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THE GEORGE W. WOODRUFF SCHOOL OF MECHANICAL ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY

DESIGN QUALIFIER

SPRING 2018

PART I. WRITTEN EXAMINATION

We are interested in learning what you know and your ability to reason in the formulation and solution of design problems.

If you find any part of this exam confusing, please state your assumptions and rephrase the question and proceed.

Please read the entire exam first.

Questions I, IIA and IIB carry equal points.

Allocate your time carefully so that you cover all three parts that you are being examined on in these two questions, namely Methodology and Analysis.

PART II. ORAL EXAMINATION

Please arrive 30 minutes before the scheduled time for the oral exam. During this period we will give you a question to think about. The scope of the oral exam is as follows:

- provide an opportunity for you to state how design fits into your research activities;
- probe your understanding on the question that we posed to you in the preceding half hour.

QUESTION I. – DESIGN METHODOLOGY (10 points)

DESIGN PROBLEM – COMPOSTING FOR SMALL TO MEDIUM SIZE FARMS

Farmers with small to medium sized farms have to manually mix their compost. They want the warmest compost in the center of the pile to disperse and distribute heat as well as aerate the microbes. A pile of compost may be about a cubic yard and so mixing can be physically difficult and of uncertain quality. Large industrial mixers and small garden size mixers, shown in Figure 1, are either too large and expensive or too small for these farmers. You are tasked with designing an automated mixing device that handles intermediate volumes of compost.

Figure 1: A home garden composter that mixes by manual rotation (left) and an industrial mechanical mixer (right)

Your boss wants you to start from benchmarking solutions and to document your design process thoroughly. You are required to follow the guidelines of a systematic design methodology and turn in a report documenting the main deliverables as follows.

DELIVERABLES (YOU ARE REQUIRED TO ELABORATED THESE ISSUES)

1.1 *Requirement Analysis:*

To clarify the design task, you need to identify the design requirements based on customer needs and functional requirements.

(a) Develop a list of quantifiable design requirements through a systematic design process. **(2 pt.)**

1.2 *Conceptual Design:*

(a) Develop a list of functional requirements in solution neutral terms for your design based on customer needs. Compose appropriate functional diagram(s) that characterize the overall function and its decomposition into sub-functions. You are required to use one of the formal function analysis tools (examples include, but are not limited to EMS models, Functional Basis, FBS, IDEF0, FAST, UML). List the name of the method and include a quick sketch of the device you made a functional model of. **(3 pt.)**

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1.3 *Design Evaluation:*

(a) Formulate a structured, systematic procedure for evaluating your design concept(s). Hint: You may use one of the formal methods (No intuition-based approach please, e.g., evaluating by subjective scores). You could use such formal methods as Pugh Selection Matrix, QFD, or multi-attribute decision making, etc. **(3 pt.)**

1.4 *Embodiment:*

(a) Outline what types of engineering analysis or experimentation that may be needed in order to justify the technical feasibility of your design. Note we are not talking about engineering analysis at the detailed design stage, but the system-level design – embodiment design. This includes back of the envelop calculations for key system parameters or planned experiments to determine feasibility of the design. **(2 pt.)**

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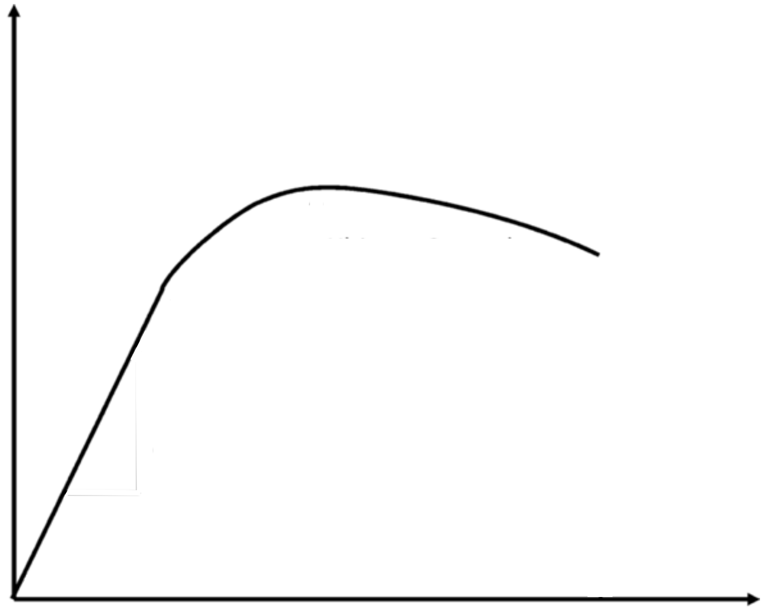
Question IIA. (10 points)

