

LIGO VACUUM SYSTEM STUDY

Jeffrey C. Livas
Massachusetts Institute of Technology

Boude C. Moore
California Institute of Technology

ABSTRACT

A laser interferometer gravitational wave observatory (LIGO) is being developed with sensitivities which will have a high probability of detecting gravitational waves from astrophysical sources. Detectors are also planned by others in Europe and eventually in space. A major component of the proposed LIGO is a total of 16 km of 1.2 m (48 inch) diameter tube at a pressure of less than 10^{-8} torr. It will be of 304L stainless steel procured directly from the steel mills with the initial hydrogen content specially reduced. (Target is 1 ppm by weight.) Projections of the outgassing rates of hydrogen and of water vapor as a function of time will be given and the uncertainties discussed. Based on these, a preliminary analysis of the vacuum system will be presented.

INTRODUCTION

The development of laser interferometric gravitational wave detectors is proceeding at the prototype level in several countries: France, Germany, Italy, Japan, United Kingdom, and the United States. Plans to build a full scale detector in each of the countries are being considered; the result would be an international network of detectors capable of doing useful astronomy with gravitational waves. The network would open a new window on the universe complementing the existing windows in the optical, infrared, radio, and X-ray bands and add to our understanding of the cosmos as did the opening of the radio window in the 1930's and the X-ray window in the 1960's. A particularly interesting possibility would be the direct observation of black holes.¹ Descriptions of the physics of gravitational wave detection and recent prototype developments have been described elsewhere.^{1,2}

In the United States, a collaboration of Caltech and MIT scientists, funded by the National Science Foundation (NSF), is planning the construction of two separate full-scale detectors under a single management (the LIGO project). At least four spatially separated detectors are required to unambiguously determine the location of a source; the two in the U.S. will provide a solid foundation on which to build the international network. Two detectors are also needed for a cross-correlation analysis to eliminate false signals caused

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by environmental noise at each separate detector. Since many of the theoretically predicted sources of gravitational waves emit at frequencies below 10 Hz where ground motion and gravity gradient noise reduce the sensitivity of earth-based detectors, there are plans to construct space-based detectors.³

The objective of this study is to ensure that the technical requirements for the vacuum system are met with minimum cost. A similar study has been published for the detector planned in the United Kingdom.⁴ A classical approach to reduce costs of pumping systems is to bake and thereby reduce the gas load. For the LIGO project, the cost and time for baking the system are significant. It is therefore useful to determine if the requirements for the vacuum can be met without baking. A brief description of a proposed detector is presented together with the vacuum requirements. The outgassing characteristics of stainless steel will be shown for hydrogen and for water vapor. Based on these, a conceptual design of the vacuum system will be presented.

FACILITY DESCRIPTION

The LIGO Project proposal is for a single observatory consisting of two detectors, separated by a continental baseline. Each LIGO detector consists of two lengths of vacuum pipe connected to form the two arms of a right angle. (This geometry takes advantage of the polarization of the gravity wave and reduces the demands on the frequency stability of the laser.) Laser beams travel back and forth between mirrors in each arm. Each arm will be four kilometers in length and 1.2 meters (48 inches) in diameter. Components of the laser interferometer will be contained in chambers located at the junction of the arms, at their midpoints, and at their ends, as illustrated in Fig. 1. Thus the same beam tube design can be applied to the four identical 2 kilometer sections between chambers. A sketch of a 2 kilometer section and its vacuum system is shown in Fig. 2.

The laser interferometer measures changes in the distance between the two masses in each arm and then compares the changes in the two arms.¹ To indicate the level of difficulty of the measurement, these changes are expected to be on the order of .004 of the diameter of a proton for the LIGO detectors. Vibration from vacuum pumps or equipment could obviously interfere with this measurement.

The arms must be evacuated so that scattering of the laser beam by the residual gas molecules is reduced. However the acceptable levels of pressure (which increase with arm length) can be achieved with existing technology. If all the gas were hydrogen, then a pressure of 1.3×10^{-6} Pa (1×10^{-8} torr) would be acceptable. Similarly, if all the gas were water vapor, 1.2×10^{-7} Pa (9×10^{-10} torr) would be acceptable. An important feature of these requirements is that they need not be met immediately on facility completion. The laser interferometers are in a state of development, and are not expected to reach the planned sensitivity for some time. Initial operations may be conducted at somewhat higher pressures without limiting the observations.

Considered as a vacuum system, the LIGO is unusually large. Each of the eight 2 kilometer beam tubes (four at each site) has a volume of 2.3×10^6 liters, and a surface area of 7.7×10^7 cm². Because of its large size, the cost of baking the system, as is often done to reduce the gas load, would be very high. Again because of its size, the option of using vacuum melted steel to reduce outgassing would be prohibitive.

