PERFORMANCE DATA OF U.S. NAVAL OBSERVATORY VLG-11 HYDROGEN MASERS SINCE SEPTEMBER 1983

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In 1983, two VLG-11 masers were delivered to the U.S. Naval Observatory by the Smithsonian Astrophysical Observatory. Last year the short-term stability of these masers was reported and the effect of this short-term stability on timekeeping performance was discussed by G.M.R.Winkler.[1] Since the date of installation, 13 September 1983, data on the masers' long-term performance have been accumulated. Figure 1 from reference [1] shows the Allan variance, $\sigma(\tau)$, of the relative frequency between the masers. This variance reaches a minimum of about 4 parts in 10^{16} at averaging times of $5x10^3$ seconds and rises at longer averaging times due, at least partly, to systematic frequency drift.

In this paper we discuss the systematic frequency drifts, expressed as $\frac{1}{f}\frac{df}{dt}$ and given in units of fractional frequency difference per day.

Figure 2 is a plot of $\frac{1}{f}\frac{df}{dT}$ in units of 10^{-15} per day versus calendar day starting in September of 1983 and continuing through October of 1984. Table 1 is a chronology of activity involving SAO VLG-11 masers P18 and P19.

TABLE 1

CHRONOLOGY OF VLG-11 MASER ACTIVITY AT U.S.N.O.

13 Sept. 1983	Power to masers turned off at SAO. Masers shipped to the U.S.N.O. by truck.
14 Sept. 1983	Masers arrive at U.S.N.O. Power turned on -- both masers oscillating. P19 degaussed.
22 Sept. 1983	$\Delta f/f$ (P18-UTC USNO) = -1.13×10^{12} $\Delta f/f$ (P19-UTC USNO) = 0.93×10^{12} $\Delta f/f$ (P18-P19) = -2×10^{13} (This, with synthesizer set at 1420405751.68700, which was our best estimate for UTC at SAO via Loran "C". Our probable error in UTC is $\pm5\times10^{13}$.) Conclusion: Shipment did not alter the cavity frequency significantly.
26 Sept. 1983	Both P18 and P19 were tuned. After tuning $\Delta f/f$ (P19-P18) = 0.11×10^{-13} Maser cavity frequency shift was found to have been as follows: Δf_c(P18) = +40.1 Hz., Δf_c(P19) = +24.68 Hz.
27 Oct. 1983	$\Delta f/f$ (P19-P18) = 3.03×10^{-13} After tuning P19 $\Delta f/f$ (P19-P18) = 2.08×10^{-13} Δf_c(P19) = +34.55 Hz.
30 Jan. 1984	$\Delta f/f$ (P19-P18) = 3.9×10^{-13} After tuning P18 and P19 $\Delta f/f$ (P19-P18) = 0.8×10^{-13} Δf_C(P18) = +28.9 Hz, Δf_C(P19) = +59.2 Hz.
27 Feb. 1984	Power off P18 for several hours for installation of U.S.N.O. Master Clock System.
24 Mar. 1984	Power off P19 for several hours for installation of U.S.N.O. Maser Clock System.
10 May 1984	P19 automatically tuned using U.S.N.O. System. Δf_C(P19) = +46.4 Hz.
16 May 1984	- $\Delta f/f$ (P19-P18) = -0.6×10^{-13} After tuning P18 $\Delta f/f$ (P19-P18) = $+2.4\times10^{-13}$ Δf_C(P18) = +25.4 Hz.

From the drift rate plot shown in Fig. 2, we see that tuning the masers had no apparent effect on the drift rate. From the chronology we see that the cavity resonator frequency of both P18 and P19 required systematic frequency corrections to lower frequencies. The cavity frequency shifts obtained from the tuning data are shown in Fig. 3. From these data and our knowledge of the line Qs of the masers we can predict an average drift rate of the maser output frequency. For P19 we have 7×10^{-15} per day and for P18 we have 4×10^{-15} per day, between September 1983 and April 1984. This is in reasonably good agreement with drift data in February 1984, when P19 drifts $+9\times10^{-15}$ per day and P19 drifts 4×10^{-15} per day. The mistuning rate of the cavity, if ascribed to a change in axial length of the cylindrical cavity, requires a change of length for P18, $\frac{\Delta\ell_{18}}{\Delta T} = -1.9\times10^{-8}$ cm/day and for P19, $\frac{\Delta\ell_{19}}{\Delta T} = -3.8\times10^{-8}$ cm/day.