1. On the plot below (2 points)
  a. Label the axes with "Stress" or "Strain"
  b. Indicate where the yield strength is
  c. Indicate where the ultimate strength is
  d. Indicate where the fracture point is
  e. Describe how you can find the Young's Modulus of the material from the plot.



2. Fill in the blanks below. (1.5 points)

The Coulomb-Mohr Theory predicts failure for materials whose ____________ in

____________________ and ________________ are not equal.

3. In gear design, what does the contact ratio indicate? (1 point)

4. For the following bearing types, indicate whether they can be used for thrust loading, radial loading, or both. (2 points)

Ball bearing ____________________________________

Straight roller bearing ____________________________________

Needle bearing ____________________________________

Tapered roller bearing ____________________________________

5. In the Modified Goodman Equation (shown below), what does σ_a represent (0.5 points)?

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} = \frac{1}{n}$$

6. What is the difference between tolerances and limits? **(1 point)**

7. What are the four end types for compression springs? (**1 point):**

8. Match the description to the parameter name by drawing a line to connect them. (1 point)

The ratio between the force applied to the member and the deflection produced by that force

The ratio of the proportional decrease in a lateral measurement to the proportional increase in length in a sample of material that is elastically stretched

The ratio of shear stress to displacement per unit sample length

The ratio of the energy absorbed to the unit volume without permanent deformation

Poisson Ratio

Modulus of Resilience

Modulus of Rigidity

Spring Rate

Problem IIB –Machine Design

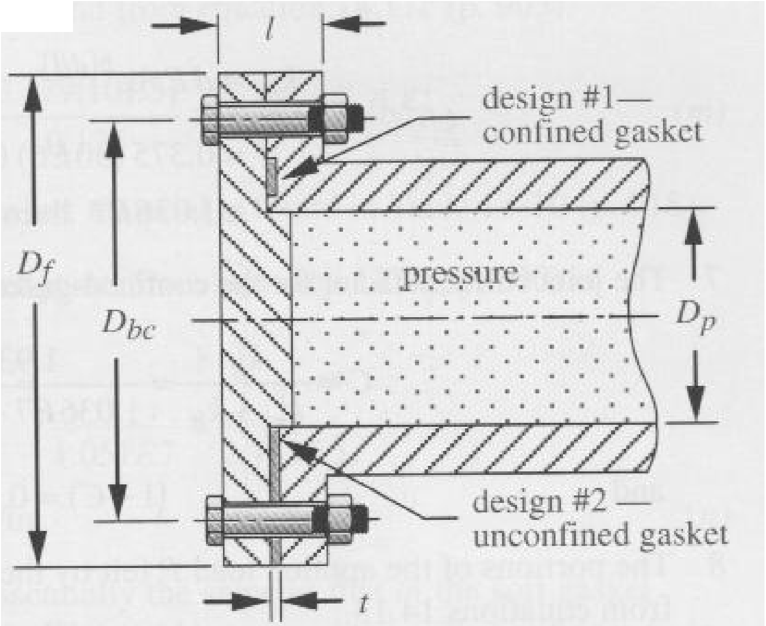


Figure 2 –Bolted Flange of Gas Cylinder

In Figure 2, a schematic drawing of a flanged cylindrical pipe is given. The pipe is sealed off by a lid that is bolted onto the pipe's flange. The pressure in the cylinder is 1500 psi. Furthermore, the initial design has the dimensions $D_f = 5.8$ inch; $D_{bc} = 5.5$ inch; $D_p = 5$ inch. The outer diameter of the pipe is 5.2 inches.

