New Folder Name Convoluted Vacuum Tubes

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CONVOLUTED VACUUM TUBES FOR LONG BASELINE INTERFEROMETRIC GRAVITATIONAL WAVE DETECTORS

J R J Bennett, R J Elsey and R W Malton. Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom.

A discussion is given of the advantages of thin walled convoluted vacuum tubes for the long arms of interferometric gravitational wave detectors currently being proposed by a number of institutions around the world. Typically the tubes will be 3 km long and 1.5 m in diameter. Pressures of $\leq 10^{-7}$ mbar are required for hydrogen and at least an order of magnitude lower for the sum of all the other gases.

The results of tests of some of the mechanical and vacuum properties of a prototype section of convoluted tube are presented. The tube is 5 m long, 1.4 m internal diameter and is constructed from 0.91 mm thick 316L stainless steel sheet. The convolutions have a semicircular form of 20 mm radius, giving the tube a strength equivalent to a plain tube of the same diameter but 13 mm wall thickness. A specific outgassing rate of $\sim 3\times 10^{-13}$ mbar l/s/cm^2 is achieved by a vacuum bake at 150°C. Examination of the residual mass spectra reveals that >99% of the gas is hydrogen.

1. Introduction

The interferometric gravity wave detectors[1], which are proposed by a number of laboratories world wide, will have arms several kilometer long to gain the required sensitivity. The detectors must operate in a hydrocarbon-free vacuum of 10^{-7} mbar or better to reduce noise and avoid contamination of the super mirrors. Thus the devices will basically consist of two tubes, ~ 3 long and over 1 m in diameter arranged in the shape of an L, with a number of tanks containing the detector equipment at the ends of the arms. The tubes will be empty except for baffles to prevent scattered laser light entering the detector system.

The proposed German-British detector, GEO[1], will have vacuum tubes 3 km long and 1.38 m internal bore diameter. The specification of the the vacuum system and a description of tests for the determination of the system design are given in detail in reference 2, but are summarised here for completeness. The average pressure in the system should not exceed 10^{-8} mbar for hydrogen and 10^{-9} mbar for the sum of all other gases. The hydrocarbon content is difficult to quantify but every effort is to be made to reduce it as far as economically reasonable. There will be no 'O'-rings or other hydrocarbons in the system with the possible exception of the 1.25 m bore diameter gate valves isolating the experimental tanks from the tubes and parts of the vibration isolation system for the test masses. In addition, the pressure fluctuations must be less than 10^{-16} mbar in the operating frequency range of 100 to 3000 Hz. This has led to the adoption of non-evaporable getter (NEG) pumps (21 off 14000 l/s for hydrogen) for the final uhv pumping system with only very small turbomolecular pumps (4 off 200 l/s) to remove the hydrocarbons and noble gases that the NEGs do not pump. The tube will be constructed from 316L stainless steel, baked in air at 200°C for 24 hours and vacuum baked at 150°C for 10 days to achieve specific thermal outgassing rates of 10^{-12} mbar l/s/cm^2 for hydrogen and a 10 times lower rate for the sum of all the other gases.

Vacuum tests[2] on samples of 316L stainless steel sheet have shown that outgassing rates of 4×10^{-13} mbar $l/s/cm^2$ are obtained after a vacuum bake at 150°C for 10 days and that an air bake at 200°C for 24 hours followed by the vacuum bake at 150°C lowers the rate to $<10^{-14}$ mbar $l/s/cm^2$. Moreover, over 99% of the residual gas is hydrogen.

This paper describes the novel design of the tube, mechanical and vacuum tests on a prototype section of tube and considers developments to further improve the design.

2. Tube Design

Vacuum tubes for the arms of the detectors must be constructed from metal with few if any 'O'-ring joints to obtain the hydrocarbon-free vacuum. Hence, most tubes will be of all-welded or metal seal joint construction. The tubes will require a vacuum bake to remove the water on the surface: the temperature is likely to be at least 100°C. Clearly the tubes must not leak. Manufacturing tolerances on diameter, ovality and staightness need not be stringent. The tubes will need to be supported at suitable intervals along their length to reduce the sag between the supports to an acceptable value. In addition flexible bellows will have to be introduced at intervals to accomodate the thermal expansion from both the bake and normal temperature variations. Finally the tube must be designed to the relevant safety codes for strength and stability.

