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A FEASIBILITY STUDY FOR A LARGE SHOCK TUBE FOR BLAST-EFFECT DETERMINATIONS

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I. INTRODUCTION

The question has been raised whether a very large shock tube can be used for scale-model blast measurements. This paper will discuss several features of this problem in a qualitative way in the hope that the comments and suggestions made will be useful in further, more detailed considerations of the problem. Included are discussions of ways of producing the main shock wave, of the several reflected shocks and rarefactions, of the instrumentation required, and of the general construction of the tube.

It is the opinion of the authors that a very large shock tube could be constructed which would be suitable for approximately 1/4-scale blast-effect determinations. Such a tube could be 20 feet on a side or larger. However, several of the problems that will be encountered may require a large amount of experimental work before a satisfactory tube is obtained.

II. PRODUCTION OF SHOCK

For the purposes of this discussion, a shock tube is considered to be a tube in which a shock wave can be produced and its effects observed under controlled conditions. In general, there are two classes of shock

tubes. The first and better known is a tube in which an initial pressure ratio is supported by some form of diaphragm which divides the tube into two chambers. In the present application, assuming atmospheric pressure in the expansion chamber, the diaphragm must support approximately 60 pounds per square inch in order to produce a shock wave whose pressure ratio is two. Any one of several methods may be used to rupture this diaphragm.

The second class of tubes employs a gaseous or solid explosive to produce the shock wave. A diaphragm may or may not be used. In this system it is unnecessary to support an initial pressure ratio.

All the tubes in successful operation today are of the first type, and in most of them the diaphragm is a thin plastic sheet which may or may not be supported. Metal diaphragms have been used with some success on the largest tubes. The following sections of this chapter will discuss various methods for producing shock waves.

A. Simple Diaphragm

Perhaps the simplest diaphragm would be a single unsupported sheet of metal or plastic. Such a diaphragm would be an efficient way to produce a shock wave because it would rupture quickly and because the entire tube area would then be open. However, in order to produce a shock whose pressure ratio is 2.0, the diaphragm would have to support a pressure difference of approximately 60 pounds per square inch. If one assumes a hemispherical diaphragm to be ideally supported in a cylindrical tube, even though none of these conditions would be obtained in practice, a thickness of only about 3/16 inch of aluminum would be required to support the compression-chamber pressure. The

difficulty of obtaining and mounting a preformed aluminum hemisphere 20 feet in diameter makes it seem advisable to consider a flat diaphragm. Here the stresses in the diaphragm at the edges would be much greater since the tension at the sides of the tube increases inversely as the cosine of the angle between the wall and the diaphragm. Because of considerations to be discussed later, a rectangular cross section is preferable, and in this case the stresses would be more severe than in a cylindrical tube. These considerations, plus the need for a safety factor, would probably increase the needed thickness by 10 or 20 times. In other words, a single sheet of 1/8-inch aluminum would probably be sufficient to produce a shock whose pressure ratio is 1.1. It should be mentioned that 1/8-inch aluminum sheet was used for the diaphragm in the 24-inch cylindrical tube at Aberdeen Proving Grounds.

The forces on a single diaphragm can be reduced by employing several similar diaphragms in series. It would then be necessary to adjust carefully the pressures across each of them. Thus, in such a system, perhaps as many as ten or twenty sheets of 3/16-inch aluminum would be required to produce a satisfactory shock wave. The cost of the material needed in either type of simple diaphragm system is quite excessive.

Another very serious objection to this system lies in the fact that, after the diaphragm is shattered, the particles are blown down the tube and become formidable projectiles which could inflict severe damage on models or test equipment in the tube. It has been found that small pieces of .002-inch cellophane are capable of chipping the leading edges of airfoils made of hardened high-speed tool steel. It is possible, however, that if a shock tube were sufficiently long, diaphragm fragments would settle to the floor before they reached the model. The whole problem

of diaphragm fragments should be carefully investigated before any particular diaphragm system is seriously considered.

B. Grid-Supported Diaphragm

The obvious next step is to support a simple diaphragm by some kind of reinforcing gridwork. This reduces the tension that the diaphragm must withstand, but it also obstructs a rather large part of the cross-sectional area of the tube. The strength of the shock wave produced by a given initial pressure ratio across the diaphragm will be reduced by this obstruction. For instance, assume a square grid made of steel bars one foot apart and one inch wide. In order to support the huge forces acting on the diaphragm, (4000 tons for a tube 20' x 40' in cross section), the grid would have to be of the order of 1 foot deep. The bars alone would then obstruct 16 per cent of the tube area and the boundary layer which would develop on the bars would probably obstruct at least an equal additional proportion of the area.