The clamped length of the joint (denoted *l* in Figure 2) is 1.5 inch. Both the lid and pipe are made out of the same material (steel) with modulus of elasticity of 30 MPsi. The bolts are steel 3/8-16 UNC SAE class 5.2 bolts with tensile stress area of .0775 inch^2 and proof strength 85 kpsi. Modulus of elasticity is also 30 MPsi. The length of the bolt shank is 1 inch.

Assume that four bolts are used in the assembly and <u>no gaskets are used</u> (contrary to what is shown in the diagram).

Answer the following questions:

a) Calculate the joint stiffness factor (or bolt constant) C (5 pt)
b) Assuming a bolt constant of 0.35, calculate the minimum pre-load F_i required to avoid joint separation. (2 pt)
c) Assuming a preload of 6000 lbs per bolt, calculate the factor of safety against static bolt failure. Will the joint fail? (3 pt)

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Design Qualifying Exam Equation Sheet - Page 1

$$n_d = \frac{\text{loss-of-function strength}}{\text{allowable stress}} = \frac{S}{\sigma(\text{or } \tau)}$$

$$V = \frac{dM}{dx}$$

$$\sigma^3 - (\sigma_x + \sigma_y + \sigma_z)\sigma^2 + \left(\sigma_x\sigma_y + \sigma_x\sigma_z + \sigma_y\sigma_z - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{zx}^2\right)\sigma - \left(\sigma_x\sigma_y\sigma_z + 2\tau_{xy}\tau_{yz}\tau_{zx} - \sigma_x\tau_{yz}^2 - \sigma_y\tau_{zx}^2 - \sigma_z\tau_{xy}^2\right) = 0$$

$$\frac{dV}{dx} = \frac{d^2M}{dx^2} = q$$

$$\tau_{1/2} = \frac{\sigma_1 - \sigma_2}{2} \qquad \tau_{2/3} = \frac{\sigma_2 - \sigma_3}{2} \qquad \tau_{1/3} = \frac{\sigma_1 - \sigma_3}{2}$$

$$\int_{V_A}^{V_B} dV = V_B - V_A = \int_{x_A}^{x_B} q\,dx$$

$$\sigma = E\epsilon \qquad \epsilon_x = \frac{\sigma_x}{E} \qquad \epsilon_y = \epsilon_z = -\nu\frac{\sigma_x}{E}$$

$$\int_{M_A}^{M_B} dM = M_B - M_A = \int_{x_A}^{x_B} V\,dx$$

$$\epsilon_x = \frac{1}{E}\left[\sigma_x - \nu(\sigma_y + \sigma_z)\right]$$

$$\epsilon_y = \frac{1}{E}\left[\sigma_y - \nu(\sigma_x + \sigma_z)\right]$$

$$\epsilon_z = \frac{1}{E}\left[\sigma_z - \nu(\sigma_x + \sigma_y)\right]$$

$$\tau_{yx} = \tau_{xy} \qquad \tau_{zy} = \tau_{yz} \qquad \tau_{xz} = \tau_{zx}$$

$$\sigma = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\phi + \tau_{xy}\sin 2\phi$$

$$\tau = -\frac{\sigma_x - \sigma_y}{2}\sin 2\phi + \tau_{xy}\cos 2\phi$$

$$\sigma = \frac{F}{A} \qquad \sigma_x = -\frac{My}{I} \qquad I = \int y^2 dA$$

$$\tan 2\phi_p = \frac{2\tau_{xy}}{\sigma_x - \sigma_y}$$

$$\sigma_{\max} = \frac{Mc}{I} \qquad \sigma_{\max} = \frac{M}{Z}$$

$$\frac{\sigma_x - \sigma_y}{2}\sin 2\phi_p - \tau_{xy}\cos 2\phi_p = 0$$

$$\tau = \frac{VQ}{Ib} \qquad \tau = G\gamma \qquad \tau = \frac{V}{A}$$

$$\tan 2\phi_s = -\frac{\sigma_x - \sigma_y}{2\tau_{xy}}$$

$$\tau = \frac{T\rho}{J} \qquad \tau_{\max} = \frac{Tr}{J} \qquad \theta = \frac{Tl}{GJ}$$