2.1 Strength and Stability

The tubes must withstand the external radial atmospheric pressure when under vacuum. Axial loads are zero since some form of end mounting will be needed to take the end load for a tube containing flexible sections to allow for thermal expansion. The radial load produces a circumferential or hoop, compressive stress in the tube, given by[3]

$$\sigma = \frac{p\times R}{t} \qquad t << R$$

where p is the pressure, R the radius of the tube and t the wall thickness. From this it is possible to calculate the required thickness of the tube so that the stress in the metal is not greater than the compressive yield strength at the highest working temperature.

Another mode of failure is through radial instability. Calculation of the stability of circular tubes is not exact since the collapse is brought about by imperfections in the geometry, material and construction of the tube and is affected by the method of support. The buckling pressure of a circular ring is[3]

$$p' = \frac{3EI}{R^3}$$

where E is the modulus of elasticity and I is the second moment of inertia of the section about its neutral axis.

However, it is usual to work to a safety code of practice, such as British Standard 5500, (British Standards Institution, London, UK) or ASME Code, Section VIII, (American Society of Mechanical Engineers, New York, USA), which give design procedures for both strength and stability. These codes are based on the results of practical tests for different metals and working temperatures and take account of unavoidable imperfections in manufacture and materials.

2.2 Plain and Convoluted Tubes

Tubes can be made in a number of forms; the simplest are smooth, plain tubes, Fig 1a. The strength of a plain tube under external pressure, is derived from the thickness of the wall, see Fig 1 for the 2nd moment of inertia, I. If the wall thickness is reduced, then the tube must be stiffened by the addition of, for example, circular rings at regular intervals along the length of the tube. A convoluted tube is an extension of this principle, where the tube itself forms the stiffening rings in a semi-continuous way. Convoluted tubes can have a range of profiles: some are shown in Fig 1 with their corresponding values of I per unit length and material volume, v, per unit length.

Clearly it is important to mimimise the cost in both materials, construction and assembly of the long tubes to be used in interferometric gravitational wave detectors. Hence, different tube profiles must be considered.

It is readily seen that the volume of material in a convoluted tube can be significantly less than that of a plain tube of the same diameter and stability (moment of inertia). Consider the case of the semi-circular profile, Fig 1c. The ratio of the volumes of this tube to the plain tube, is,

$$\frac{v_c}{v_a} = \sqrt[3]{\frac{2I^2}{3r^6}}$$

and expressing I in terms of the semi-circular profile, $I_c = \frac{1}{4}\pi t r^2$, gives

$$\frac{v_c}{v_a} = \sqrt[3]{\frac{\pi^2 t^2}{24 r^2}}$$

The wall thickness cannot be reduced below the limit of the material strength: thus, $t = 0.7$ mm and then $r = 20$ mm for stability. This gives $v_c/v_a = 0.08$. The weight of steel in 6 km length of a plain tube of 1.38 m internal diameter and 13 mm wall is ~2700 tonnes and would cost £5.4M at todays rate of ~£2000/tonne. The semi-circular profiled tube has a weight of only 200 tonnes and costs £0.5M!

A comparison of the various convoluted tube profiles shown in Fig 1 indicates that they can all have similar material volumes for a given t and minimum buckling stability. For the particular case where $h = r = 1$, the relative material volumes of the semicircular, rectangular and triangular sections are

$$v_c : v_d : v_e = \pi : 4 : 2\sqrt{2} = 1.11 : 1.41 : 1$$

The triangular profile has the lowest volume, marginally lower than the semicircular section. The stiffened tube, with $T = t$, $h = 1$, has the same material volume as the rectangular convoluted tube, but the moment of inertia is lower by a factor of 5/8.

The optimum convoluted tube is probably the traditional corrugated form shown in Fig 1f. It is similar to the triangular form of Fig 1e, but with rounded corners which reduce local stress. This shape is being examined at present to find the optimum geometry:- amplitude, pitch and radius of the corrugations.

