7

HIGH PRESSURE AIR CYLINDERS.

Reservoirs of H.P. air cylinders are used extensively in H.M. Service, and it is thought that a brief summary of their history and method of manufacture may be of interest. The two most important applications for batteries of cylinders are firstly for the storage of air for blowing diving tanks, etc., in submarines, and secondly for accumulators or as a reserve for gun air blast in battleships and cruisers for use in the event of the air compressors being damaged. There are also many occasions, such as during torpedo preparation tests when an air supply can be obtained from these reservoirs, thus obviating the necessity of running an air compressor.

History.—As is well known, cylinders are used extensively in the commercial world for transporting compressed gases.

Prior to 1890, commercial cylinders were usually made either of wrought iron or mild steel, but shortly afterwards cylinders made of harder (higher carbon) steel were being introduced. In 1893, a cylinder made from 0·45 per cent. carbon steel burst with fatal results at Bradford Railway Station when it was dropped from a boy's shoulder. As a result of this accident an agreement was reached between the Cylinder Manufacturers and the Railway Companies that the upper carbon limit for bottles should be 0·25 per cent.

In 1895 another serious accident occurred at Fenchurch Street Railway Station due to a cylinder bursting when being transported and a Committee was appointed by the Home Secretary to consider and report on the use and conveyance of cylinders containing compressed gases.

This Committee endorsed and amplified the terms of the agreement reached between the Railway Companies and the compressed-gas trade, and the principal recommendations made are given in Table I.

These recommendations remained in force until 1921, when the report of the Gas Cylinders Research Committee, appointed in 1918 to reconsider the recommendations of the 1895 Committee, was published.

This Committee consisted of 12 members and contained representatives of the Admiralty, Air Ministry and the Home Office. While a complete agreement between the members was not reached, the majority report concurred in the use of a higher carbon steel for cylinders for the permanent gases.

The principal recommendations of the majority report are shown in Table I.

Attention was drawn in the report to the potential danger of the low-temperature anneal recommended by the 1895 Committee.

It is explained that if the cylinders have been strained or deformed prior to the annealing, there is every possibility of grain growth resulting, whilst if the bottle is not strained this annealing is unnecessary. The Committee recommended that in cases where a heat treatment was considered essential for any reason, the same treatment as that applied to the bottle after manufacture should be used.

Air reservoirs were first introduced into the Service in 1880, when automobile torpedoes were fitted in the Admiral Class.

This type of reservoir consisted of a series of tubes, 6 ft. long and 3 in. external diameter, fitted with screwed and sweated gunmetal caps very similar to the charging columns used at the present day. They were connected together by short copper piping, and were made up in batteries of 25, 50 and 100 tubes.

In 1901 the working pressure was increased to 2,500 lbs./in.^{2} but the tubular type of reservoir was retained and it was not until 1905 that an actual cylinder was obtained for trial. This cylinder conformed very closely as regards material specification to the recommendations of the 1895 Committee, but the working and test pressures were increased to conform with the service requirements and the mechanical tests were consequently more severe as shown in Table I.

From this time cylinders of various shapes and sizes, depending on the space available have always been employed for air reservoirs.

In 1912 it was decided to increase the working pressure to 3,500 lbs./in.^{2} and a design of cylinder was prepared which was first installed in the *Queen Elizabeth* class ships. All subsequent ships have been equipped with an air system of this pressure, but a working pressure of 2,500 was retained for submarines. In Submarine " X.1 " pressure was incresased to 3,000 lbs. /in.^{2} and in *Oberon* and later classes to 3,500 lbs./in.^{2}

In 1919 it was proposed to further increase the pressure to 4,500 lbs./in.^{2} and a cylinder design was prepared and an air compressor purchased, but the scheme was never adopted.

Before the post-war ships were constructed the report of the Gas Cylinders Research Committee had been published and with a view to saving weight the cylinders for the submarine *Oberon*, H.M. ships *Nelson* and *Rodney* and the 10,000 ton cruisers were made of a higher carbon steel of 40 tons/in.^{2} U.T.S., the specification being based on the recommendations of the Committee. (*See* Table I.)

For the R Class submarines the U.T.S. was further increased to 45 tons/in.^{2}, but it was found that practicable commercial production had not yet reached this stage and consequently it was decided to revert to 40-ton steel for all subsequent cylinders.