Gate valves are provided at each end of the 2 kilometer sections so that the vacuum chambers can be brought up to atmosphere for access to the laser interferometer equipment, while the beam tubes remain under vacuum. It is planned that these tubes will not be exposed to the atmosphere after the initial pumpdown and leak testing.

STAINLESS STEEL OUTGASSING – HYDROGEN

The most difficult gas to remove in a stainless steel vacuum system is the hydrogen. In fact, it has only been reduced, not eliminated, in efforts to date. Messer and Treitz⁵ report an outgassing rate of 10^{-14} Pa L/s·cm² (10^{-17} torr·L/s·cm²) or 300 molecules/s·cm², after high temperature (875K) bake in a vacuum oven. Such low levels are not economically feasible on a large chamber, but a rate of 1.3×10^{-10} Pa L/s·cm² (10^{-12} torr·L/s·cm²) is often achieved.⁶

Typically, 99% or more of the residual gas in a baked system is hydrogen.⁶ The source of this gas is atomic hydrogen dissolved in the bulk material during the manufacturing processes. This diffuses out to the surface, combines into molecular hydrogen and is released into the gas phase. The diffusion is greatly accelerated at high temperatures. A quantitative description of this process has been given by Calder and Lewin.⁶

$$Q = 4 C_o \frac{D}{d} \left[\sum_{n=0}^{\infty} e^{-\left(\frac{\pi(2n+1)}{d}\right)^2 Dt} \right] + \frac{K}{d} P_H^{1/2} \quad (1)$$

where:

Q = outgassing rate, torr liters/cm² second

C_o = initial gas concentration in the metal, standard torr liters/cm³, uniformly distributed

D = diffusion coefficient, cm²/second

d = wall thickness, cm

t = time, seconds

K = permeability constant (= 1.2×10^{-16} torr^{1/2} L/cm·s at room temperature)

P_H = partial pressure of atmospheric hydrogen⁴ (= 5.3×10^{-2} Pa (4×10^{-4} torr))

To use this formula, it is necessary to know the values of C_o and D . Values for C_o given in the literature vary from 1.1 to 4.5 parts per million (ppm) by weight.^{6,7} A half dozen random samples recently tested were found to have concentrations between 1.5 and 3.7 ppm. These appear to be small differences but they cause a very large change in the degassing time of unbaked systems, as will be shown below.

The other value required is the diffusion coefficient, D . The value used in the calculations below is $5 \times 10^{-14} \text{cm}^2/\text{second}$ at 27C. This value was extrapolated⁶ from measurements by Eshbach, et al⁸ taken on 304 stainless steel at much higher temperatures. The value is uncertain, due to the large extrapolation, and also due to changes which have been observed in iron over this temperature range. Alpha iron⁹ has shown much lower rates at room temperature than would be extrapolated from high temperatures. Thus if there is an error in the diffusion coefficient it may be in the direction of less outgassing.

The outgassing rate at 27C according to Equation (1), as a function of *time since manufacture*, is shown in Fig. 3 for levels of initial hydrogen concentration of 0.5, 1, 2, and 4 ppm by weight. The wall thickness is assumed to be .4 cm (.155 inch) thick (a value suitable for the LIGO application). The outgassing rate will decline from the time of manufacture rather than time under vacuum, since the internal concentration is so much higher than the equilibrium due to ambient hydrogen. Initially, the outgassing rate declines as $1/\sqrt{t}$, and the concentration at the center of the chamber wall is unchanged. After sufficient time, about 30,000 years, this center concentration begins to fall, and then the outgassing rates fall exponentially. Finally they reach a constant level due to permeation of atmospheric hydrogen through the wall, There may be additional permeation as a result of the water vapor in the air.

The important part of the curves in Fig. 3, for this problem, is expanded in Fig. 4. The time to reach any specified rate varies as the square of the initial concentration. The 8:1 range of concentrations plotted becomes a 64:1 range in the time required to reach a given rate.

This estimate of the rate of hydrogen outgassing as a function of time and of initial concentration will be used below in the conceptual design of the LIGO vacuum system. It will also be a guide for the future procurement of steel for the facilities.

STAINLESS STEEL OUTGASSING – WATER VAPOR

Water vapor is relatively simple to remove from a vacuum system. After bakeout, it is frequently reported to be unobservable. For practical purposes, it can often be ignored as a residual gas in a baked system.

However, in an unbaked system most of the initial outgassing is water vapor.⁷ The initial rate is observed to decrease as $1/t$ and its magnitude will vary with the surface cleaning procedures used. We found no data for degassing times greater than 100 hours^{7,10} for unbaked systems. Dayton's⁷ review gives a rate of $1.9 \times 10^{-5} \text{ Pa L/s} \cdot \text{cm}^2$ ($1.4 \times$

10^{-7} torr · L/s · cm²) after one hour. The outgassing rate can be expressed as:

$$Q = Q_1 \times (t_1/t) \quad (2)$$

where:

Q = outgassing rate

Q_1 = outgassing rate at time t_1 (= Dayton's value at 1 hour)

t = time

As t becomes large the outgassing rate is expected to become less than given by this expression,⁷ else the quantity outgassed would exceed the quantities observed. Further evidence for this view is provided by outgassing experiments at higher temperatures, to be discussed below.

