ENGINEERING TRIPOS PART IB

Friday 7 June 1996 2 to 4

Paper 8

SELECTED TOPICS

Answer not more than **four** *questions.*

Answer questions from **two** *sections only.*

Do not answer more that **two** *questions from any section.*

Do not answer questions from **both** *sections C and D.*

Answers to questions in each section should be tied together and handed in separately.

(TURN OVER

SECTION A (Civil and Structural Engineering)

1 A continuous beam 1 m wide is to form the roof of a cut-and-cover tunnel as shown in Fig. 1(a). The beam is to have two spans, each 15 m long, and is to carry an ultimate load of 125 kN/m, which includes its own dead weight, as shown in Fig. 1(b). Under this load, the reaction at the central support would be 2344 kN.

It has been decided that the beam is to be singly reinforced for sagging bending, but is to be doubly reinforced for the relatively short length of hogging bending. It is to have a constant depth through its length, and is to be built from concrete with a cube strength of 40 N/mm^2 and high yield reinforcement.

(a) Plot the bending moment diagram, showing the maximum hogging and sagging bending moment, and the points of contraflexure.

(b) Determine a suitable thickness for the beam.

(c) Determine a suitable cross-sectional area for the steel to resist flexure in the sagging region.

(d) Determine a suitable cross-sectional area for the steel to resist flexure in the hogging region.

(e) Discuss where reinforcing bars could be curtailed for economy.

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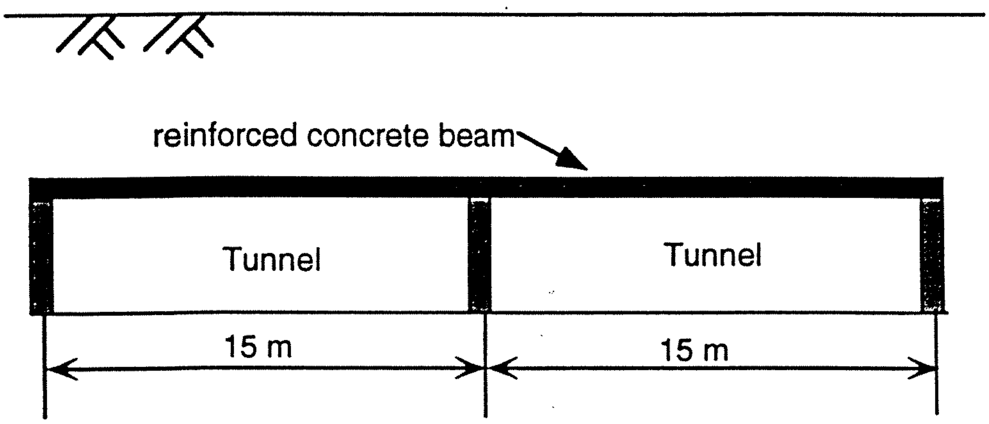

Fig. 1(a)

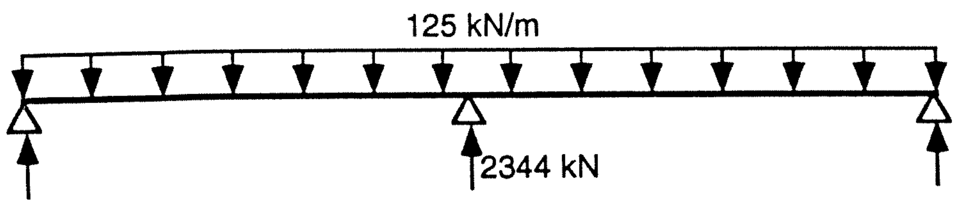

Fig. 1(b)

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2 The native surface soil in the vicinity of an abandoned industrial site is a poorly graded silty sand with a void ratio of 0.75 and a specific gravity of 2.67. Prior to redevelopment it is necessary to take care of a quantity of waste materials which contain the toxic heavy metals in solution in the Cu^{++} and Zn^{++} forms. It is proposed that these wastes are collected and stored on-site in containment ponds as shown in Fig. 2. In order to prevent excessive seepage into the ground and to the underlying aquifer, a clay liner must be constructed using the native silty sand mixed with Bentonite clay compacted to produce a low permeability material (i.e., a material having a coefficient of permeability k less than 1×10^{-10} m/s).

In order to economise in the use of expensive Bentonite clay, a number of tests are conducted to determine a suitable mixture. These indicate that the permeability requirement can be met and good field compaction can be obtained if (i) there is sufficient water such that the clay will be at its plastic limit (it is assumed that all water in the mixture is associated with the clay) and (ii) there is sufficient clay so that at this water content it just fills all the voids in the sand. The Bentonite has a liquid limit of 550 percent, a plasticity index of 450 percent, and a specific gravity of 2.80.

(a) Assuming that the void ratio of the silty sand in the mixture is the same as in its natural state, how much dry Bentonite clay is required? Give your answer as a percentage of the weight of dry silty sand.

(b) What will be the water content and the void ratio of the mixture after compaction?

(c) From the conditions of waste materials on the site, it is expected that after dumping of the waste the water will stand 2 m above the liner as shown in Fig. 2. The contaminants are not to reach the bottom of the liner in the next 250 years. What is the minimum thickness of the liner? Describe all the assumptions that you made for the calculation.