2.3 Advantages and Disadvantages Of Convoluted Tubes

It is clearly an advantage to be able to construct a convoluted tube of the same strength and stability as a plain tube but with a fraction of the mass: the material and transport costs are reduced, handling is easier, supports lighter and less expensive. Manufacturing costs are also reduced with the material handling, cutting, bending and welding being easier for the thin material. However there is an additional cost in forming the convolutions. Estimates from a number of manufacturers have shown a cost (material plus manufacture) advantage of up to a factor of 10 in favour of the convoluted tube.

The convoluted tube has axial flexibility, acting as a stiff, but continuous, bellows. Hence, additional bellows are not required to allow for axial thermal expansion. The lateral stiffness is not as great as the equivalent smooth-walled tube and supports are needed at about 3 m intervals to limit sag to a few mm. However, since the supports are light and inexpensive this is not a problem, but more of an advantage, since it allows alignment, hence obviating the necessity of great precision of manufacture. Even a thin-walled tube with stiffening rings does not have the flexibility of the convoluted tube. Another advantage is to be able to use the relatively high electrical resistance of the thin wall to heat the tube by passing a current along its length for baking to achieve low outgassing rates. A thick-walled tube would require a higher current to achieve the same heating power.

Although plain tubes have a smaller surface area than convoluted tubes, since the latter are made from thin sheet, the material generally has a better surface finish, which reduces the real difference in surface areas. Stiffened plain tubes would have an advantage in surface area if made from thin sheet, but the manufacturing costs are much higher than for convoluted tubes.

From the above discussion, it is clearly an advantage to construct the large tubes required for interferometric gravity wave detectors with thin-walled convoluted profiles. Indeed, this form should be considered for any large vacuum tube.

3. The GEO Tube, Construction Details

The tube originally proposed[1] for GEO is of semi-circular profile of 20 mm radius and 1380 mm bore diameter: Fig 2 shows the dimensions, which have been calculated to the standards of the Expansion Joint Manufacturers Association, Inc, USA. Approximately 70 circular stainless steel baffles, ~ 1 mm thick with an aperture of 1260 mm diameter, will be placed inside each 3 km long tube. The tube will be supported on light, electrically insulating legs, which will be adjustable to align the tube. The legs will be spaced at ~ 5 m intervals to limit the sag to <5 mm, leaving a clear bore of

~ 1250 mm diameter for the laser beams of the interferometers after allowing 5mm for alignment errors.

The tube will be constructed from 0.71 mm thick, 316L stainless steel sheets. To avoid considerable transport costs, it is likely that the tube will be manufactured at the GEO site. The sheets will be welded together to form tubes ~ 1.5 m long, in which the profile is formed by rolling or by press tool, thereby reducing their length to ~ 1m. The meter long sections of convoluted tubes will be TIG welded together, (see Fig 2 for the weld detail), to form ~ 100 m lengths. End caps will be welded to the 100 m lengths of tube for a helium leak test. The maximum acceptable leak will be ~ 10^{-11} mbar l/s. The 100 m long sections will be placed on their supports in their final position and then welded to form the 3 km long tubes.

The sheet material from which the tubes are constructed will be in a clean and bright condition as supplied by the manufacturer. The sheets will be kept as clean as possible during the manufacture into 1 m long convoluted sections and only handled with clean cotton gloves. The sections will then be passed thorough baths of a 5% solution of alkaline detergent, Decon 90, (Decon Laboratories Ltd) in demineralised water and rinsed with demineralised water. From this point on every effort must be made to maintain cleanliness and it is particularly crucial once the 1 m sections are welded together due to the crevices formed at the weld between tube sections, see Fig 2. However, if there is some small amount of contamination, the 200°C air bake will remove this from the final assembly.

4. Prototype GEO Tube

It was decided to build a 5 m long section of convoluted tube to test the mechanical properties, and to confirm the strength and stability calculations. Also, the vacuum performance of a tube manufactured under factory conditions could be assessed and compared with the tests[2] on laboratory prepared sample sheets of stainless steel.

The tube was manufactured by Bird Precision Bellows, Congleton, UK. The profile was formed by rolling, which necessitated material of 0.91 mm thickness to obtain the form to the required accuracy.