The supports could be made to serve as catchers for fragments of the diaphragm. Proper ruling or scratching of the diaphragm would help insure that it ruptured in such a way that the fragments would fold around the grid bars and be removed from the flow.

C. Mechanical Valve

No shock tube now in operation uses a mechanical valve or gate in place of a diaphragm because mechanical systems cannot be opened fast enough. However, since a compression wave steepens as it moves, it might be that the length of a large shock tube would be sufficient to allow an acceptable shock to be produced by a mechanical system. A system might possibly be made with venetian-blind-like elements operated by the

pressure difference across them. Serious consideration is not recommended, however, because of the severe stresses involved and other mechanical complications.

D. Variable Cross Section

A final suggestion which would reduce the pressure difference that the diaphragm must support is to design the tube with a variable cross section; in other words, make the compression chamber and diaphragm section larger than most of the expansion chamber and test section. It is known that a shock wave in a converging channel is strengthened as it progresses along the channel. The exact change in shock strength to be expected for a given change in area could be calculated. However, if one makes the naive assumption that the shock strength varies as the area ratio, one obtains the result that doubling the compression chamber area reduces the required pressure difference across the diaphragm by more than a factor of two. The total force that the diaphragm must support would be reduced; but the increase in size of a supporting gridwork necessitated by the increase in span might possibly outweigh the advantages of the larger area.

E. Gaseous Explosives

All the systems for producing shocks considered so far have consisted of some arrangement capable of holding a static pressure difference sufficient to produce a shock wave of a given strength. Unfortunately, the problems of such systems increase rapidly with the area of the shock tube and soon becomes practically insurmountable. The ideal solution to the diaphragm problem would be to build up the pressure in the compression chamber instantaneously behind a very weak simple membrane which would then break spontaneously.

An approach to this situation can be obtained by filling the compression chamber with an explosive mixture of gases at atmospheric pressure. After the mixture is detonated, the temperature and pressure in the compression chamber build up rapidly and break a simple diaphragm. Then the process will proceed approximately as in an ideal shock tube in which the temperatures and gases in the two chambers are different.

The description given above is very much over-simplified. The shock wave from the detonation front will persist for some time after it leaves the combustible gases; but it will be attenuated because there will be no process capable of supplying it with energy. This shock and the tube shock will interact in some way. It seems a reasonable assumption that they would coalesce and form a single peaked shock in the expansion chamber.

Since the velocity of the detonation front in the explosive mixture is not infinite, the compression chamber will not be a region of uniform state when the diaphragm breaks. Difficulties caused by this nonuniformity can probably by minimized by an experimentally determined optimum arrangement of ignition elements.

Finally, it may be that some of the gases from the compression chamber will still be burning when they reach the test section. If this situation did exist, it would not interfere with the experiment because the gases certainly would be unable to ignite the models and would not affect force measurements taken with gauges with low temperature coefficients.

Tables of pressure produced behind detonation fronts given by Doering and Burkhardt* indicate that a hydrogen-oxygen mixture would

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* W. Doering and G. Burkhardt, Contributions to the Theory of Detonation, Air Materiel Command Technical Report No. F-TS-1227-1A, May, 1949.

produce a shock wave whose strength is of the order of two or three. Shock strength variations could be obtained by adding impurity gases such as CO_2 or N_2 or by using a different explosive mixture. However, it might be difficult to obtain weak shocks from any explosive mixture.

It would not be necessary to evacuate the entire tube in order to introduce the gases. Satisfactory injection could be obtained by slowly withdrawing a closely fitting piston from the diaphragm section toward the rear of the compression chamber and allowing a metered quantity of gas to flow in simultaneously. Efficient ignition could be obtained from one or more wires suspended along the length of the compression chamber exploded by condenser discharge.

Satisfactory solutions to the variety of problems suggested above can only be obtained experimentally. The experiments would not be particularly difficult to perform since a long pipe could act as the shock tube and the only instrumentation required would be pressure gauges and associated recording equipment.