To relate this scale of dimensions to something very small, we note that a hydrogen atom has a diameter of about 10^{-8} cm. From the drift behavior and cavity frequency measurements we note the following:

1. The frequency change of the cavity is the dominant effect on the masers' frequency
2. The early drift rate appears more severe than the later drift and the overall drift rate seems to be asymptotically approaching zero.

The properties of ultra stable materials and the behavior of optically contacted surfaces in extremely stable materials have been described by S.F. Jacobs[2] from observations made using an iodine stabilized laser to measure length changes.

Figure 4, reproduced from reference 2, shows the settling of optically contacted surfaces in very high stability materials. The cavity cylinder and end plates of the SAO VLG-11-series masers are made of Cer-Vit C101®. After being ground to shape they are stress relieved by being etched in the surface microcracks[3] created in the grinding process. The mating surfaces are then optically polished and the cavities assembled under clean conditions so that white light fringes are observed over the circumference of the joints between the cylinder and the endplates.

The cavities were assembled in May of 1983, and it is likely that the settling of the end plates was still in progress during late 1983, and early 1984. The settling behavior we observe with the polished surfaces of these cavities is at a much smaller rate than the previously observed settling behavior of cavity joints that were made with surfaces ground to a roughly 16 micro-inch finish. The settling rate was about 1 r.m.s. surface roughness distance in the first 40 days. The present surfaces are at least 10 times smoother and flatter, and the amount of initial mistuning after assembly has been substantially reduced.

The long-term dimensional behavior of structures made of extremely high stability material can be described in terms of $\frac{1}{\ell}\frac{\Delta\ell}{\Delta t}$, the "creep rate". Measurements of creep were made by S.F. Jacobs[2] in terms of optical path changes detected using a stabilized laser. His data give $\frac{1}{\ell}\frac{\Delta\ell}{\Delta t} \sim +5\times10^{-10}$ per day for Cer-Vit® (Cer-Vit C101 - Owens Illinois). Other materials, such as Zerodur® (Heraeus-Schott), Ultra Low Expansion Titanium Silicate® (Corning), Homosil® fused silica (Heraeus-Schott), and Corning® 7940 fused silica have creep rates between $+5\times10^{-10}$ and -5×10^{10} per day.

If we ascribe the maser frequency drift of the later months shown in Fig. 2 to cavity mistuning from material creep we obtain a rate of about -3×10^{-10} per day for Cer-Vit.

This agrees in magnitude with Jacobs' measurement on stable materials. It is opposite in sign for his creep rate for Cer-Vit, but agrees with his data for the other materials, which all have negative creep rates. This difference in sign for Cer-Vit may result from variations from sample to sample or from our

700°C cavity silvering process.

The performance of these masers indicates that the long-term stability of today's masers is chiefly governed by properties of the cavity materials. Electronic systems that stabilize the cavity resonance frequency beyond these levels must be capable of maintaining the maser frequency to better than a few parts in 10^{15} per day for long periods of time.

REFERENCES

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2. Jacobs, S.F., "Dimensional stability measurements of low thermal expansivity," Proc. 2nd Freq. Standards and Metrology Symp., U.S. National Bureau of Standards, pp. 269-278 (1976).

3. Muffoletto, C. Verne, "Reflective and refractive scattering of ultraviolet radiation caused by state-of-the-art optical grinding and polishing techniques." In Reflecting optics for synchrotron radiation. Soc. Photo-optical Instrumentation Engineers, vol. 315, pp. 85-88 (1981).