The 1 m long sections of tube were welded together at 12 mm thick rings 50 mm long. These rings will not be used for the GEO tube: the sections will be welded directly to each other, see Fig 2. Dished end plates, 6 mm thick were welded to the ends of the prototype tube. In the centres of the end caps were welded short 60 mm bore diameter tubulations with Conflat* style flanges to attach the vacuum equipment.

To prevent the tube collapsing axially when evacuated, two large rings were attached to the end plates at their junction to the tube and 4 mild steel tubes inserted between the rings to take the end load. Fig 3 shows the assembled tube. The tube was stretched slightly in assembly so that even when heated to 200°C the tube would not be in compression (the mild steel tubes are assumed to remain at room temperature) thus removing the possibility of "squirming instability"[3].

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[*] Conflat is a registered trade mark of Varian Associates.

4.1 Mechanical Tests

A ~ 1 m long section of the tube was hydraulically pressure tested until it collapsed. A plain tube was fitted over the convoluted tube and their ends welded together. The interspace between the tubes was slowly pressurised with water from a hand pump until at 4.2 bar the convoluted tube collapsed locally, but did not rupture, see Fig 4. The calculated pressure for failure was 7 bar for buckling stability, taking account of the short length of the tube and that it was supported by the outer tube at its ends. The 0.2% proof stress of the material was reached at ~ 4.2 bar. The test showed that the tube withstood the vacuum load with an adequate margin of safety.

The ~ 1 m long sections of tube were measured: the tubes were straight to ±1 mm, their mean internal diameters did not vary by more than ±4 mm and any one convolution was round to within ±1 mm, and the diameter of the semi-circular profile did not vary by more than ± 1 mm. The axial spring rate was measured to be 2.3×10^{-3} mm/kg/convolution, compared to the calculated value of 2.5×10^{-3} mm/kg/convolution.

Measurements of the dimensions of the assembled tube were made. The tube was straight to within ~ 6 mm. The tube sagged under its own weight by ~ 10 mm at its centre. Under evacuation the tube straightened and the sag reduced to ~ 5 mm. This measurement was confirmed by measuring the frequency of the first violin mode of oscillation of the tube, which is given by[3]

$$f = 5.66y^{-\frac{1}{2}}$$

where y is the sag in the tube. The frequency was 8.11 Hz, corresponding to a sag of 4.9 mm.

4.2 Vacuum Tests

A turbomolecular pump (nominal speed 330 l/s) and a non-evaporable getter (NEG) pump (nominal speed 100 l/s for hydrogen) were attached to the tubulation at one end of the tube, see Fig 5, and a 2 stage rotary vane pump of 40 m^3/hr nominal speed, a Bayard-Alpert ion gauge and a small quadrupole mass spectrometer attached to the other end. The pumps could be valved-off from the tube. The turbomolecular pump had a net speed of 130 l/s (hydrogen) to the tube and the NEG, 30 l/s for hydrogen and 10 l/s for nitrogen, carbon dioxide, water and other active gases.

The tube was initially evacuated with the rotary pump. After about 3 hours, at a pressure of ~ 0.1 bar, the pump was valved-off from the tube and the turbomolecular pump brought the pressure down to 10^{-6} mbar in 30 hours. The pressure continued to fall, reaching 2.3×10^{-8} mbar in 1500 hours. The mass spectrometer indicated masses 2, 18, 28 and 44 (amu) in the ratios 7.6×10^{-2}, 1, 3.1×10^{-2}, and 2.1×10^{-2}, respectively.

Then the tube was heated to 150°C for 10 days to drive off the water. Electrical connections were made to the tubulations in the centres of the dished ends and an alternating (50 Hz) current of 1300 A passed through the tube. The vacuum chamber was thermally insulated with 100 mm thick mineral wool blanket and overwrapped with aluminium foil. The temperature was reached with 3.4 kW: the calculated value was only 2.6 kW. It was concluded that circulating currents of air, both under and through the mineral wool blanket were taking some of the heat away. Moreover, the ends around the vacuum tubulations were not covered with insulation and there was considerable heat loss at the supports on the end rings. The vacuum fittings at the ends of the tube were baked by small heater tapes. At the end of the 10 day heating cycle, the NEG pump was regenerated by heating to 750°C for 15 minutes. The vacuum bake-out was then terminated.