Design.—The Gas Cylinders Research Permanent Gases Committee recommend that the maximum stress at the full working

TABLE I.

—	Recommended by 1895 Committee.	As specified by Admiralty.	As specified by Admiralty.	Recommended by Gas Cylinders Research Committee for permanent gases.	As specified by Admiralty for *Nelson* and *Rodney*, &c.	As specified by Admiralty for *Rainbow*.	Latest Admiralty Specification.
U.T.S. ton/in.^{2}	26–33	28–32	28–32	40	40	45	40
Yield ton/in.^{2}	Not specified	Not specified	Not specified	20	22	22	20
Elongation	15 per cent. in 8 ins.	30 per cent. in 2 ins.	30 per cent. in 2 ins.	14 per cent. in 6½ ins.	18 per cent.‖	16 per cent.‖	18 per cent.‖
Izod Longitudinal ..	—	—	—	5*	—	5*	15†
Transverse	—	—	—	3	—	3	12
Carbon Content	0·25 per cent.	0·25 per cent.	0·25 per cent.	0·43–0·48 per cent.	0·43–0·48 per cent.	0·43–0·48 per cent.	0·43–0·48 per cent.
Working Pressure ..	1,800 lbs./in.^{2}	2,500 lbs./in.^{2}	3,500 lbs./in.^{2}	1,800 lbs./in.^{2}	3,500	3,500	3,500
Proof Test Pressure ..	3,360 lbs./in.^{2}	4,000 lbs./in.^{2}	5,600 lbs./in.^{2}	3,000 lbs./in.^{2}	5,600	5,600	5,600
Stress at Working Pressure	8 tons/in.^{2}	9 tons/in.^{2}	9 tons/in.^{2}	10 tons/in.^{2}	11·5	11·5	10
Heat Treatment	—	—	—	Heat 820–850‡ Cool in air	Heat 820–850‡ Cool in air	Heat 820–850‡ Cool in air	Heat 870–920§ Cool in air Re-heat 800–850,‡ Cool in air

Tests recommended by 1895 Committee to be carried out on one bottle in every batch of 50.
Tests recommended by Gas Cylinders Research Committee to be carried out on one bottle in every batch of 100.
Tests specified by Admiralty to be carried out on a test ring cut from each cylinder before bottling and heat-treated with the Cylinder.
* 10 × 5 mm. test piece.
† 10 × 10 mm. test piece.
‡ Cylinders to remain in furnace only for a sufficient time to ensure all parts are at same temperature.
§ Cylinders to remain in furnace at this temperature for not less than half an hour and not more than two hours.
‖ Measured on a gauge length equal to $4\sqrt{\text{area of test piece}}$.

pressure shall not exceed 10 tons/in.^{2} when calculated on the simple thin cylinder formulæ, but owing to the higher pressures used in the Service and the consequent increase in the ratio of wall thickness to diameter the thick cylinder formulæ is invariably used.

The question of weight reduction is always of primary importance for H.M. Service.

It can be shown that the relation $f\ w \propto p\ v$ is approximately true where—

f = maximum stress permissible at working pressure.
w = weight of the cylinder.
p = working pressure.
v = volume of cylinder.

This is shown in Table II.

Working pressure times volume of cylinder is a measure of the quantity of free air stored, or weight of air in the cylinder and it therefore follows that for a given free air capacity the weight of a reservoir varies inversely as the maximum permissible stress.

As the maximum stress is fixed for any given type of material the weight of an installation of cylinders is constant and independent of the pressure, but space required can be reduced in proportion to the pressure rise.

The capacity of a battery of cylinders is determined by the duties for which it is required. For a submarine the capacity is dependent on the number of consecutive dives that may be undertaken without opportunity to recharge the reservoirs. For a battleship or cruiser, it is dependent on the gun air blast requirements, the reservoir acting as an accumulator, assisting the compressors when the demand is large and taking the excess of the compressor output when the demand diminishes.

Material.—The cylinder must be designed so that the maximum stress produced, *i.e.*, proof test stress is within the elastic limit of the material. For plain iron carbon steels the maximum stress allowed is about two tons/in.^{2} less than the specified yield point.

It is evident that an important quality required by a material for cylinders is toughness. Cylinders when fully charged may, during an action, be subject to severe shock and it is essential that under these conditions the material will not fragment if hit, but tear and remain in one piece, and so lead to no serious consequential damage.