(d) Briefly comment on the problem of redevelopment of contaminated land.

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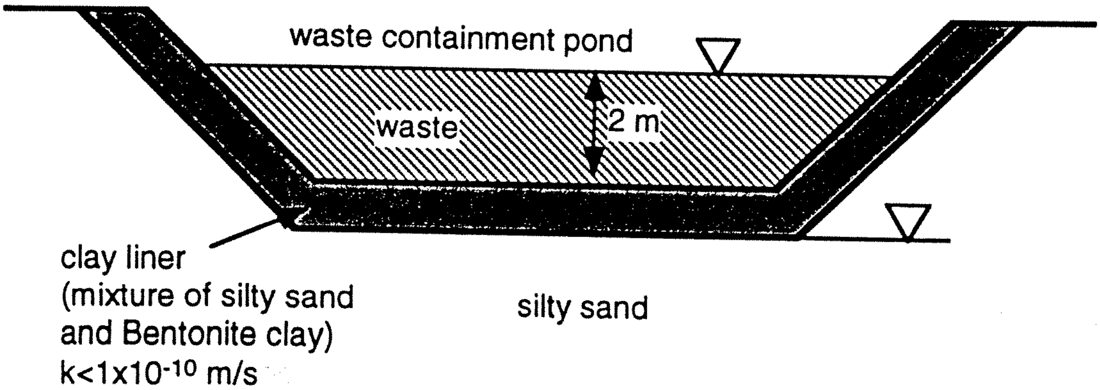

Fig. 2

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3 A 6 m high reinforced concrete cantilever retaining wall will be constructed along one side of a new building on a sand foundation as shown in Fig. 3. The proposed backfill is a grey uniform sand from the site, for which triaxial strength test results are available, as indicated in Table 1. The specific gravity of the sand is 2.70, and the minimum and maximum void ratios are 0.39 and 0.88 respectively. During the site investigation, a clay layer of 1 m thickness was found 2 m below the present ground surface.

(a) Assuming the water table is well below the foot of the wall, calculate and sketch the active earth pressure which the sand would exert on the wall if it were placed behind the wall at a relative density of 60 percent.

(b) During the rainy season, the water table may rise up to 3 m below the top of the fill. Estimate the value of the largest active earth pressure in a condition where drainage has failed. Sketch the pressure diagram acting on the wall.

(c) At a future date, a railway track will be constructed across the top of the fill along a line parallel to the wall. The loading applied to the top of the fill with a train on the track may be assumed to be an equivalent line load of 40 kN/m. If the track is constructed very close to the wall, calculate and sketch the additional earth pressure on the wall. Discuss the minimum distance behind the wall at which the track should be placed if the total force on the wall is not to be increased.

(d) Discuss the possible failure mechanisms of the wall.

Initial void ratio e	Maximum friction angle ϕ_{max}
0.40	42°
0.50	38°
0.60	35°
0.70	33°
0.80	30°

TABLE 1 Triaxial test data

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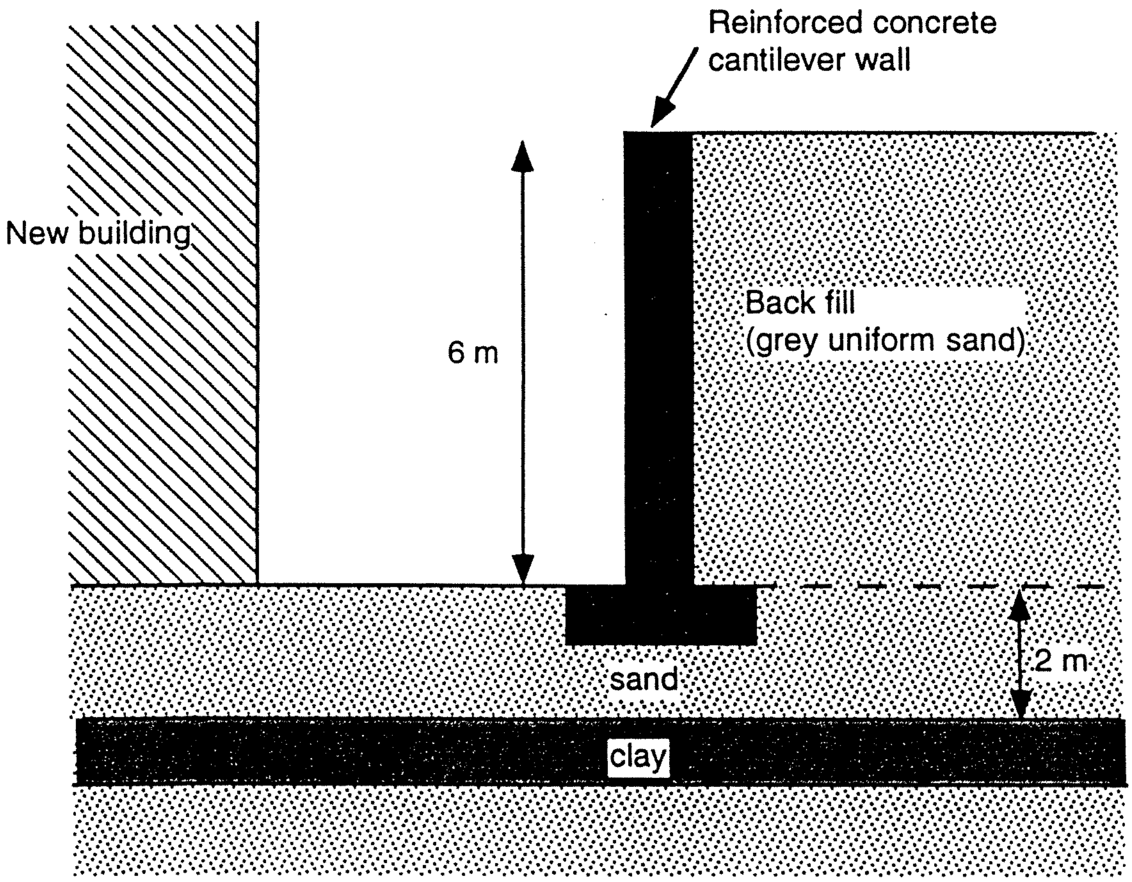