The simplest model of gas sorption on a surface is that of an average sojourn time which is a function of the heat of adsorption.¹¹ The surface coverage is then:

$$S = Q \tau \quad (3)$$

where:

S = quantity of gas adsorbed per cm² of surface

Q = quantity of gas adsorbed or desorbed per cm² per sec.

τ = average sojourn time on surface, in seconds

Frenkel's equation (1924) for the variation of sojourn time with temperature¹¹ is:

$$\tau = \tau_o e^{H/RT} \quad (4)$$

where:

τ = sojourn time on surface, as defined above

τ_o = time of oscillation of adsorbed molecules, normal to surface, assumed = 10^{-13} seconds¹¹

H = heat of adsorption, cal/mole

R = gas constant = 1.9872 cal/mole K

T = temperature, Kelvin

The heat of adsorption, H , has been given as 22 to 25 kcal/mole for water on metals.¹² In a recent desorption experiment¹³ a 304 stainless steel cylinder was heated at a rate of 0.2 degrees Kelvin per second. Two desorption peaks were reported, one at 22 and the other at 25 kcal/mole. The corresponding temperatures were 55C and 93C.

This measurement of outgassing rates at higher temperatures can be used to estimate the rate at room temperature. If a surface holding a quantity S_o , of adsorbed gas is allowed to desorb, starting at time $t = 0$, then from equations (3) and (4) it follows that the outgassing rate would be:¹²

$$Q = \frac{S_o}{\tau} e^{-\frac{t}{\tau}} \quad (5)$$

where:

Q , t , and τ are as defined above,

S_o = quantity of gas adsorbed on the surface at the time $t = 0$

The plot in Fig. 5 shows the exponential decay for four values of the heat of desorption, H : 22, 23, 24, and 25 kcal/mole. These have been normalized to Dayton's⁷ estimate of the outgassing rate after one hour under vacuum. The extrapolated $1/t$ function has also been shown. It is clear that the average sojourn model does not explain the initial $1/t$ outgassing observed.

In an attempt to resolve this discrepancy, Dayton⁷ suggested that the $1/t$ function could be a result of the water being desorbed from the surface with a spectrum of energies rather than any single value, reflecting the complexity of a real surface. To illustrate this approach, the outgassing rates of the four groups of molecules, with the heats of desorption shown above, were added in a weighted fashion at each point in time. The details of the weighting are given in the Appendix. The result is shown in Fig. 5, and it is seen to follow the $1/t$ function for a few hundred hours and then decay exponentially. The subsequent large gap between these two functions demonstrates the uncertainty of the outgassing rate for times greater than 1000 hours.

To summarize this water outgassing discussion, no observations of unbaked systems have been found in the literature for times greater than 100 hours. A rough estimate can be made based on outgassing at higher temperatures, but the accuracy of this estimate is open to question at this time.

CONCEPTUAL VACUUM SYSTEM DESIGN

A conceptual design of the vacuum system for a 2 kilometer beam tube is shown in Fig. 2, and its performance over time is given in Fig. 6. Ion pumps are used for low vibration. (Other pumps will be used to reduce the pressure from atmosphere but they will be turned off during laser interferometer operation.) Seven pumps are spaced at 250 meter intervals. Their operational pumping speed is assumed to be 2000 L/s for hydrogen,

and 1000 L/s for water vapor. The ends of the tube are assumed to be open to the vacuum chambers, where additional pumps and gas load result in the same pressures as in the tube.

The ratio of the peak pressure (halfway between the pumps), to the minimum pressure (at the pumps) is 1.08 for hydrogen, and 1.11 for water vapor.¹⁴ The average pressure is the important parameter for beam scattering, so this is shown in Fig. 6. The average is 1.05 of the minimum pressure for hydrogen, and 1.074 for water vapor.

The hydrogen is plotted for an initial concentration of 1 ppm of this gas within the walls of the vacuum system. The time required to reach the design pressure for hydrogen is 8 months from the time of manufacture, here assumed to be 1000 hours before pumpdown.

The water vapor plots are limits. It can be seen that a completely unbaked system may be quite feasible, but in the absence of direct experimental data this is not certain. Experiments to provide this information are underway.

SUMMARY

The vacuum levels required for the LIGO are well within the state of the art. However, the unusually large size of the vacuum vessels dictates that every effort be made to minimize the system's initial and operating costs. The 2 kilometer beam tubes will be permanently under vacuum. They may not need to achieve the vacuum design goals immediately. These conditions suggest that the possibility of an unbaked system be examined.

