Predicting drop sizes in aerodynamic breakup from shock tube studies

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We obtain high quality movies of the breakup of drops in a high speed air stream behind a shock in a shock tube. A drum camera with a framing rate of 200,000 pictures per second is used to make movies of breakup from a string of photographs 5μs apart; these movies can be seen on:

http://www.aem.umn.edu/research/Aerodynamic_Breakup

The drops break into fragments which are accelerated to the velocity of the air stream; the fragments do not break further since the disrupting action of a relative velocity disappears; they then can pull into spherical drops under the action of surface tension. The distribution of drop sizes is required as input for dissemination codes like PEGEM.

The movies are a complete and permanent record of the *fragmentation history*; this record could not be obtained before. A fragmentation history specifies the major events and times of breakup; for example, some major events which can be identified in the movies:

i. Flattening due to potential flow
ii. Radically outward boundary layer flow from the nose of the drop to its equator
iii. Accumulation of liquid at the equator
iv. Blow-off of liquid from the rings into drops and mist
v. Formation of lenticular drops
vi. Fingering of gas into the drop due to Rayleigh-Taylor instability
vii. Flattening and bursting of very viscous drops
viii. Pancake formation and explosive breakup of drops

Different fluids can have very different fragmentation histories; the major events and times of breakup are a sensitive indicator of the fluids rheology under the non-conventional dynamic conditions of deformation which prevail in aerodynamic breakup.

Photographs of breakup of drops of water, glycerin and thickened TEP taken from our movies all at Mach 3 are shown below. The breakup events and times are very different; and the differences are due to different fluid properties.

The shock tube movies capture the whole history of fragmentation up to a final distribution of fragments which are no longer breaking up but have as yet to pull into drops.

To predict drop sizes we will exploit the observation that *drops with similar fragmentation histories will give rise to similar drop size distributions*. To implement this idea we are going to divide the universe of fragmentation histories into a relatively small number of *envelopes*. In each envelope, we enter records of breakup which have similar properties; we need also to include data from witness cards from reverse ballistic tests wherever possible. The witness cards can be used to identify the drop size distribution in a given envelope; all the other fluids in that envelope (for which witness cards are not available) will give rise to a similar drop size distribution.

Ultimately, as criteria for envelopes are further refined, and more data have been collected, we shall have developed an empirical and verifiable drop size predictor which actually circumvents the need for deep fundamental understanding, on the one hand, and expensive reverse ballistic tests on the other.

Envelopes can be used to develop deep fundamental understanding. Presumably fluids in a given envelope with similar fragmentation histories will also have common material properties which can be identified and correlated to theoretical predictions.

Simulation of intercept conditions with a shock tube

We can simulate in the shock tube the intercept conditions for altitudes up to about 25 km using the present configuration, with appropriate choice of diaphragm materials. Because the intercept conditions over this range of 0 to 25 km altitude requires large ranges of driver and driven section pressures in the shock tube, we would need to use a variety of diaphragm materials. This would entail an initial period in the program for diaphragm calibration tests. Simulation of intercept conditions at 30 km and above become more difficult because both the driver and driven section pressures are so low that we will need to find diaphragm materials with low (and repeatable) bursting strengths. It should be noted that at these higher altitudes the dynamic pressure of the flow approaching the liquid sample in both the shock tube and the live tests rapidly becomes smaller with increasing altitude values where breakup may not be observed.

Advantages of shock tube studies of aerodynamic breakup

- The only test method presently viable for prediction drop sizes from events occurring at high altitude is the shock tube (low pressures are easily achieved in shock tubes)
- The only other method for predicting drop sizes at low altitudes is reverse ballistic tests using witness cards. Witness card data from reverse ballistic testing and fragmentation histories from shock tube studies are complimentary.
- The shock tube studies are much cheaper. For a budget of 10 million dollars you get witness cards for something under 100 different conditions; for $500,000 dollars for two years ($250,000/year) we could provide movies of breakup easily for over 200 different test conditions:

  $ 100,000 per test condition, Reverse Ballistic
  $ 2500 per test condition, Shock Tube

- Testing at a new test condition requires only a small preparation time in the shock tube.
- The envelope method of predicting drop sizes from shock tube testing has a potential for empirically based predictions. The creation of a large data bank enhances our confidence in predicting drop sizes under all conditions.

