# Lightweight, Low-CTE Tubes Made From Biaxially Oriented LCPs

**CTEs can be tailored by tailoring biaxial orientations.**

*John H. Glenn Research Center, Cleveland, Ohio*

Tubes made from biaxially oriented liquid-crystal polymers (LCPs) have been developed for use as penetrations on cryogenic tanks. ("Penetrations" in this context denotes feed lines, vent lines, and sensor tubes, all of which contribute to the undesired conduction of heat into the tanks.) In comparison with corresponding prior cryogenic-tank penetrations made from stainless steels and nickel alloys, the LCP penetrations offer advantages of less weight and less thermal conduction. An additional major advantage of LCP components is that one can tailor their coefficients of thermal expansion (CTEs). The estimated cost of continuous production of LCP tubes of typical sizes is about $1.27/ft ($4.17/m) [based on 1998 prices].

LCP tubes that are compatible with liquid oxygen and that feature tailored biaxial molecular orientation and quasi-isotropic properties (including quasi-isotropic CTE) have been fabricated by a combination of proprietary and patented techniques that involve the use of counterrotating dies (CRDs). Tailoring of the angle of molecular orientation is what makes it possible to tailor the CTE over a wide range to match the CTEs of adjacent penetrations of other tank components; this, in turn, makes it possible to minimize differential-thermal expansion stresses that arise during thermal cycling.

The fabrication of biaxially oriented LCP tubes by use of CRDs is not new in itself. The novelty of the present development lies in tailoring the orientations and thus the CTEs and other mechanical properties of the LCPs for the intended cryogenic applications and in modifications of the CRDs for this purpose.

The LCP tubes and the 304-stainless-steel tubes that the LCP tubes were intended to supplant were tested with respect to burst strength, permeability, thermal conductivity, and CTE. The following conclusions were drawn from the tests:

- The thermal conductivities of the LCP tubes ranged from 0.21 to 0.40 W/(m·K) — 98 percent smaller than those of the corresponding 304-stainless-steel tubes.
- The CTEs of the LCPs were fully tailorable down to an exceptionally low value of $5.8 \times 10^{-6}$ (°C)$^{-1}$.
- It was necessary to fabricate an LCP tube with a wall thickness of 0.080 in. ($\approx 2.0$ mm) to obtain a flexural strength equal to that of a 304-stainless-steel tube with a wall thickness of 0.028 in. ($\approx 0.7$ mm). Even with its greater thickness, the LCP tube weighed 53 percent less than did the stainless-steel tube.
- The LCP tubes exhibited exceptionally low permeability: The average rate of transport of oxygen though an LCP tube having dimensions typical of those of a cryogenic tank at a temperature of –183 °C was found to be of the order of $4 \times 10^{-21}$ cm$^3$ (standard temperature and pressure) per day.
- All of the LCP tubes exceeded the hydrostatic-burst-strength requirement by at least 400 percent.

# Using Redundancy To Reduce Errors in Magnetometer Readings

**Fundamental laws of electromagnetism impose constraints that can be exploited.**

*NASA's Jet Propulsion Laboratory, Pasadena, California*

A method of reducing errors in noisy magnetic-field measurements involves exploitation of redundancy in the readings of multiple magnetometers in a cluster.
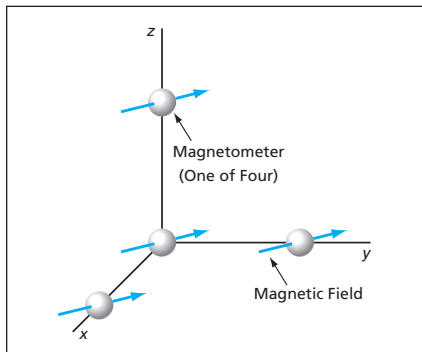


**Four Magnetometers** at corners of a cube provide noisy, redundant measurements of a magnetic field. The redundancy can be used to partly correct for the noise contributions.

By "redundancy" is meant that the readings are not entirely independent of each other because the relationships among the magnetic-field components that one seeks to measure are governed by the fundamental laws of electromagnetism as expressed by Maxwell's equations.

Assuming that the magnetometers are located outside a magnetic material, that the magnetic field is steady or quasi-steady, and that there are no electric currents flowing in or near the magnetometers, the applicable Maxwell's equations are

$$\nabla \times \mathbf{B} = \mathbf{0} \text{ and } \nabla \cdot \mathbf{B} = 0,$$

where **B** is the magnetic-flux-density vector. By suitable algebraic manipulation, these equations can be shown to impose three independent constraints on the values of the components of **B** at the various magnetometer positions.

In general, the problem of reducing the errors in noisy measurements is one of finding a set of corrected values that minimize an error function. In the present method, the error function is formulated as (1) the sum of squares of the differences between the corrected and noisy measurement values plus (2) a sum of three terms, each comprising the product of a Lagrange multiplier and one of the three constraints. The partial derivatives of the error function with respect to the corrected magnetic-field component values and the Lagrange multipliers are set equal to zero, leading to a set of equations that can be put into matrix·vector form. The matrix can be inverted to solve for a vector that comprises the corrected magnetic-field component values and the Lagrange multipliers.