For the most difficult task, reducing the hydrogen partial pressure, the unbaked system is feasible; the required pressure can be achieved in an acceptable time. The partial pressure of water vapor, on the other hand, can only be estimated within limits until more outgassing data is obtained. Experiments to provide this information are now underway.

APPENDIX

Four groups of molecules adsorbed on a surface have been defined with heats of adsorption of 22, 23, 24, and 25 kcal/mole. The magnitude of each group has been adjusted so it fits Dayton's outgassing rate at one hour. These groups have been plotted on Fig. 5.

These four groups are now weighted and combined as follows:

$$D(t) = A_{22}(t) + A_{23}(t)/B + A_{24}(t)/B^2 + A_{25}(t)/B^3$$

$$Q(t) = K D(t)$$

$$K = \frac{Q_1}{D_1}$$

where:

$A_{22}(t)$ = outgassing rate of 22 kcal/mole water at time t . $A_{23}(t)$ thru $A_{25}(t)$, similar

$Q(t)$ = outgassing rate at time t . Q_1 = rate at 1 hour

$D(t)$ = weighted sum of outgassing rates

$D_1 = D(t)$ at 1 hour

B = constant. $B = 3$ is plotted

This sum is shown in Fig. 5.

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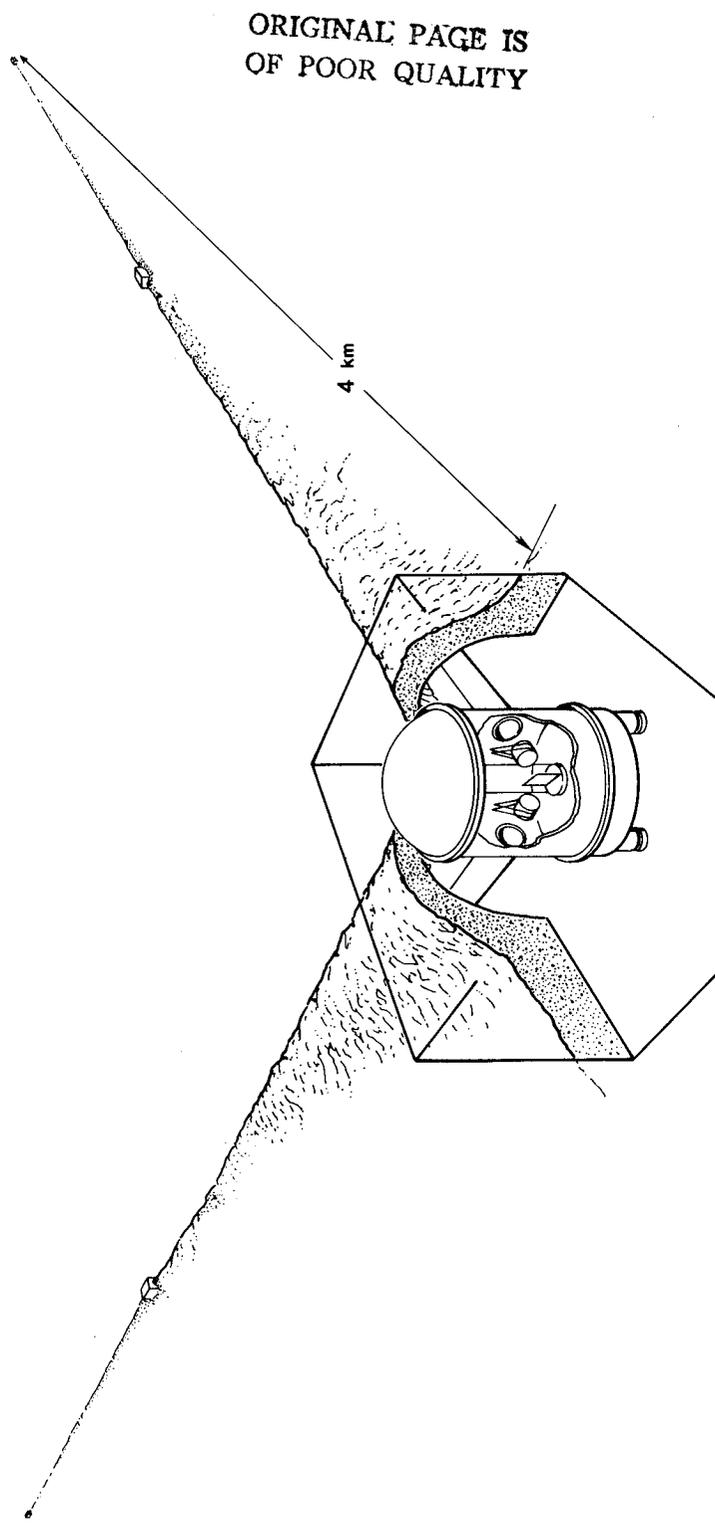


Fig. 1 Artist's conception of a LIGO detector installed at one of the two sites.