The property of toughness is usually measured by a notched bar impact test, but without a series of practical trials of the cylinders to destruction it is not possible to state what is the critical value of toughness which divides the two methods of fracture of a cylinder, viz., by fragmenting and by tearing. Tests to destruction of a proportion of each batch of cylinders to ascertain whether they fragment is obviously not practicable with large cylinders owing to

Table II.

Size of Cylinder.			Material Specification.		Capacity in ft.³ V.	Working Pressure in lbs./in.² P.	Stress at Working Pressure in tons/in.² F.	Weight of Cylinder in cwts. W.	Weight per ft.³ of free air in lbs./ft.³	$\frac{P\,V}{W\,F}$
Internal Diameter.	External Diameter.	Length.	U.T.S.	Yield.						
Ins.	Ins.	Ft. Ins.								
13½	14½	6 4	40	20	5¾	650	5·37	3·5	1·5	200
16	17	5 9	40	20	7·06	900	6·63	5	1·3	190
13	14¾	3 8⅜	28–32	—	2·74	2,500	9·0	4·3	1·03	178
7½	8½	5 10½	28–32	—	1·66	2,500	9·07	2·25	1·01	204
7⅛	8½	6 7	28–32	—	1·66	3,500	9·0	3·5	1·00	185
17⅛	20	6 0	40	20	8	3,500	10·3	15	0·88	186
9	10½	6 9*	40	20	2·7	3,500	10·3	4·8	0·84	184
9⅛	10½	7 6	40	22	3·125	3,500	11·3	5	0·75	193
17½	20	6 0	45	22	8·375	3,500	11·6	13·8	0·77	183
18¼	20	6 0†	56	40	9·2	3,500	17·5	10·3	0·525	180

* Estimated weight-cylinders at present under manufacture.
† Provisional estimate of cylinder manufactured of alloy steel.

the cost involved and it is usual therefore to specify that the material shall have a degree of toughness which has previously been proved to be sufficient for the purpose in similar cylinders of similar material.

It is of interest in this connection to note that small oxygen flasks for the Air Ministry are tested for fragmentation by perforating a proportion of fully charged cylinders with a rifle bullet.

During the investigations of the Gas Cylinders Research Committee a number of cylinders were carefully examined at the National Physical Laboratory. The usual mechanical tests were applied and the composition of the material analysed but in addition the bottles were given a "rough handling test." This consisted of dropping a fully charged flask 30 ft. on to a concrete bed. If the bottle fragmented under this test the material was considered to be unsuitable.

As a result of these examinations the Gas Cylinders Research Committee drew up a specification for high carbon steel bottles which would have sufficient toughness to withstand "rough handling" on service.

It does not follow that a material which has the specified physical properties will be suitable unless it has the correct composition and is properly heat treated and it is most important therefore that every requirement of the specification must be strictly observed.

As was shown by the Committee's tests, another interesting feature brought out is that geometrically similar cylinders of the same material do not behave in the same manner; a small flask possibly failing by fragmentation, while a large one of the same material will stand the test. It is thought that the tendency to fragmentation may be associated with wall thickness, a certain minimum thickness being necessary to avoid this tendency.

When high carbon steel cylinders were introduced in the Service the Gas Cylinders Research Committee's specification was closely followed (*see* Table I), and further the customary bend test was adhered to.

The heat treatment that had been specified by the Admiralty was that after manufacture the cylinders should be heated to a temperature of not less than 820° C. and not exceeding 850° C. and to remain at that temperature only for sufficient time to ensure that all parts were at the same temperature. Before the temperature had fallen appreciably the cylinders were to be removed and allowed to cool in still air.

This heat treatment was the one recommended by the Gas Cylinders Research Committee, but because cylinders for the Service are considerably larger than those used in commerce, and the increased mass must affect the heat treatment it was considered that an improvement could be effected by using a double heat treatment.

Accordingly it was specified in 1931 that cylinders after manufacture should be heated to from 900-920° C., for a period of not less than ½ hour and not exceeding 2 hours, withdrawn from furnace and allowed to cool to a temperature not exceeding 500° C. and then reheated to from 820–850 and allowed to cool in still air.