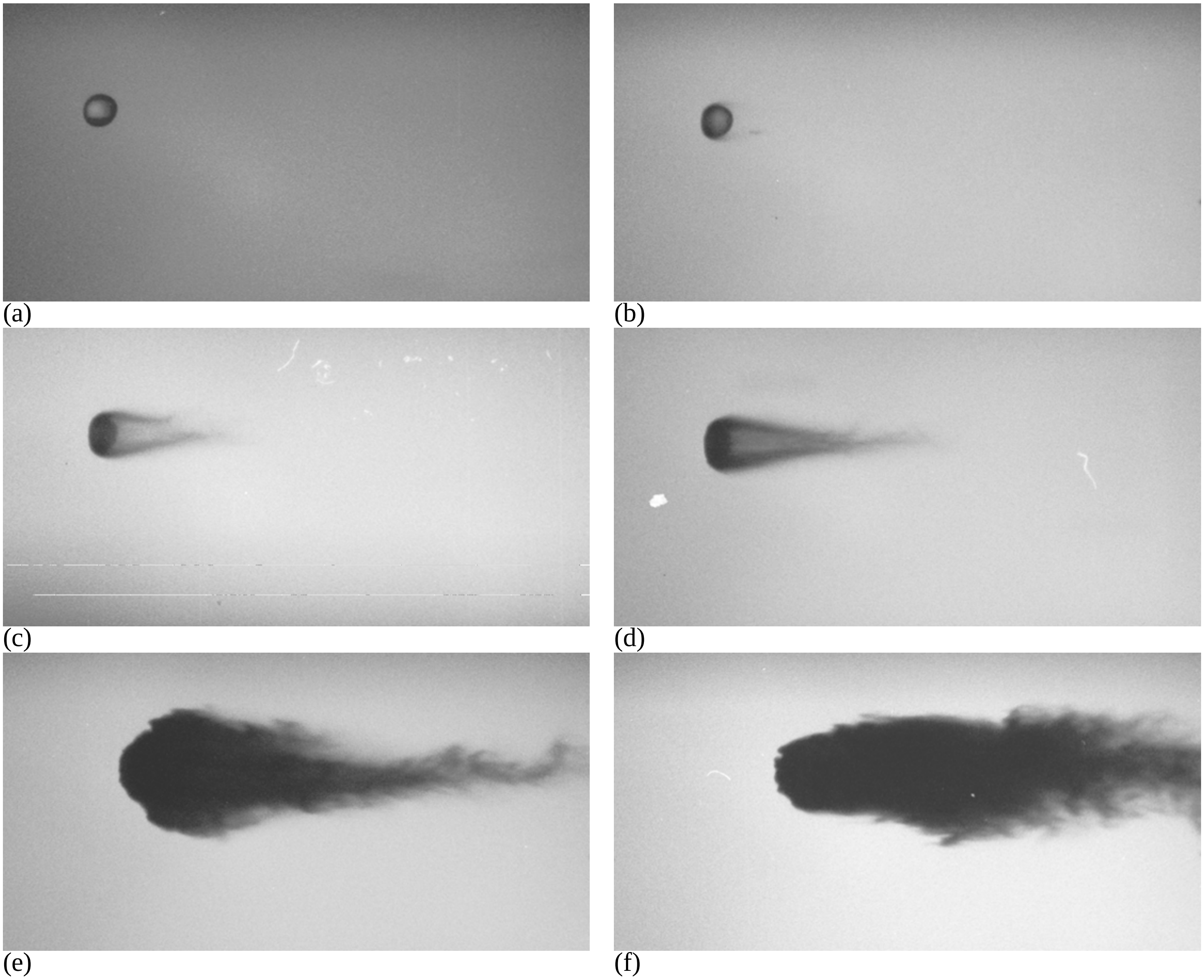


Figure 6. Stages in the breakup of a water drop (diameter = 2.5 mm) in the flow behind a Mach 3 shock wave. Air velocity = 764 m/sec; dynamic pressure = 606.4 kPa; Weber no. = 43,300
Time (microseconds): (a) 0 (b) 15 (c) 30 (d) 40 (e) 95 (f) 135