Fig. 3

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SECTION B (Mechanical Engineering, Manufacture and Management)

4 A steel gas pipeline has an outside diameter of 200 mm and a wall thickness of 10 mm. The pipe was originally buried beneath the sea floor. However, the action of coastal currents has led to sections of the pipe being uncovered and in places unsupported. A vibrating pig fitted with rotating eccentric masses is to be used to locate unsupported spans of around 15 m. At midspan, the pig excites the span's resonance and measures the vibration amplitude with an array of accelerometers.

(a) Estimate an appropriate rotational speed for the eccentric masses to detect the lowest natural frequency of a 15 m span.

(b) An array of accelerometers are used to detect the resultant midspan acceleration of ± 1 g. A charge amplifier then converts the accelerometer output to a voltage in the range ± 1 V. Design a suitable band-pass filter circuit using operational amplifiers to remove any unwanted signals outside the range of interest defined in (a). The filter should have unity gain in the pass band.

(c) What are the most common sources of accelerometer signal noise?

(d) The filtered accelerometer signals are to be sampled and the resulting data stored digitally. What is a minimum practical sampling frequency? How much data storage is required to store the data from two accelerometers and an odometer for a 10 hour logging run?

5 You are the Chief Designer in a company which sells pipeline inspection services. You have been investigating the feasibility of using a vibrating pig to detect the variations in support conditions of underwater pipelines. Your results look promising. Prepare a report to the company Board of Directors to persuade them to fund further development of the vibrating pig. Include discussion of all important marketing, design, production and management issues.

If, instead, you were the New Product manager in a brewing company trying to gain Management approval for a new beer, how might the discussion of production issues differ from that for the vibrating pig.

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6 A vibrating pig is shown schematically in Fig. 4. The pig of length L and diameter d, is held in the centre of a pipe of diameter D, by two polyurethane support disks of thickness t and spacing l positioned symmetrically about the length of the pig.

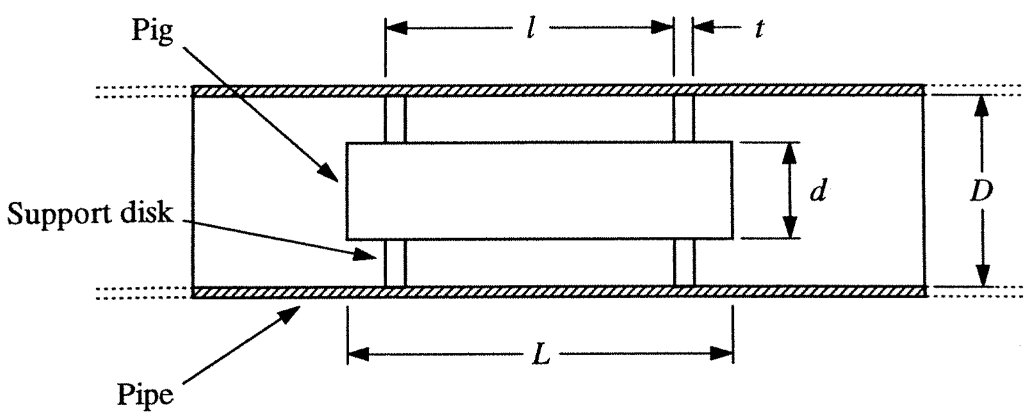

Fig. 4

(a) What function do the support disks perform during the operation of the vibrating pig?

(b) What precautions should be taken in the design of the support disks to ensure correct operation of the pig system?

(c) Estimate, using a simple approximation for the radial disk stiffness, the pig bounce and pitch natural frequencies of oscillation. You may assume that the support disks make complete contact with the pig and the pipe; $d = 100$ mm ; $D = 200$ mm ; $t = 20$ mm ; $l = 300$ mm ; $L = 400$ mm ; the mass of the pig is evenly distributed with a total mass of 15 kg ; and the shear modulus G of polyurethane is 200 MPa and its Young's modulus E may be approximated by $E = 3G$.

(d) Compare your results to those derived using the following data book formula for the radial stiffness k of a support disk.

$$k \approx t\,G\left\{\frac{80\pi(D^2+d^2)}{25(D^2+d^2)\ln(D/d)-9(D^2-d^2)}\right\}$$

(e) Discuss the relative accuracy of the natural frequencies estimated in (c) and (d) above.

