^{1/4}$ $Nu = 0.15\ Ra^{1/3}$
(b) Lower surface of a hot plate (or upper surface of a cold plate) 		10^5–10^{11}	$Nu = 0.27\ Ra^{1/4}$
Vertical cylinder 	L		A vertical cylinder can be treated as a vertical plate when $D \geq \frac{35\,L}{Gr^{1/4}}$
Horizontal cylinder 	D	10^5–10^{12}	$Nu = \left\{0.6 + \frac{0.387\ Ra^{1/6}}{[1 + (0.559/Pr)^{9/16}]^{8/27}}\right\}^2$
Sphere 	$\frac{1}{2}\pi D$	$Ra \leq 10^{11}$ $(Pr \geq 0.7)$	$Nu = 2 + \frac{0.589\ Ra^{1/4}}{[1 + (0.469/Pr)^{9/16}]^{4/9}}$

Summary of the solutions for one-dimensional transient conduction in a plane wall of thickness $2L$, a cylinder of radius r_o and a sphere of radius r_o subjected to convention from all surfaces.*

Geometry	Solution	λ_n's are the roots of
Plane wall	$\theta = \sum_{n=1}^{\infty} \frac{4 \sin \lambda_n}{2\lambda_n + \sin(2\lambda_n)} e^{-\lambda_n^2 \tau} \cos(\lambda_n x/L)$	l_n tan l_n 5 Bi
Cylinder	$\theta = \sum_{n=1}^{\infty} \frac{2}{\lambda_n} \frac{J_1(\lambda_n)}{J_0^2(\lambda_n) + J_1^2(\lambda_n)} e^{-\lambda_n^2 \tau} J_0(\lambda_n r/r_o)$	$\lambda_n \frac{J_1(\lambda_n)}{J_0(\lambda_n)} = \mathrm{Bi}$
Sphere	$\theta = \sum_{n=1}^{\infty} \frac{4(\sin \lambda_n - \lambda_n \cos \lambda_n)}{2\lambda_n - \sin(2\lambda_n)} e^{-\lambda_n^2 \tau} \frac{\sin(\lambda_n x/L)}{\lambda_n x/L}$	$1 - \lambda_n \cot \lambda_n = \mathrm{Bi}$

*Here $\theta = (T - T_\infty)/(T_i - T_\infty)$ is the dimensionless temperature, $\mathrm{Bi} = hL/k$ or hr_o/k is the Biot number, $\mathrm{Fo} = \tau = \alpha t / L^2$ or $\alpha\tau / r_o^2$ is the Fourier number, and J_0 and J_1 are the Bessel functions of the first kind whose values are given in Table 4–3.

Coefficients used in the one-term approximate solution of transient one-dimensional heat conduction in plane walls, cylinders, and spheres (Bi = hL/k for a plane wall of thickness $2L$, and Bi = hr_o/k for a cylinder or sphere of radius r_o)

	Plane Wall		*Cylinder*		*Sphere*	
Bi	λ_1	A_1	λ_1	A_1	λ_1	A_1
0.01	0.0998	1.0017	0.1412	1.0025	0.1730	1.0030
0.02	0.1410	1.0033	0.1995	1.0050	0.2445	1.0060
0.04	0.1987	1.0066	0.2814	1.0099	0.3450	1.0120
0.06	0.2425	1.0098	0.3438	1.0148	0.4217	1.0179
0.08	0.2791	1.0130	0.3960	1.0197	0.4860	1.0239
0.1	0.3111	1.0161	0.4417	1.0246	0.5423	1.0298
0.2	0.4328	1.0311	0.6170	1.0483	0.7593	1.0592
0.3	0.5218	1.0450	0.7465	1.0712	0.9208	1.0880
0.4	0.5932	1.0580	0.8516	1.0931	1.0528	1.1164
0.5	0.6533	1.0701	0.9408	1.1143	1.1656	1.1441
0.6	0.7051	1.0814	1.0184	1.1345	1.2644	1.1713
0.7	0.7506	1.0918	1.0873	1.1539	1.3525	1.1978
0.8	0.7910	1.1016	1.1490	1.1724	1.4320	1.2236
0.9	0.8274	1.1107	1.2048	1.1902	1.5044	1.2488
1.0	0.8603	1.1191	1.2558	1.2071	1.5708	1.2732
2.0	1.0769	1.1785	1.5995	1.3384	2.0288	1.4793
3.0	1.1925	1.2102	1.7887	1.4191	2.2889	1.6227
4.0	1.2646	1.2287	1.9081	1.4698	2.4556	1.7202
5.0	1.3138	1.2403	1.9898	1.5029	2.5704	1.7870
6.0	1.3496	1.2479	2.0490	1.5253	2.6537	1.8338
7.0	1.3766	1.2532	2.0937	1.5411	2.7165	1.8673
8.0	1.3978	1.2570	2.1286	1.5526	2.7654	1.8920
9.0	1.4149	1.2598	2.1566	1.5611	2.8044	1.9106
10.0	1.4289	1.2620	2.1795	1.5677	2.8363	1.9249
20.0	1.4961	1.2699	2.2880	1.5919	2.9857	1.9781
30.0	1.5202	1.2717	2.3261	1.5973	3.0372	1.9898
40.0	1.5325	1.2723	2.3455	1.5993	3.0632	1.9942
50.0	1.5400	1.2727	2.3572	1.6002	3.0788	1.9962
100.0	1.5552	1.2731	2.3809	1.6015	3.1102	1.9990
∞	1.5708	1.2732	2.4048	1.6021	3.1416	2.0000