$$\frac{\sigma_x - \sigma_y}{2}\cos 2\phi_p + \tau_{xy}\sin 2\phi_p = 0$$

$$E = 2G(1 + \nu) \qquad \epsilon_x = \epsilon_y = \epsilon_z = \alpha(\Delta T)$$

$$\sigma = \frac{\sigma_x + \sigma_y}{2}$$

$$\sigma = -\epsilon E = -\alpha(\Delta T)E$$

$$H = T\omega \qquad T = 9.55\frac{H}{n}$$

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

$$K_t = \frac{\sigma_{\max}}{\sigma_0} \qquad K_{ts} = \frac{\tau_{\max}}{\tau_0}$$

$$\tau_1, \tau_2 = \pm\sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

$$H = \frac{FV}{33\,000} = \frac{2\pi Tn}{33\,000(12)} = \frac{Tn}{63\,025}$$

Design Qualifying Exam Equation Sheet - Page 2

$$k_c = \begin{cases} 1 & \text{bending} \\ 0.85 & \text{axial} \\ 0.59 & \text{torsion}^{17} \end{cases}$$

$$k_d = 0.975 + 0.432(10^{-3})T_F - 0.115(10^{-5})T_F^2 + 0.104(10^{-8})T_F^3 - 0.595(10^{-12})T_F^4$$

$$P_{\text{cr}} = \frac{\pi^2 EI}{l^2}$$

$$k_e = 1 - 0.08\,z_a$$

$$\sigma_{\max} = K_f \sigma_0 \qquad \text{or} \qquad \tau_{\max} = K_{fs}\tau_0$$

$$k_a = aS_{ut}^b$$

$$K_f = \frac{\text{maximum stress in notched specimen}}{\text{stress in notch-free specimen}}$$

$$P_{\text{cr}} = \frac{C\pi^2 EI}{l^2}$$

$$K_f = 1 + \frac{K_t - 1}{1 + \sqrt{a/r}}$$

$$\frac{P_{\text{cr}}}{A} = S_y - \left(\frac{S_y}{2\pi}\frac{l}{k}\right)^2 \frac{1}{CE} \qquad \frac{l}{k} \le \left(\frac{l}{k}\right)_1$$

$$K_f = 1 + q(K_t - 1) \qquad \text{or} \qquad K_{fs} = 1 + q_{\text{shear}}(K_{ts} - 1)$$

$$\left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}\right]^{1/2} \ge S_y$$

$$q = \frac{K_f - 1}{K_t - 1} \qquad \text{or} \qquad q_{\text{shear}} = \frac{K_{fs} - 1}{K_{ts} - 1}$$

$$\sigma' = \left[\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}\right]^{1/2}$$

$$\sqrt{a} = 0.190 - 2.51(10^{-3})S_{ut} + 1.35(10^{-5})S_{ut}^2 - 2.67(10^{-8})S_{ut}^3$$

$$\sigma' = \left(\sigma_A^2 - \sigma_A\sigma_B + \sigma_B^2\right)^{1/2} \qquad \sigma' \ge S_y$$

$$\sigma' = \frac{1}{\sqrt{2}}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)\right]^{1/2}$$

$$\sigma' = \left(\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 + 3\tau_{xy}^2\right)^{1/2}$$

$$\sqrt{a} = 0.246 - 3.08(10^{-3})S_{ut} + 1.35(10^{-5})S_{ut}^2 - 2.67(10^{-8})S_{ut}^3$$

$$S'_e = \begin{cases} 0.5S_{ut} & S_{ut} \le 200 \text{ kpsi (1400 MPa)} \\ 100 \text{ kpsi} & S_{ut} > 200 \text{ kpsi} \\ 700 \text{ MPa} & S_{ut} > 1400 \text{ MPa} \end{cases}$$