SECTION C (Aerothermal Engineering)

7 (a) A bypass engine is fitted to an aircraft which cruises at Mach 0.85 at an altitude where the ambient pressure is 29 kPa and the ambient temperature is 227 K. Determine the stagnation pressure P_{02} and stagnation temperature T_{02} at inlet to the engines.

(b) After the core air-stream has passed through the fan, the stagnation temperature T_{024} is 301 K and the stagnation pressure P_{024} is 73.6 kPa. The core compressor has a stagnation pressure ratio of 25 and an isentropic efficiency of 0.9. Find the stagnation pressure P_{03} at exit from the core compressor. Show that the stagnation temperature T_{03} at exit from the core compressor is 805.5 K.

(c) The high-pressure turbine has an isentropic efficiency of 0.90. The stagnation temperature T_{04} at inlet to the high-pressure turbine is 1450 K. Determine the stagnation temperature T_{045} and the stagnation pressure P_{045} at entry to the low-pressure turbine. Explain why the pressure ratio across the high-pressure turbine is less than that across the core compressor.

(d) The stagnation temperature falls by 361 K across the low pressure turbine, which has an isentropic efficiency of 0.92. Determine the stagnation pressure P_{05} at entry to the propelling nozzle. Hence find the velocity of the core jet V_9.

(e) The velocity of the core jet and the bypass jet are the same. Determine the bypass ratio of the engine if the fan compresses the bypass stream isentropically.

Assume that the combustion products behave as a perfect gas with the same properties as air. Neglect any losses in the ductwork and the propelling nozzles.

(TURN OVER

8 (a) Explain what is meant by the terms *gross thrust* and *net thrust.*

(b) In a simple turbojet engine, the propelling nozzle is choked. Explain why the engine is unaffected by changes in ambient pressure P_a but is affected by changes in the stagnation pressure P_{02} at inlet to the compressor. What other parameters are sufficient to determine the operating point of the engine?

(c) The engine has a simple convergent propelling nozzle with an exit area A_N. The mass flow rate of fuel may be neglected. Use a control volume downstream of the nozzle to show that the gross thrust X_G of the engine may be written as

$$X_G + P_a A_N = \dot{m}_{air} V_9 + P_9 A_N$$

where $\dot{m}_{air}$ is the mass flow rate of air and V_9 and P_9 are the velocity and the pressure at the exit of the nozzle respectively.

(d) A stationary test is run on the ground. The engine is run at simulated cruise conditions. The ambient pressure is 101 kPa and the ambient temperature is 288 K. The mass flow rate of air through the engine is 500 kg/s and the turbine entry temperature is 1610 K. At cruise conditions in flight, the stagnation pressure is 45 kPa and the stagnation temperature is 255 K at entry to the compressor. Determine the mass flow rate of air and the turbine entry temperature in flight.

(e) The propelling nozzle has an area of 0.5 m^2. In a stationary test on the ground, the thrust of the engine was 50 kN. At cruise conditions in flight, the ambient pressure is 27 kPa. Determine the gross thrust.

9 (a) Why is the area of an aircraft wing determined by conditions at take-off?

(b) Explain why aircraft cruise at high altitude.

(c) For an aircraft with four engines, explain why the size of an engine is determined by the conditions at the top of climb.

(d) Breguet's range formula is

$$s = -\frac{V\,L/D}{g\ sfc}\ \ln\left(\frac{W_{end}}{W_{start}}\right)$$

where s is the distance between the start and end of the flight, sfc is the thrust specific fuel consumption, L/D is the lift-drag ratio, g is the gravitational acceleration and W is the weight of the aircraft. State any assumptions made in the derivation of this formula. Discusss the implications of the formula for air transport.

(e) Show that the propulsive efficiency η_p of an engine may be written as

$$\eta_p = \frac{2V}{V + V_j}$$

where V is the flight speed and V_j is the jet velocity. State any assumptions that you make. Discuss the significance of the propulsive efficiency.

(f) Explain why most high thrust applications use bypass engines.

(TURN OVER

SECTION D (Chemical and Process Engineering)

10 Discuss the atmospheric pollution caused by the combustion of solid, liquid and gaseous fossil fuels. Your answer should include, for each type of fuel, discussion of:

(a) its historical and future importance;

(b) the types of pollutant, possible effects, and evidence for those effects;

(c) pollution control strategies.

11 (a) The overall mass transfer coefficient K_g for mass transfer between gas and liquid phases of a binary mixture in contact is given by

$$\frac{1}{K_g} = \frac{1}{k_g} + \frac{H}{k_l}$$

where k_g and k_l are the gas-side and liquid-side mass transfer coefficients respectively, and H is the Henry's Law constant. Derive the above expression and discuss the assumptions that you make.

(b) A wetted-wall column of height h and diameter d is used to remove a pollutant, which is present in dilute quantities, from a gas stream. The concentrations of the pollutant in the gas stream at the bottom and top of the column are c_{gB} and c_{gT}. The liquid enters the top of the column where it is free of pollutant. It leaves the bottom of the column with concentration c_{lB}. Consider varying the liquid flowrate L. Show from a material balance that for large L, c_{lB} is approximately zero. Hence explain why, under these conditions, the fraction of pollutant remaining in the gas stream $f = c_{gT}/c_{gB}$ attains a minimum value $f_{\min}$.