After several days, pressures of 3×10^{-9} mbar were measured on the ion gauge, with both turbomolecular and NEG pumps connected to the system. With the NEG pump alone the pressure was 1×10^{-8} mbar but rose gradually due to methane which the NEG does not pump. Much of this was produced in the ion gauge and quadrupole RGA[2].

The hydrogen outgassing rate was determined by the known pressure and pumping speed to the tube and also by isolation pressure rise measurements. To eliminate the effects of pumping and gas emission by the ion gauge and RGA, an isolation pressure rise test was carried out with all gauges in the tube switched off; after a suitable accumulation time, the system was connected to a small turbomolecular pump, equipped with gauges and an RGA, and the change in pressures recorded. This is a modified Messer and Treitz[4] method. This method was also used for measuring the outgassing rate when the tube was being pumped by the NEG pump only. It was concluded[2] that the residual gas consisted of over 99% hydrogen, the outgassing rates were 3×10^{-13} mbar l/s/cm^2, for hydrogen, $\leq2\times10^{-16}$ mbar l/s/cm^2 for each of water, carbon monoxide and carbon dioxide, and $<2\times10^{-17}$ mbar l/s/cm^2 for methane. It was also concluded that the ion gauge in the tube probably read higher than the true value, due to local outgassing of the gauge and the limited conductance of the tubulation in which it was situated.

Hence, the tube has exceeded the required specification in terms of outgassing rate, partial pressures (>90% hydrogen) and has reached pressures of $<10^{-8}$ mbar with only 6 l/s of NEG pumping speed per meter length of tube compared to 20 l/s/m proposed for GEO. Moreover, this has been achieved without the air bake and shows that a tube manufactured under factory conditions can perform as well as the samples prepared under laboratory conditions. Clearly, the tube was adequately clean and did not require the air bake to remove contaminants. Furthermore, the tube was stable and did not collapse under vacuum even when at 150°C. Tests following a 200°C air bake will be carried out later.

5. Developments in Tube Design and Manufacture for GEO

The construction of the convoluted tube by spirally winding and welding is being examined. Steel sheet from a roll is passed through rollers to form the convolutions before being bent into a tube and TIG welded along the spiral joint. The whole operation can be automated thereby reducing costs. Continuous long lengths, perhaps 100 m, will be produced on site. It may even be beneficial to purchase the tube manufacturing equipment which, with collaboration, could be used profitably by all institutions building similar interferometric gravity wave detectors. The spirally welded tube is expected to cost about £1.5M, including material, manufacture and tooling, half the estimated cost of the convoluted tube made from short sections, and one fifth of the cost of the plain tube.

Almost certainly the profile will be of the corrugated profile shown in Fig 1f since it would appear to have the best strength to weight ratio and will probably be easier to form than the semi-circular section.

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Fig 1 Sections through Plain and Selected Convoluted Tube Profiles. Values of the second moment of inertia, I, and the volume of material, v, are given per unit length of tube.

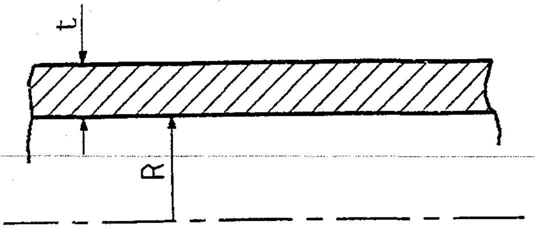

Fig 1a Plain Tube

$I_a = \frac{t^3}{12}$

$V_a = \pi(2R+t)t$

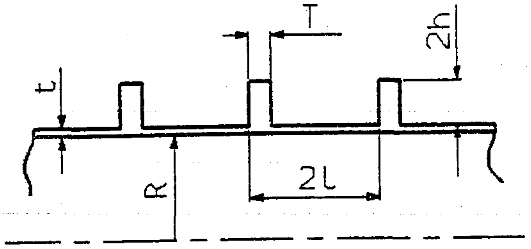

Fig 1b Tube strengthened with Circular Rings

$\left.\begin{array}{l} I_b = \frac{5}{6}th^2 \\ V_b = 4\pi Rt \end{array}\right\}$ for T=t and L=h