The reason for this double heat treatment was that the condition of the material before treatment must depend on the amount of work done on it during manufacture, which will consequently vary throughout the cylinder. The first heat treatment is primarily to relieve all forging stresses and therefore a minimum time limit is specified. The maximum time limit is specified to prevent grain growth. This treatment should leave the cylinder free from forging stresses but the grain structure will possibly vary throughout the material, and will not be as refined as practicable. The second treatment is therefore given to develop a fine and uniform structure.

The temperature limits specified proved to be too close for practical control of such a large mass and were amended to 870–920° C. for the first treatment and 800-850° C. for the second.

In view of the high temperature and the time required for the first heat treatment great care must be exercised to prevent scaling which would result in reducing the cylinder wall thickness. Until quite recently the specification provided that the treatment should be carried out with the cylinders placed in boxes suitably packed so that all air was excluded and the furnace gases prevented from coming into contact with the metal. Packing the boxes however, does not exclude all the air, because the inside of the bottles cannot be packed, and consequently there is little gained. The substance with which to pack the boxes also presents a certain amount of difficulty, ashes are the most practical, but there is always the danger that small particles of coal may be present which will carbonise the material.

It was therefore agreed that it was safest not to pack the boxes. The most important condition is that furnace gases should not impinge on the cylinder, and this is complied with by using unpacked boxes.

It was then pointed out by a manufacturing firm that by using a specially adapted furnace it could be arranged so that there was no possibility of the hot gases impinging on the flask, and as when cylinders are in boxes they cannot be sighted or their temperature accurately obtained greater control could be exercised if special furnaces and no boxes were employed. This was fully appreciated, but because all firms do not possess the necessary furnace it is now specified that the heat treatment is to be either carried out in a special furnace or the cylinder is to be placed in a box.

The test results of cylinders made to this specification show that the treatment is very effective and that no difficulty is experienced in obtaining the specified mechanical properties. The results obtained and the structure indicated by the test piece fracture are remarkably uniform.

Manufacture.—Two distinct methods of manufacture are employed.

(*a*) Hot drawn machine finished,
(*b*) Cold drawn finished.

Cylinders manufactured by both processes are in use in the Service. It is claimed that a very close grained material is obtained with the cold drawn finished cylinders which is more resistant to corrosion but the cylinders have not been in use for sufficient time to demonstrate if this claim is correct.

(1) **Hot Drawn Machine Finished.**—A detailed account of this process has appeared in No. 12 Issue of these papers.

(2) **Cold Drawn Finished.**—The first part of this process is the same as previously described, except that the wall thickness is not reduced to the same extent by hot drawing.

After the final hot pass the cylinders are annealed and the wall thickness is gauged so that it can be set up in a lathe with the bore true. The outside is then rough machined to make it concentric with the bore and the closed end is turned to shape. A careful examination is then given for surface defects, and any that are found are chipped out.

The cylinder is then drawn cold over a mandrel, about four passes being given. The cylinder is annealed between each pass.

The cylinder walls are then gauged for thickness, no machining being done on them and if correct the test ring is cut and the cylinder is ready for bottling, the remaining process being as previously described.

In both methods described the original billet is forged into a cylinder, with one end closed and formed to shape. With the cold drawn process, however, the method is sometimes modified by first forming a tube. The initial passes are carried out hot and the final ones cold as before, and after examination and gauging of the walls, each end is closed by the bottling process. This method is only satisfactory if a fitting is required at each end, but it has the advantage that a more rigid examination can be carried out.

Future Development.—In order to reduce the weight of air cylinders it is essential that material that can be more highly stressed shall be used. From the experience gained when 45 tons/sq. in. plain iron carbon steel was employed it was concluded that the limit of U.T.S. for this type of steel for commercial production notwithstanding laboratory tests was 40 tons / in.^{2} Increasing the carbon content to increase the U.T.S. would tend to make the metal brittle and unreliable, so that it is obvious that further development can only be obtained by using alloy steels.

Such a steel must be capable of being drawn and the heat treatment must be simple, as it is not practical with a cylinder to quench, either in oil or water ; all cooling must be done in air.

In the heat treated condition the steel must also possess the valuable property of toughness already stressed.

Small cylinders for the Air Ministry have been made from a nickel chrome molybdenum steel whose trade name is Vibrac. As already stated such cylinders are tested by penetrating with a rifle bullet, and no failures have yet occurred with this alloy steel under such a test.

It does not follow, however, that large cylinders made from the same material will behave as satisfactorily, and this is now under investigation.