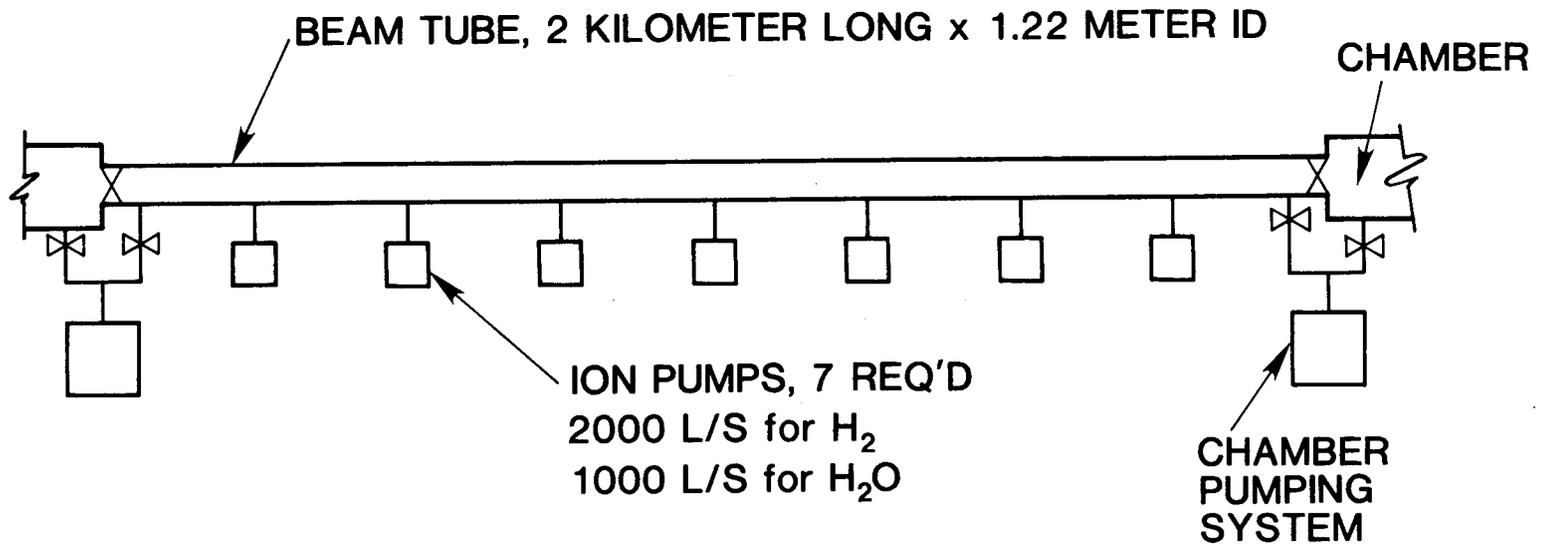


Fig. 2 Concept of LIGO 2 kilometer beam tube, with ion pumps at 250 m intervals.