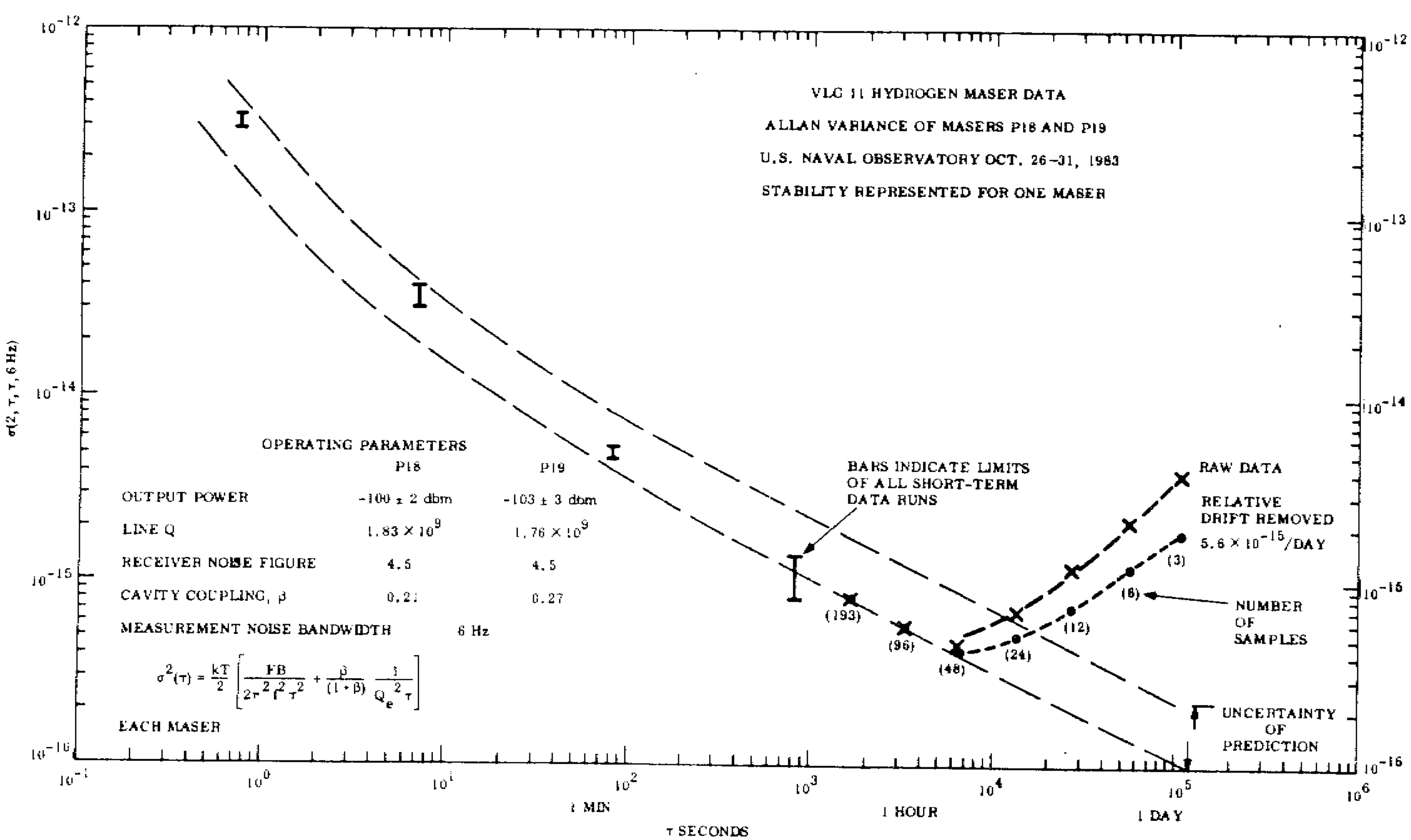

VLC 11 HYDROGEN MASER DATA
ALLAN VARIANCE OF MASERS P18 AND P19
U.S. NAVAL OBSERVATORY OCT. 26–31, 1983
STABILITY REPRESENTED FOR ONE MASER
OPERATING PARAMETERS
P18
P19
OUTPUT POWER
-100 ± 2 dbm
-103 ± 3 dbm
LINE Q
1.83 × 10^9
1.76 × 10^9
RECEIVER NOISE FIGURE
4.5
4.5
CAVITY COUPLING, β
0.2?
0.27
MEASUREMENT NOISE BANDWIDTH
6 Hz
$\sigma^2(\tau) = \frac{kT}{2}\left[\frac{FB}{2\pi^2 f^2 \tau^2} + \frac{\beta}{(1+\beta)}\frac{1}{Q_e^2 \tau}\right]$
EACH MASER
BARS INDICATE LIMITS OF ALL SHORT-TERM DATA RUNS
RAW DATA
RELATIVE DRIFT REMOVED
5.6 × 10^-15/DAY
NUMBER OF SAMPLES
UNCERTAINTY OF PREDICTION
(193)
(96)
(48)
(24)
(12)
(6)
(3)
σ(2, τ, τ, 6 Hz)
τ SECONDS
1 MIN
1 HOUR
1 DAY