No doubt, strenuous and valid arguments would be raised against this method of producing a shock wave. However, the expense and mechanical difficulties of producing the wave by any of the other methods mentioned above would be more objectionable.

F. Solid Explosives

The simplest and most direct method of producing shock waves for blast-effect determinations would be to use a wall of high explosive detonated at the end of a tube. This method would eliminate all the problems inherent in constructing a diaphragm sufficiently strong to withstand a pressure of at least sixty pounds per square inch. Furthermore,

it would be safer to use than the gaseous explosives because the danger of accidental detonation would be greatly reduced. In addition, the strength of the shock wave produced could be varied over wide ranges by simply varying the weight of the explosive in the wall. Finally, such a shock tube could easily be made much larger than any tube requiring a diaphragm.

Several economic advantages of using solid explosives in a shock tube should also be mentioned. The tube could be relatively short because the rarefaction wave overtakes the shock immediately instead of hundreds of feet down the tube. No complicated and expensive diaphragm mechanism or gas injection system would be required. The high cost of the diaphragm material would be eliminated. And finally, the cost of the high explosive itself quite probably would be less than the cost of the explosive gases required to fire a large shock tube.

Since shock diffraction work is now being done in three dimensions with solid explosives, the experience gained in this work could be applied directly to the problems, such as the specification of the weight of explosive required to produce a particular shock wave, that would arise in the design of this type of shock tube. It is even conceivable that a large part of the work now done in the field could be done more economically in this tube. The reduction in the weight of explosive required to produce a given blast wave caused by the restriction of the wave to one dimension would be important.

It is true that the forces exerted on the back of the tube at the time of the explosion would be tremendous. However, the strength required to withstand these forces could be obtained by using reinforced concrete and armor plate backed by solid rock if necessary.

The cost of providing this strength would be small compared with the cost of the diaphragm mechanism required by other types of shock tubes.

Conceivably the corrosive and errosive action of the explosion and its by-products might necessitate the resurfacing of the back parts of the tube periodically. Again, it is safe to say that the cost of this operation would be comparable to, or less than, the cost of the routine maintenance that would be needed in any other type of shock tube.

The authors are convinced that the use of solid explosives to produce a shock wave in a large shock tube is the most realistic and practical approach to the problem.

III. REFLECTIONS

There are three reflections that are important in this problem. They are the reflected rarefaction from the end of the compression chamber, the reflected rarefaction or shock wave from the end of the expansion chamber, and the shock waves reflected from the sides of the tube in the vicinity of the model. These reflections shall be discussed in order.

The rarefaction wave reflected from the end of the compression chamber will eventually catch up with the primary shock wave and produce a peaked shock at least qualitatively similar to a blast wave. The lengths of the compression and expansion chambers are uniquely determined when the shock strength and the length of the blast wave at the test section are specified.*

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* For a detailed discussion of this problem, see C. W. Lampson, Resumé of the Theory of Plane Shock and Adiabatic Waves with Applications to the Theory of the Shock Tube, Technical Note No. 139, Ballistic Research Laboratories, Aberdeen Proving Grounds.

If a gaseous explosive is used in the compression chamber, the rarefaction wave will catch up with the shock wave quicker than Lampson's curves indicate, because the velocity of sound in the hot reaction products in the compression chamber is much greater than in the expansion chamber.

Whether a shock or rarefaction wave is reflected from the end of the expansion chamber depends on whether the chamber is closed or open. However, either of these waves arriving at the test section during a test could cause increased damage or, at best unrealistic pressure measurements. It would, therefore, be wise to extend the expansion chamber at least one blast-wave length beyond the test section and to terminate the tube in some manner that would not transmit any reflected wave back into the expansion chamber. The most satisfactory termination would be one analogous to the acoustic exponential horn, that is, a channel diverging into the atmosphere. A satisfactory alternative termination would be a grid work so constructed that the shock waves reflected from the solid portions of the grid would be balanced by rarefactions reflected from the open portions. Two disadvantages of the latter suggestion are the structural strength required of the grid itself and its supports to withstand the forces developed by the blast wave reflected from the grid bars, and the fact that this grid would obstruct access to the test section from the end of the expansion chamber.

The minimum size of the shock tube required to test a given model is determined by the shock waves reflected first from the model and then from the walls of the tube. For this reason, the cross section of the tube should be rectangular; and if the model is at the bottom of the tube, the width should be approximately equal to twice the height. A cylindrical or semi-cylindrical cross section is the worst possible

choice because such a shape would focus these reflected shock waves back onto the model. This situation is to be avoided if possible.