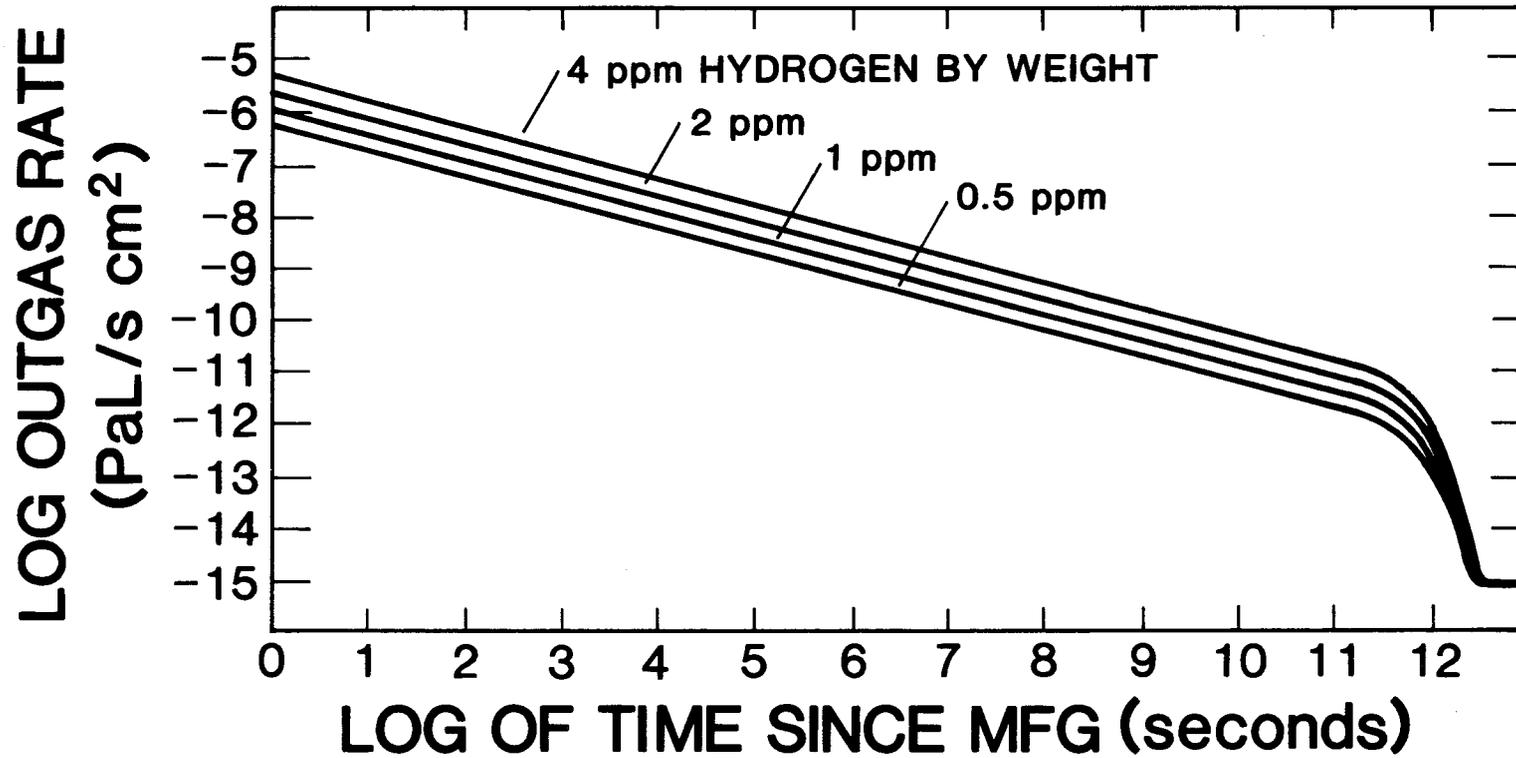


Fig. 3 Hydrogen outgassing rate from 304 stainless steel vs. time since manufacture for initial concentrations of 0.5, 1, 2, and 4 ppm by weight.