(cont.

Find f_{min} using the log mean driving force formula:

$$\text{rate of mass transfer (kmol / s)} = K_g \pi\, d\, h \left\{ \frac{(c_{gB} - H\, c_{lB}) - c_{gT}}{\ln\left[(c_{gB} - H\, c_{lB}) / c_{gT}\right]} \right\}$$

with $c_{lB} \approx 0$.

(c) Air containing a small proportion of SO_2 passes up a wetted-wall column of diameter 0.03 m and height 1 m at a mean velocity of 1.5 m/s. Using the correlation

$$Sh = 0.023 Re^{0.83} Sc^{0.44}$$

for k_g, and $k_l = 2.1 \times 10^{-4}$ m/s, evaluate K_g. Find the value of f_{min}.

How would you find L for $f = 1.2 \times f_{min}$? How might you change the design to reduce f_{min}?

Data

$$Sh = \frac{k_g d}{D}\ , \qquad Re = \frac{\rho V d}{\mu}\ , \qquad Sc = \frac{\mu}{\rho D}$$

where ρ is the density and μ is the viscosity of the carrier gas, V is the mean velocity of the gas stream, and D is the diffusion coefficient. Take $\rho = 1.19$ kg/m^3, $\mu = 1.81 \times 10^{-5}$ Ns/m^2, $D = 1.46 \times 10^{-5}$ m^2/s, and $H = 9.03 \times 10^{-3}$.

12 (a) A packed column is used for mass transfer of a pollutant from an upward flowing gas to a downward flowing liquid. Explain how the nature of the flow pattern changes as the gas flowrate increases at fixed water flowrate. Include a sketch of pressure drop versus gas flowrate in your answer.

(b) For the design of a particular column, the gas flowrate and the (dilute) inlet and outlet concentrations in the gas stream are specified and the inlet liquid is free of pollutant. By sketching a typical graph of concentration of pollutant in the gas stream c_g versus that in the liquid stream c_l, show that there is a minimum liquid flowrate L_{min} for these specifications, and find its value in terms of H, G, c_{gT} and c_{gB}. Comment on the operation of a column with liquid flowrate L_{min}.

(c) A process stream comprises air and a small proportion of SO_2, at volumetric flowrate $1.4\ m^3/s$. A 95% reduction in the volume fraction of SO_2 is required, using water in a packed column. Find L_{min}. Using a volumetric flowrate of water $L = 2 \times L_{min}$, with 38 mm Intalox saddles, and the chart provided as Fig. 5, estimate a suitable column diameter.

(d) Discuss how the design of the column would proceed from this starting point.

<u>Data</u>

$H = 9.03 \times 10^{-3}$

Density of water = $1000\ kg/m^3$

Viscosity of water = $10^{-3}\ Ns/m^2$

Density of air = $1.2\ kg/m^3$

Packing factor for 38 mm Intalox saddles $F_p = 52$

<u>Symbols in Fig. 5</u>

$\dot{m}$ = mass flowrate (kg/s)

A = cross sectional area of column (m^2)

μ = viscosity (Ns/m^2)

ρ = density (kg/m^3)