$$K_{fm} = K_f \qquad K_f|\sigma_{\max,o}| < S_y$$

$$S_f = a\,N^b \qquad a = \frac{(fS_{ut})^2}{S_e}$$

$$K_{fm} = \frac{S_y - K_f\sigma_{ao}}{|\sigma_{mo}|} \qquad K_f|\sigma_{\max,o}| > S_y$$

$$N = \left(\frac{\sigma_{\text{rev}}}{a}\right)^{1/b} \qquad b = -\frac{1}{3}\log\left(\frac{fS_{ut}}{S_e}\right)$$

$$K_{fm} = 0 \qquad K_f|\sigma_{\max,o} - \sigma_{\min,o}| > 2S_y$$

$$S_f \ge S_{ut}N^{(\log f)/3} \qquad 1 \le N \le 10^3$$

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \qquad q = \frac{1}{1 + \frac{\sqrt{a}}{\sqrt{r}}}$$

$$S_e = k_a k_b k_c k_d k_e k_f S'_e$$

$$\sigma_a = \left|\frac{\sigma_{\max} - \sigma_{\min}}{2}\right| \qquad \frac{S_a}{S_e} + \frac{S_m}{S_{ut}} = 1$$

mod-Goodman $\dfrac{\sigma_a}{S_e} + \dfrac{\sigma_m}{S_{ut}} = \dfrac{1}{n}$

Langer static yield $\sigma_a + \sigma_m = \dfrac{S_y}{n}$

Design Qualifying Exam Equation Sheet - Page 3

DE-Goodman

$$\frac{1}{n} = \frac{16}{\pi d^3}\left\{\frac{1}{S_e}\left[4(K_f M_a)^2 + 3(K_{fs} T_a)^2\right]^{1/2} + \frac{1}{S_{ut}}\left[4(K_f M_m)^2 + 3(K_{fs} T_m)^2\right]^{1/2}\right\}$$

$$\sigma'_{\max} = \left[(\sigma_m + \sigma_a)^2 + 3(\tau_m + \tau_a)^2\right]^{1/2}$$

$$= \left[\left(\frac{32K_f(M_m + M_a)}{\pi d^3}\right)^2 + 3\left(\frac{16K_{fs}(T_m + T_a)}{\pi d^3}\right)^2\right]^{1/2}$$

$$\omega_1 = \left(\frac{\pi}{l}\right)^2\sqrt{\frac{EI}{m}} = \left(\frac{\pi}{l}\right)^2\sqrt{\frac{gEI}{A\gamma}}$$

$$D_{\max} = D + \Delta D \qquad D_{\min} = D$$

$$d_{\max} = d + \delta_F \qquad d_{\min} = d + \delta_F - \Delta d$$

$$d_{\min} = d + \delta_F \qquad d_{\max} = d + \delta_F + \Delta d$$

$$d = \left(\frac{16n}{\pi}\left\{\frac{1}{S_e}\left[4(K_f M_a)^2 + 3(K_{fs} T_a)^2\right]^{1/2} + \frac{1}{S_{ut}}\left[4(K_f M_m)^2 + 3(K_{fs} T_m)^2\right]^{1/2}\right\}\right)^{1/3}$$

$$F_b = P_b + F_i = CP + F_i \qquad F_m < 0$$

$$F_m = P_m - F_i = (1 - C)P - F_i \qquad F_m < 0$$

$$P_m = P_b \frac{k_m}{k_b} \qquad T = KF_i d$$

$$n_p = \frac{S_p A_t}{CP + F_i} \qquad n_L = \frac{S_p A_t - F_i}{CP}$$

$$n_0 = \frac{F_i}{P(1 - C)}$$

$$F_p = A_t S_p \qquad \sigma_a = \frac{C(P_{\max} - P_{\min})}{2A_t}$$

$$n_f = \frac{S_a}{\sigma_a} \qquad n_f = \frac{S_e(S_{ut} - \sigma_i)}{S_{ut}\sigma_a + S_e(\sigma_m - \sigma_i)}$$