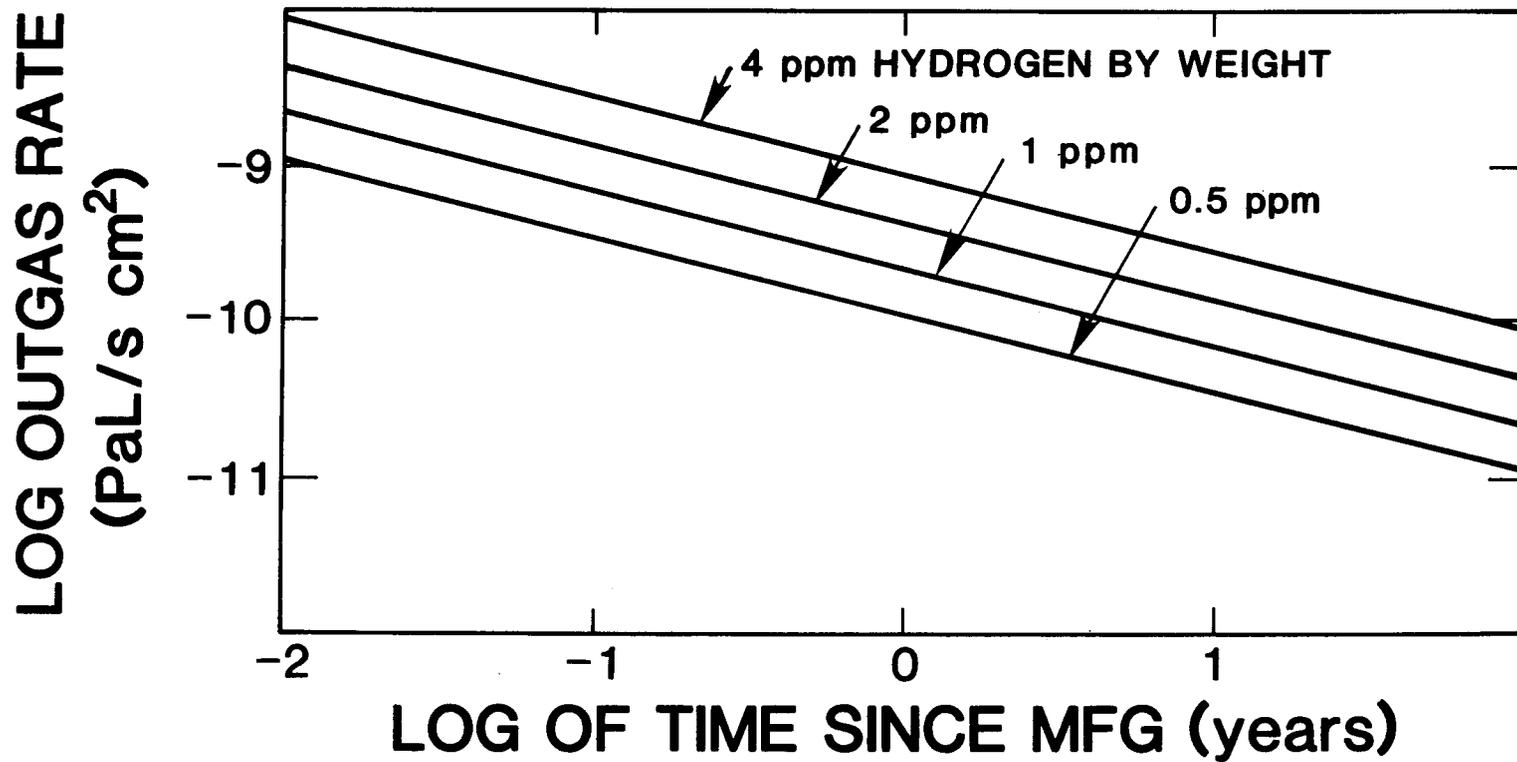


Fig. 4 Same as Fig. 3, with expanded time scale.

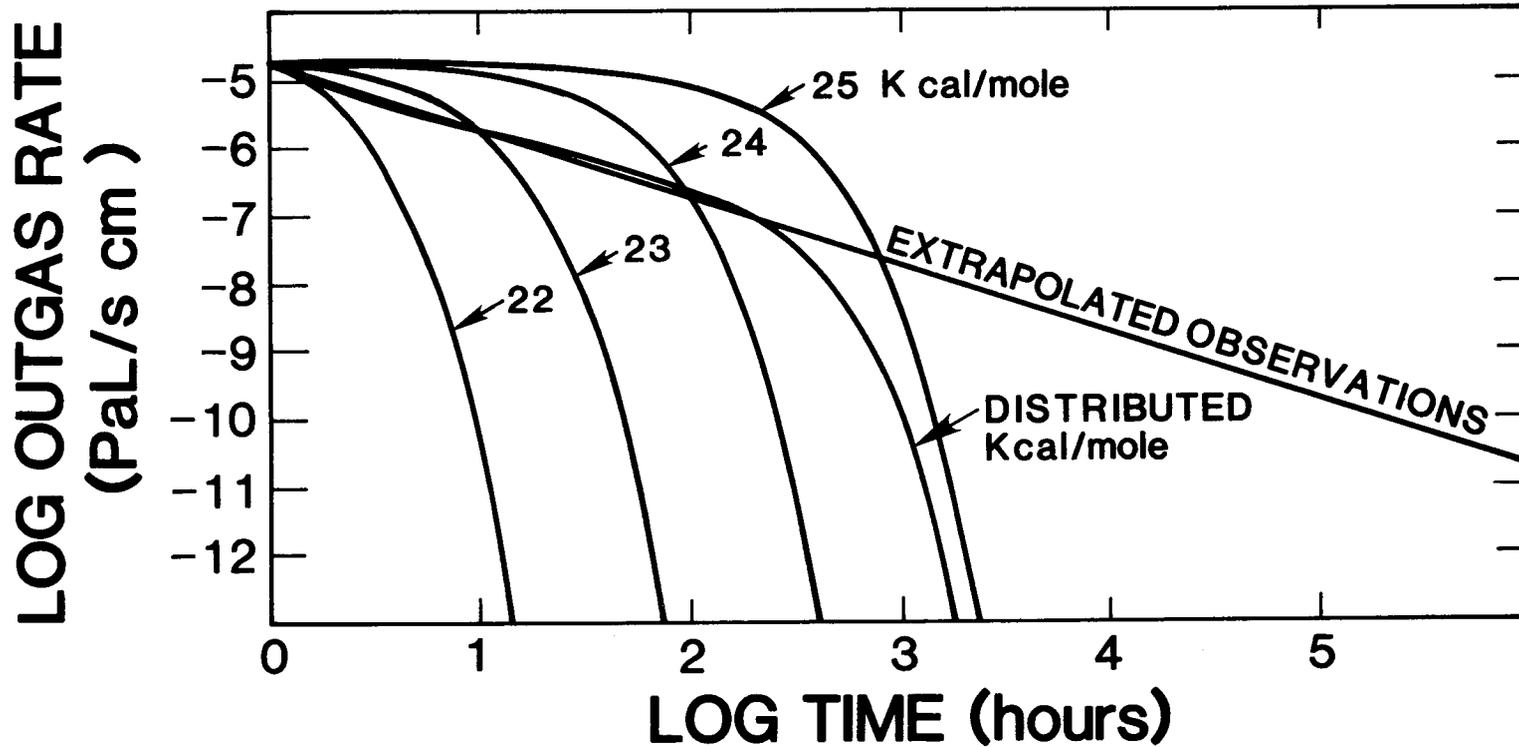


Fig. 5 Water vapor outgassing rate for 304 stainless steel vs. time under vacuum with indicated heats of adsorption, using the "average sojourn time" model. These are fit to Dayton's⁷ upper limit. A distributed heat of adsorption model, combining the outgassing from several fractions held to the surface with different energies, is also shown.