L, G subscripts denote liquid and gas streams

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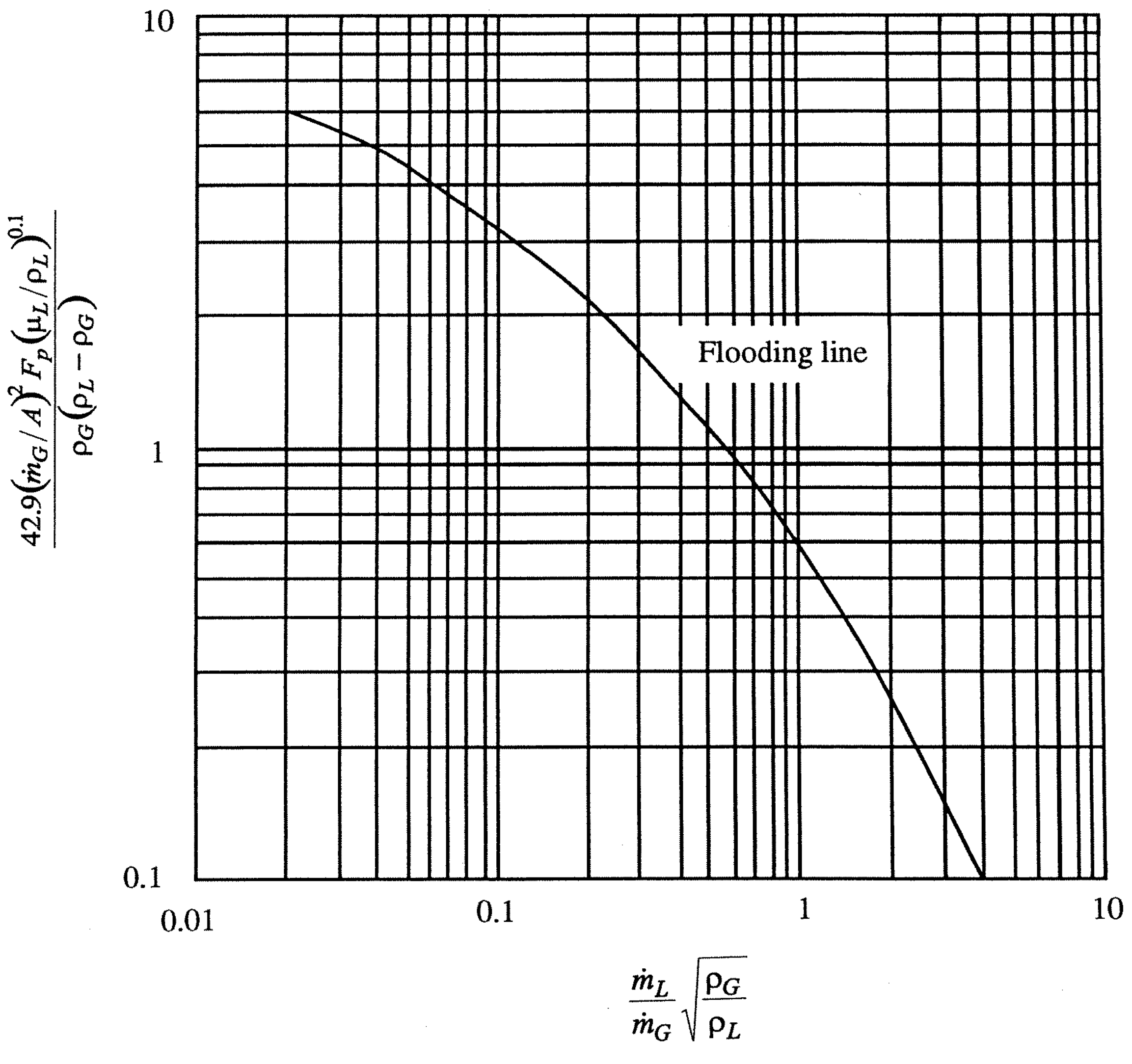
10
1
0.1
0.01
0.1
1
10
Flooding line
$\frac{42.9(\dot{m}_G/A)^2 F_p(\mu_L/\rho_L)^{0.1}}{\rho_G(\rho_L-\rho_G)}$
$\frac{\dot{m}_L}{\dot{m}_G}\sqrt{\frac{\rho_G}{\rho_L}}$

Fig. 5

SECTION E (Electrical Engineering)

13 A MESFET with a transit time of 40 ps is to be designed using a 1 μm thick layer of N-type silicon formed on an insulating substrate. The supply voltage is to be 4 V and the silicon layer has an electron mobility of 0.1 $m^2V^{-1}s^{-1}$ and a conductivity of 80 $\Omega^{-1}m^{-1}$.

(a) Determine the donor density of the silicon.

(b) Determine the distance between source and drain for the required transit time. Also, calculate the magnitude of the electric field in the channel and comment on its value.

(c) The ratio of width to length of the FET is to be 10. Calculate the current which will flow when the gate-source voltage is zero, assuming that the channel behaves as a simple resistance. Compare the resulting power density with the substrate's dissipation limit of 10^8 W m^{-2}.

(d) Determine the gate-source voltage required to cut the transistor off.

14 (a) Outline the experimental evidence supporting the view that light can behave in a particle-like manner.

(b) Explain the difference between standing and travelling waves and how each is represented mathematically.

(c) Schrödinger's time-independent equation may be written as:

$$E = T + V = \frac{\hbar^2 k^2}{2m} + V$$

Explain the meaning of each term in the equation.

An electron moves in a one dimensional potential well of length 0.1 nm bounded by barriers of infinite potential. Taking its potential energy as zero and $\hbar$ as 1.1×10^{-34} J s, use Schrödinger's equation to determine the energy levels of the particle in electron volts.

Comment on your result.

(TURN OVER

15 A 125 mm diameter wafer containing 500 chips is to be produced by a photolithography process in a class 10 laminar-flow clean room. The minimum feature size is 1 μm.

(a) Discuss the criteria which would lead to the choice between a positive or negative resist.

(b) Determine the value of the numerical aperture required if radiation with a wavelength of 0.2 μm is used to expose the resist and comment on the corresponding depth of field.

(c) Compare the merits of contact, proximity and projection exposure and state which one would be most suitable for this process.

(d) The optical system to be used has a power density of 0.05 W cm^{-2}. Estimate the required exposure time if the resist has an exposure energy density of 140 mJ cm^{-2}.

(e) No more than 100 of the chips are to be affected by dust particles with a size of 0.5 μm or greater during the exposure time estimated in (d). Assuming a sticking coefficient for the particles of 0.6, use Fig. 6 to estimate the maximum allowable laminar flow rate.

(f) Give a full specification for this lithography system and discuss whether it would be advantageous to use an electron beam system instead.

State clearly all assumptions made.