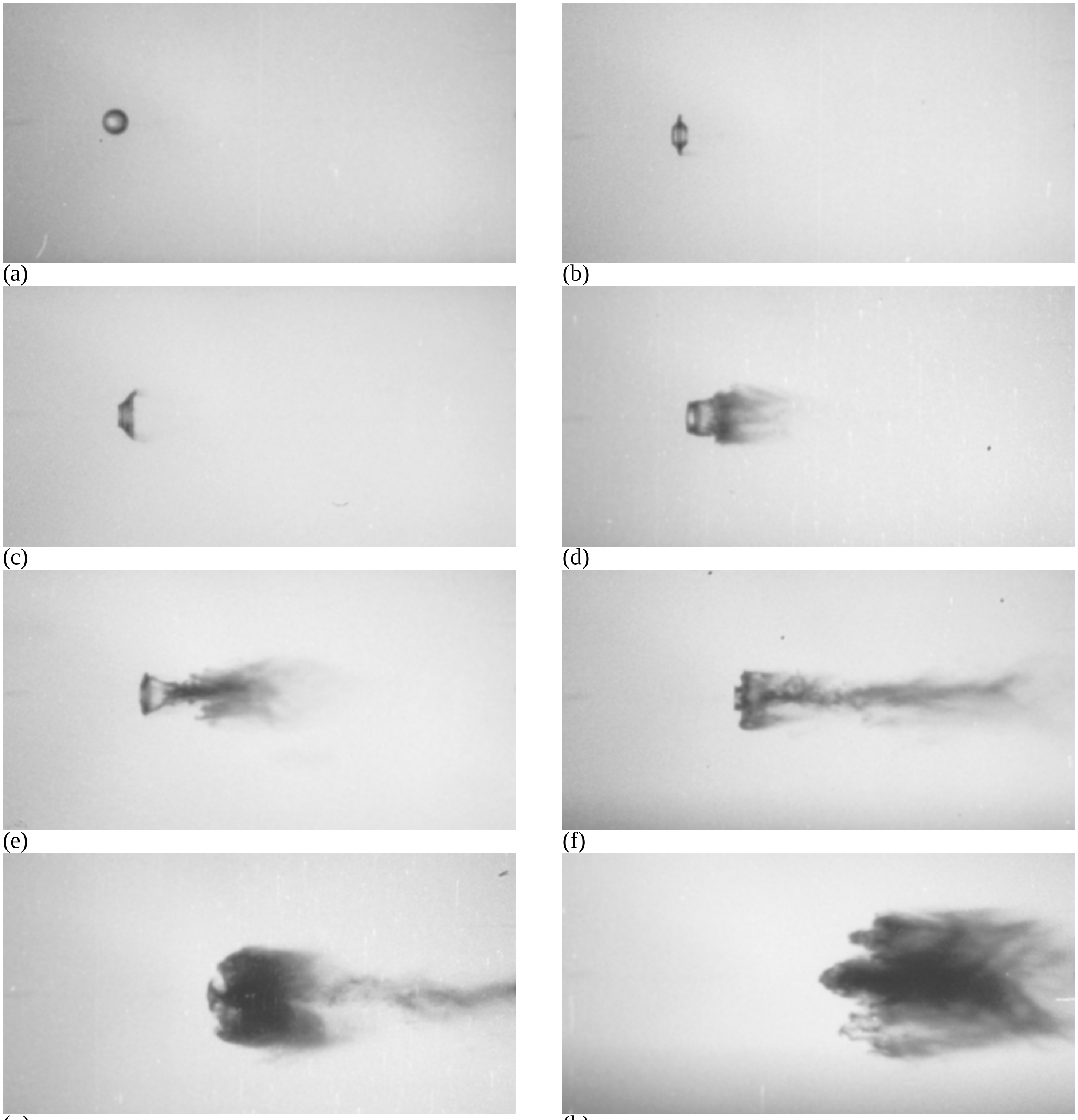
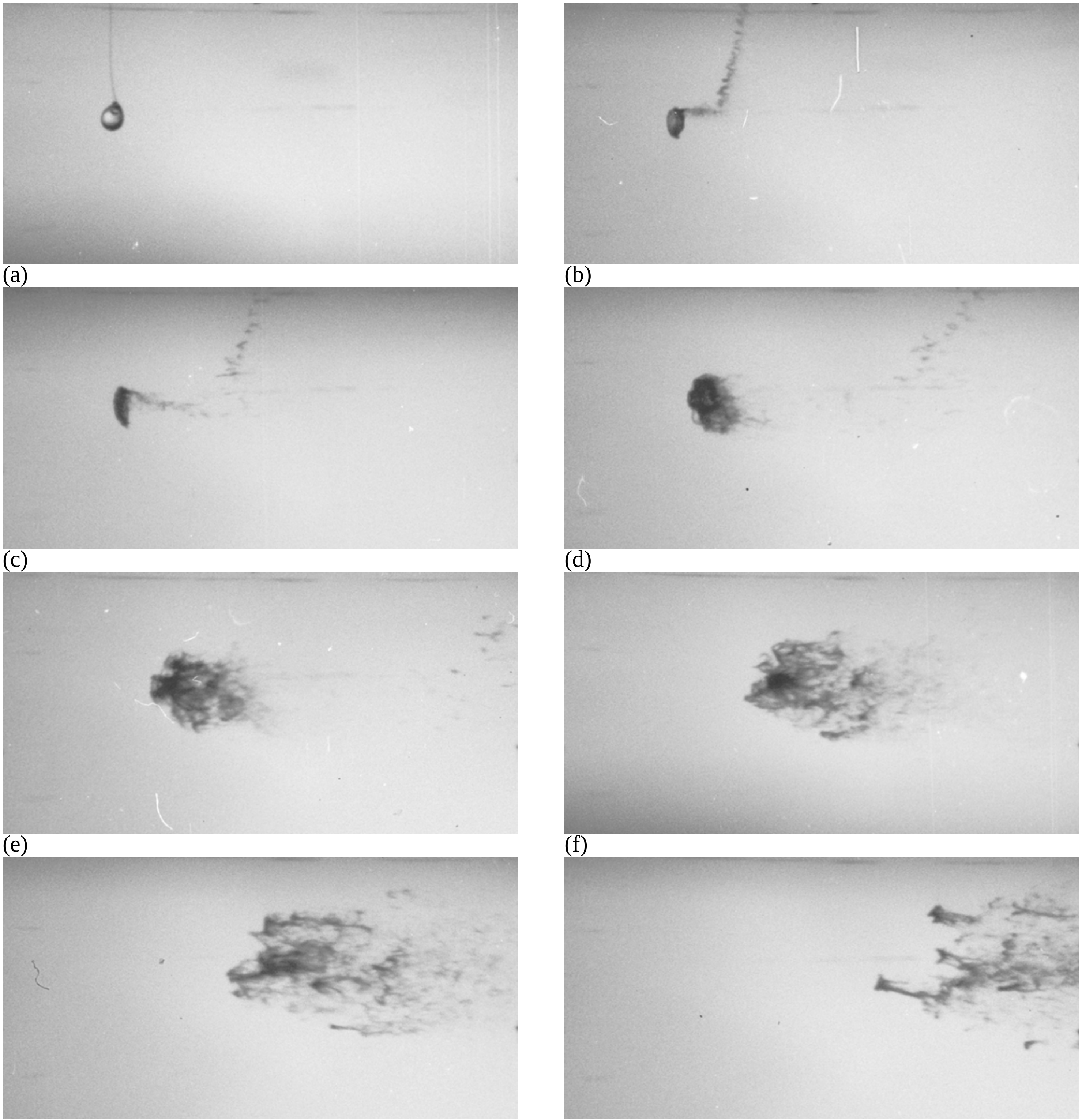

(a) (b) (c) (d) (e) (f) (g) (h)

Figure 8. Stages in the breakup of a drop of glycerine (diameter = 2.4 mm) in the flow behind a Mach 3 shock wave. Air velocity = 758 m/sec; dynamic pressure = 554.0 kPa; Weber no. = 42,200
Time (microseconds): (a) 0 (b) 35 (c) 50 (d) 70 (e) 90 (f) 125 (g) 150 (h) 185



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 12. Stages in the breakup of a drop of 2.6% solution of polystyrene butylacrylate (47025-24) in tributyl phosphate (PSBA/TBP ; diameter = 2.2 mm) in the flow behind a Mach 3 shock wave. Air velocity = 736 m/sec; dynamic pressure = 513.0 kPa; Weber no. = 107,500
Time (microseconds): (a) 0 (b) 30 (c) 50 (d) 80 (e) 105 (f) 135 (g) 160 (h) 200