Examination of interferometric studies of shock wave diffraction made by Princeton University, Department of Physics*, indicates that the shock wave reflected from a rectangular obstacle is quite weak even in the vicinity of the model. For instance, 5/8 inch above the leading edge of a rectangular block, the overpressure behind the reflected shock wave is only about 3 or 4 pounds per square inch. The strength of the shock will drop off rapidly as the distance from the model increases. This is especially true if three-dimensional models are used in the tube. Therefore, it is possible that models of the order of one third to one half the height of the tube may be tested. Accurate and more extensive information on this subject should be available from Armour Research Foundation in the near future, because a tube larger than any existing at the present time has been proposed for construction.

IV. INSTRUMENTATION

The instrumentation system required for a large shock tube need not be as extensive or as accurate as that used on smaller general-purpose tubes. The strength of the primary tube shock can be determined with

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* Walker Bleakney, The Diffraction of Shock Waves Around Obstacles and the Transient Loading of Structures, Technical Report II-3, March 16, 1950.

D. R. White, D. K. Weimer, and Walker Bleakney, The Diffraction of Shock Waves Around Obstacles and the Resulting Transient Loading of Structures, Technical Report II-6, August 1, 1950.

reasonable accuracy by a single pressure gauge in the side of the tube. If more accurate information is desired, it can be obtained by measuring the time of transit of the shock wave between two stations a known distance apart. The passage of the shock may be detected by ordinary pressure gauges, by high-voltage glow-discharge points, or by some optical system employing only the simplest techniques.

It would be exceedingly difficult to use shadowgraph, schlieren or interferometric photography to extract detailed information concerning blast effects in a large shock tube. Such information can be obtained more efficiently in small tubes. Direct measurement of pressures and forces could be made by using standard pressure gauges, strain gauges, and accelerometers strategically placed in the models to be tested.

Another source of useful information would be high-speed motion pictures. The correlation of pressure, strain, and acceleration data with actual photographs of the model during the test would provide much insight into the causes of blast damage and possible means of preventing it.

V. CONSTRUCTION

Probably the most satisfactory tube would be a reinforced concrete structure partially or completely buried in the ground. The foundations of the tube must be sufficient to withstand the terrific recoil forces produced in firing.

Some provision should be included to make it unnecessary to separate the expansion and compression chambers to insert a diaphragm, if one is needed. A method for doing this would be to make the diaphragm clamping-section removable.

The shock wave produced in a tube definitely will be influenced by the roughness of the walls. However, the shock curvature introduced by this roughness is probably unimportant in the present application. Therefore, cold-rolled steel plate or a wash-cement surface would make satisfactory walls.

Another feature to be incorporated easily into this large tube is a water tank. If such a tank were installed with the water surface coplanar with the bottom of the tube, extensive investigations of the effect of blast waves on ships of various types could be conducted on rather large models. Furthermore, the behavior of small bodies of water under various blast conditions might be a very important factor in civil defense planning.

VI. SUMMARY

This paper discusses the problem of designing and constructing a shock tube suitable for blast-effect determinations large enough to accomodate at least 1/4-scale models. In the opinion of the authors a satisfactory tube for this purpose can be constructed; but some of the problems to be encountered might require extensive experimentation before the desired result is obtained.

Various methods for producing the shock wave are considered. The conclusion is reached that any system employing a diaphragm or valve to separate the compression region from the expansion chamber is not feasible. The most promising method for the production of the shock wave appears to be the detonation of a wall of solid explosive at the back of the tube. No diaphragm of any kind would be required.

The tube itself should be made of reinforced concrete and should at least be partially buried in the ground. The interior walls could be smooth cement or preferably cold-rolled steel plate. Provision could easily be made for a water tank at the test station so that the behavior of ships of various types under blast conditions could be investigated.

The expansion chamber should be terminated by a semi-reflecting gridwork or by a diverging horn. In either case the pressure in the chamber before firing should be atmospheric. In order to minimize the effect of shock reflections in the vicinity of the model, the cross section of the tube should be rectangular.

A satisfactory instrumentation system would consist of strain gauges, pressure gauges, and accelerometers, as well as associated recording equipment used in conjunction with a high-speed motion picture camera.

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