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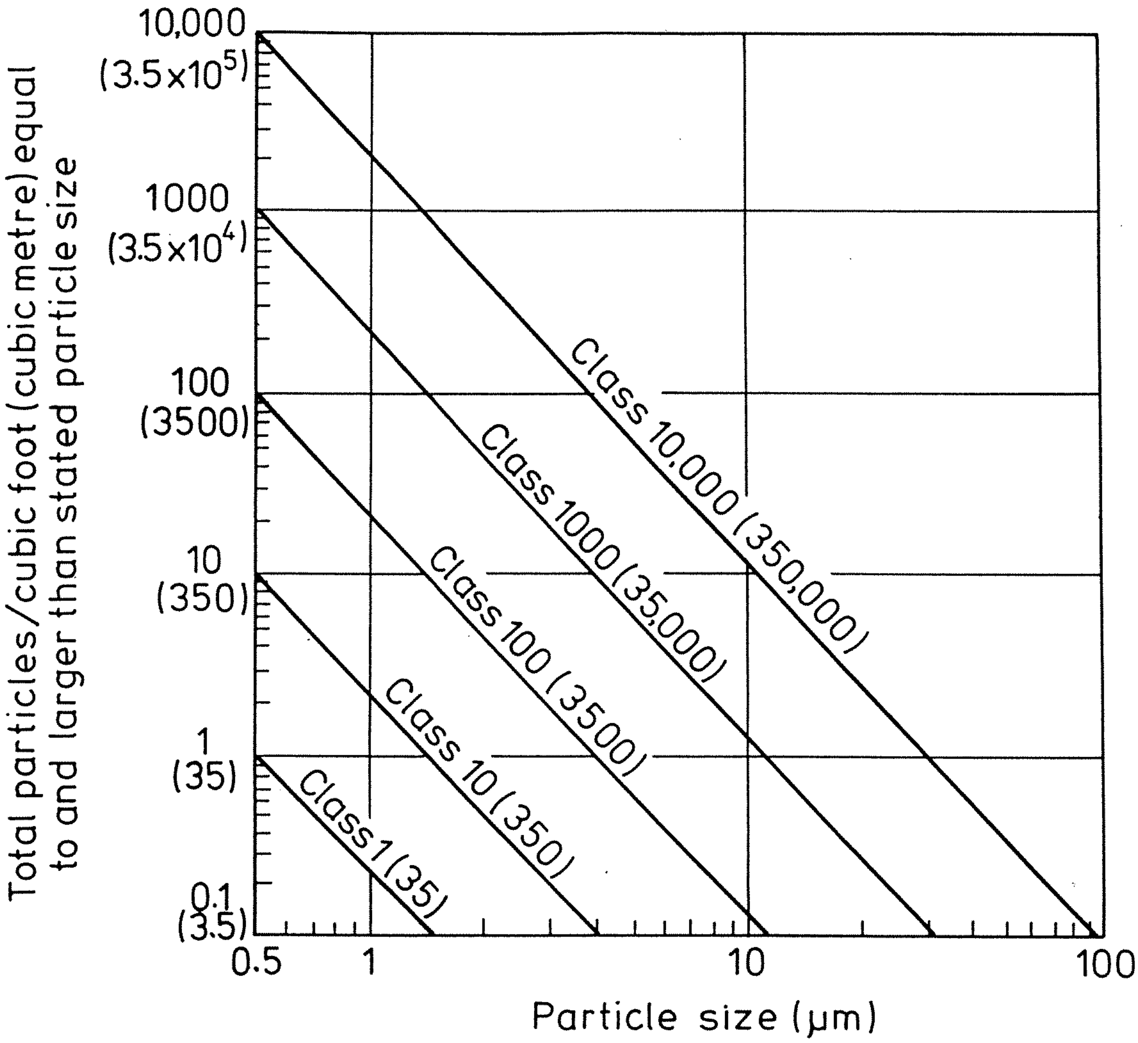

Fig. 6

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SECTION F (Information Engineering)

16 Fig. 7 illustrates the format of an Address Resolution Protocol (ARP) packet (including the DataLink header) on an Ethernet.

(a) Describe the need for, and purpose of, ARP on a single Ethernet segment on which the Internet Protocol (IP) is being used. Outline the operation of ARP; include in your description the value expected in each address field in terms of the IP and DataLink (MAC) addresses of two communicating systems.

(b) Comment on the need, if any, for ARP when the two communicating end systems are on different networks connected via a gateway.

(c) A network monitor is to be used to help to diagnose a problem with the ARP implementation on a new computer system. Explain how the monitor could be designed to select for display:

(i) all ARP packets from the network;

(ii) only those ARP packets relating to the particular computer being investigated.