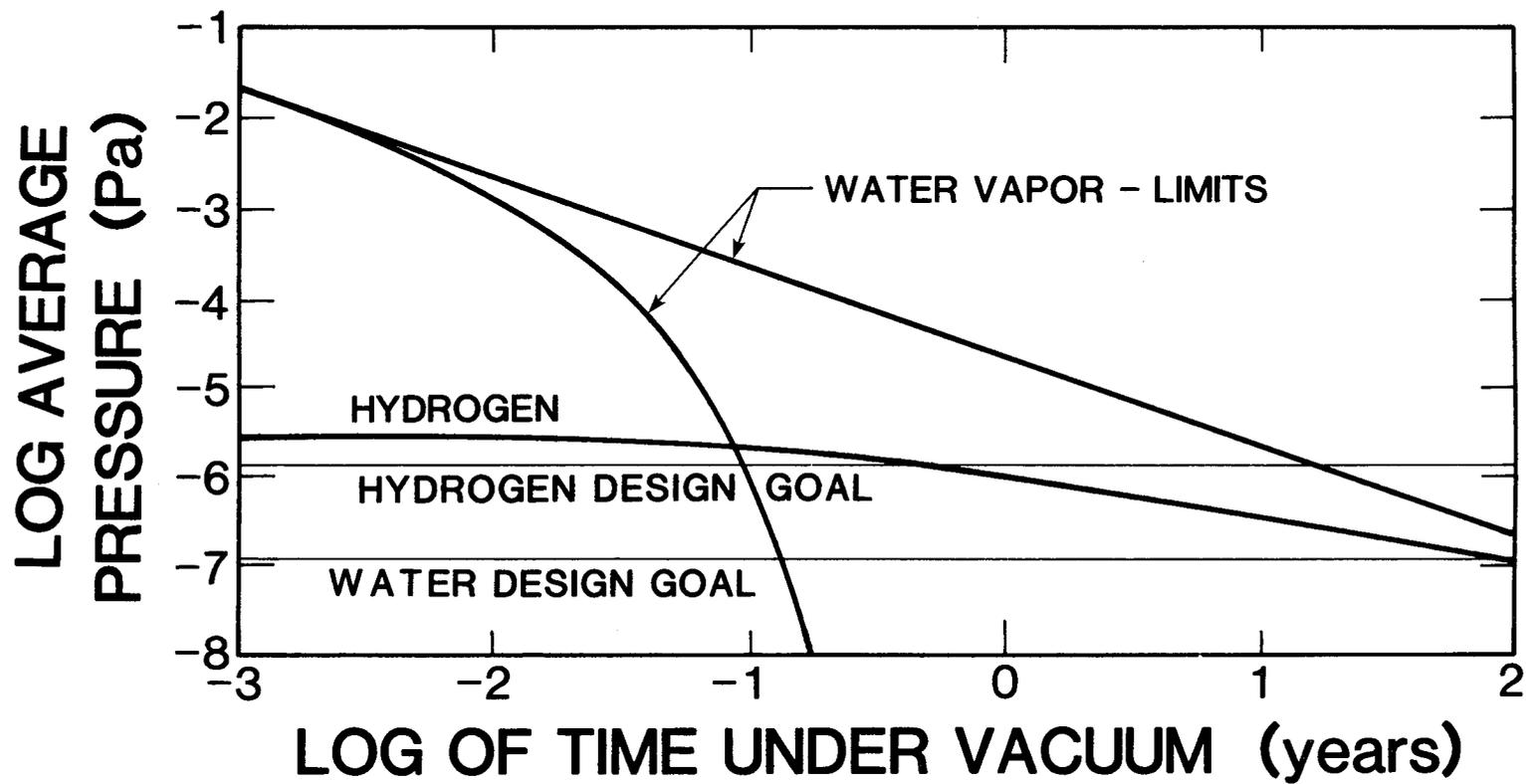


Fig. 6 Average pressure vs. time for hydrogen and water vapor in 2 km beam tube. Hydrogen time between manufacture and vacuum pumpdown = 1000 hours. Initial concentration of hydrogen = 1 ppm by weight. Design Goals for single gas species.