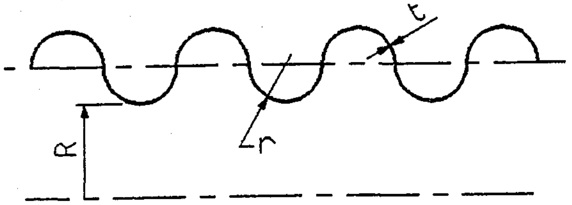

Fig 1c Semicircular Profile

$I_c = \frac{\pi}{4}tr^2$

$V_c = \pi^2(R+r)t$

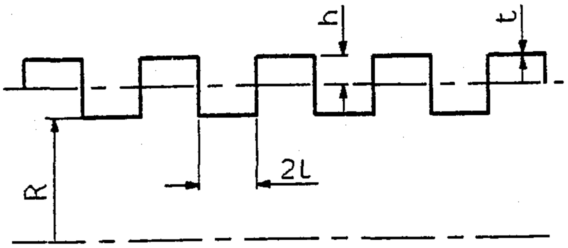

Fig 1d Rectangular Profile

$I_d = \frac{t}{3L}(h^3+3h^2L)$

$V_d = 2\pi R\frac{(L+h)t}{L}$

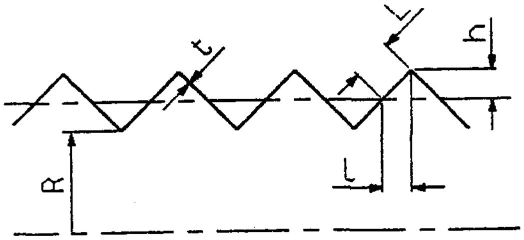

Fig 1e Triangular Profile

$I_e = \frac{h^2Lt}{3l}$

$V_e = 2\pi(R+h)\frac{Lt}{l}$

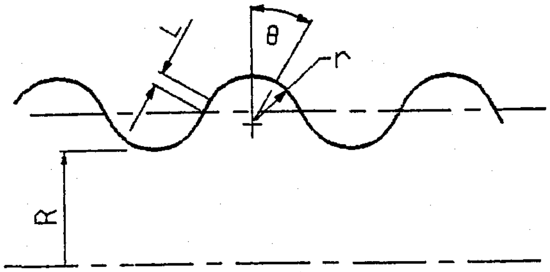

Fig 1f Corrugated Profile

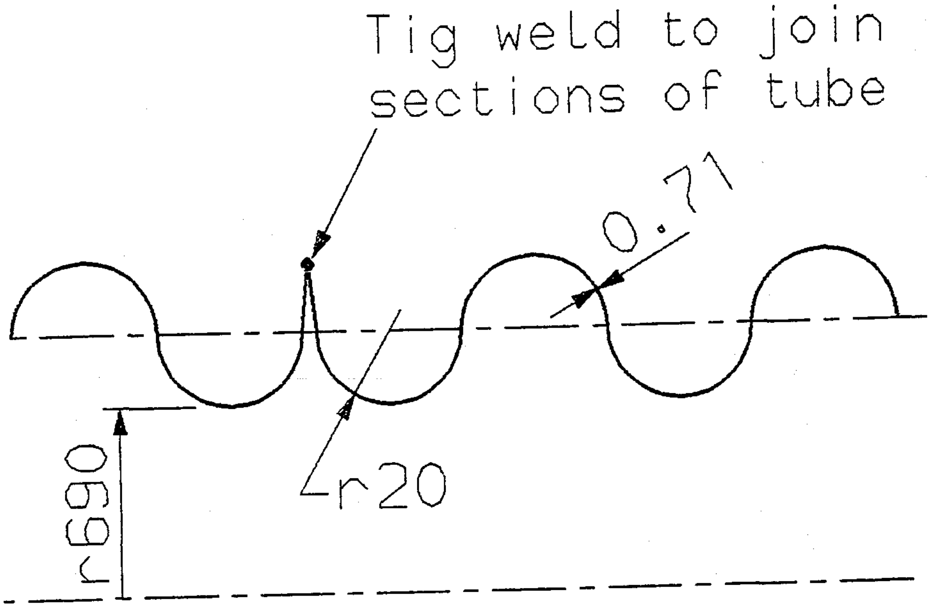

Fig 2

Proposed Semicircular Profile
for GEO Tube
All dimensions in mm