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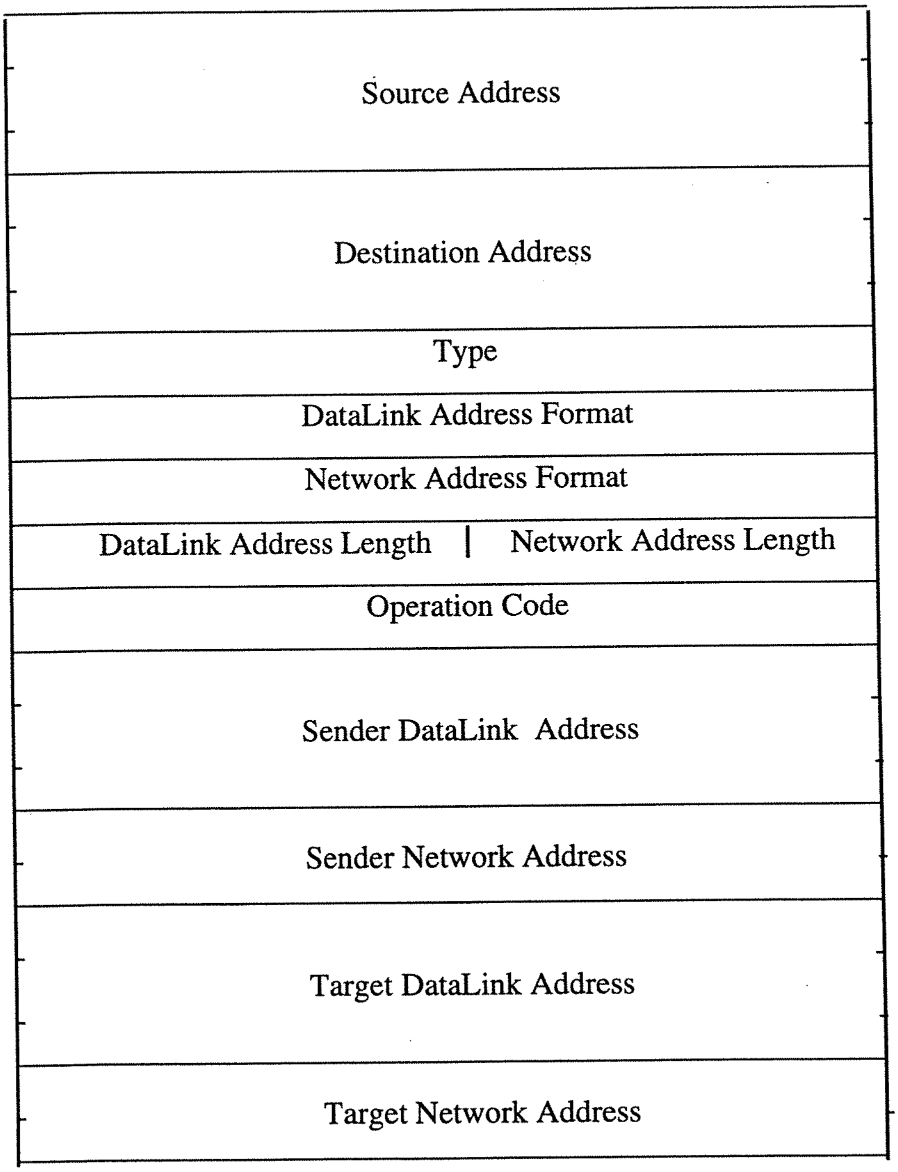

Fig. 7

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17 Explain what is meant by a Carrier-Sense Multiple Access with Collision Detection (CSMA/CD) network.

A CSMA/CD network is to be constructed using a simple interface device. This consists of an output buffer that is connected to a serial bus by an open collector transmitter in parallel with an input buffer connected to the serial bus by a receiver. When a byte of data is written to the output buffer, it is converted to serial form and transmitted across the bus. When a byte of data from any source is transmitted to the bus it is decoded and stored in the input buffer. The device only supports polled mode input/output.

The device has the following 8-bit registers:

Name	**Memory Address**	**Function**
DataIn	0FC000	Read to receive last byte transmitted over bus.
DataOut	0FC000	Write to transmit a byte over bus.
Status	0FC001	Status register with bit functions as follows: Bit 0: set if DataIn holds valid byte; Bit 1: set if DataOut is busy (i.e., byte is being transmitted); Bit 2: set if error occurred whilst receiving last byte (error condition).
Control	0FC001	Control register with bit functions as follows: Bit 0: set to delay byte transmission by N+1 time units; Bits 1 to 5: N in range 0 to 31.

Using Pascal notation, write suitable type and variable definitions to describe these registers.

The data link layer of a CSMA/CD network implemented with this device uses fixed size packets of 32 bytes each:

```
TYPE Packet = ARRAY[1..32] OF Byte;
```

(cont.

Design a Pascal procedure with heading

FUNCTION SendPacket(p : Packet):Integer;

which transmits the given packet. If a collision occurs, it should resend the packet after a random delay. The value returned is the number of retries required to send the packet. A suitable random number generator function may be assumed.

Discuss the limitations of the above as the basis of a practical networking system.

(TURN OVER

18 Explain what is meant by a process and describe how a process record is used to represent it in a single processor system. Describe the four main states that a process can be in and define a Pascal type called Status to represent them.

In an event-driven multiprocess system, each process is represented by a record defined as follows

```
TYPE  Event    =  {list of events};
      RegSet   =  {space to store CPU registers};
      Priority =  0 .. 100;

      PrRec    =  RECORD
                    state : Status;
                    prio  : Priority;
                    ev    : Event;
                    regs  : RegSet;
                  END;
```

Extend these type declarations to define a circular queue of processes.

Design a procedure, with the following heading, that will suspend the currently executing process until the specified event occurs and then select a new process for execution

```
PROCEDURE Sleep(ev : Event);
```

The algorithm must ensure that the selected process has a priority which is greater than or equal to all other ready processes in the queue, but it is otherwise "fair". A suitable procedure

```
PROCEDURE ContextSwitch(oldp, newp : ^PrRec);
```

for performing the actual context switch may be assumed, but its precise effect should be described.

END OF PAPER