$$n_p = \frac{S_p}{\sigma_m + \sigma_a}$$

$$\sigma_m = \frac{(F_{b\max} + F_{b\min})/2}{A_t} = \frac{(CP_{\max} + F_i) + (CP_{\min} + F_i)}{2A_t}$$

$$\sigma_m = \frac{C(P_{\max} + P_{\min})}{2A_t} + \frac{F_i}{A_t}$$

$$F_i = \begin{cases} 0.75F_p & \text{for nonpermanent connections, reused fasteners} \\ 0.90F_p & \text{for permanent connections} \end{cases}$$

$$n_y = \frac{S_y}{\sigma'_{\max}} \qquad \tau = K_B \frac{8FD}{\pi d^3}$$

$$k \doteq \frac{d^4 G}{8D^3 N} \qquad y_{cr} = L_0 C'_1\left[1 - \left(1 - \frac{C'_2}{\lambda^2_{\text{eff}}}\right)^{1/2}\right]$$

$$\lambda_{\text{eff}} = \frac{\alpha L_0}{D} \qquad L_0 < \frac{\pi D}{\alpha}\left[\frac{2(E - G)}{2G + E}\right]^{1/2}$$

$$C'_1 = \frac{E}{2(E - G)}$$

$$L_0 < 2.63\frac{D}{\alpha}$$

$$C'_2 = \frac{2\pi^2(E - G)}{2G + E}$$

$$L_0 = 2(D - d) + (N_b + 1)d = (2C - 1 + N_b)d$$

$$S_{ut} = \frac{A}{d^m} \qquad \sigma_A = F\left[(K)_A \frac{16D}{\pi d^3} + \frac{4}{\pi d^2}\right]$$

$$(K)_A = \frac{4C_1^2 - C_1 - 1}{4C_1(C_1 - 1)} \qquad C_1 = \frac{2r_1}{d}$$

$$(K)_B = \frac{4C_2 - 1}{4C_2 - 4} \qquad C_2 = \frac{2r_2}{d}$$

$$N_a = N_b + \frac{G}{E} \qquad \tau_B = (K)_B \frac{8FD}{\pi d^3}$$

$$F = F_i + ky$$

$$FL^{1/a} = \text{constant} \qquad F_1 L_1^{1/a} = F_2 L_2^{1/a}$$

$$C_{10} = F_R = F_D\left(\frac{L_D}{L_R}\right)^{1/a} = F_D\left(\frac{\mathcal{L}_D n_D 60}{\mathcal{L}_R n_R 60}\right)^{1/a}$$

$$\frac{F_e}{VF_r} = 1 \qquad \text{when } \frac{F_a}{VF_r} \le e$$

$$\frac{F_e}{VF_r} = X + Y\frac{F_a}{VF_r} \qquad \text{when } \frac{F_a}{VF_r} > e$$

$$n_3 = \left|\frac{N_2}{N_3}n_2\right| = \left|\frac{d_2}{d_3}n_2\right| \qquad e = \frac{n_L - n_A}{n_F - n_A}$$

$$H = T\omega = (W_t d/2)\,\omega \qquad V = \pi dn/12$$

$$W_t = 33\,000\frac{H}{V} \qquad W_t = \frac{60\,000H}{\pi dn}$$

Tables/Figures to be provided on the exam if needed by Chapter in Shigley's Mechanical Engineering Design 9th Edition

Chapter 4
Tables: 4-2

Chapter 6:
Tables: 6-2, 6-3, 6-4, 6-5,
Figures: 6-20, 6-21

Chapter 7
Tables: 7-6, 7-9,

Chapter 8
Tables 8-1, 8-2, 8-9, 8-10, 8-11, 8-17

Chapter 10
Tables: 10-1, 10-2, 10-4, 10-5, 10-6, 10-7

Chapter 11
Tables: 11-1, 11-2, 11-3

Appendix tables: A-11, A12, A13, A-14, A-15-1 through A-15-16, A-18, A-20