FIGURE 1

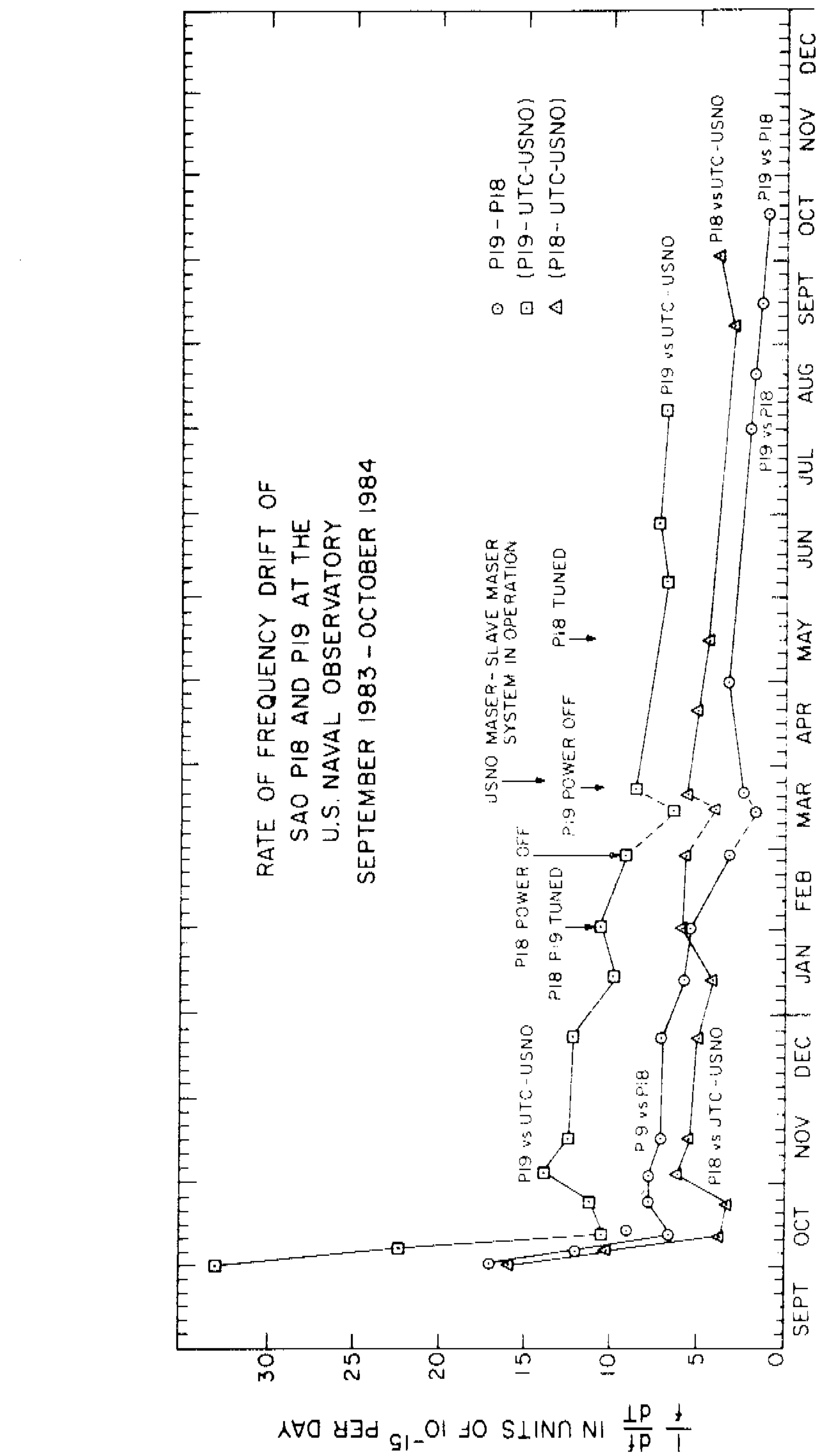

RATE OF FREQUENCY DRIFT OF
SAO PI8 AND PI9 AT THE
U.S. NAVAL OBSERVATORY
SEPTEMBER 1983 - OCTOBER 1984
PI9 - PI8
(PI9 - UTC-USNO)
(PI8 - UTC-USNO)
PI9 vs UTC-USNO
P I9 vs PI8
PI8 vs UTC-USNO
PI8 POWER OFF
PI8 PI9 TUNED
PI9 POWER OFF
USNO MASER - SLAVE MASER SYSTEM IN OPERATION
PI8 TUNED
PI9 vs UTC-USNO
PI9 vs PI8
PI8 vs UTC-USNO
PI9 vs PI8
1/f df/dT IN UNITS OF 10^-15 PER DAY
0
5
10
15
20
25
30
SEPT
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEPT
OCT
NOV
DEC
1983
1984

FIGURE 2

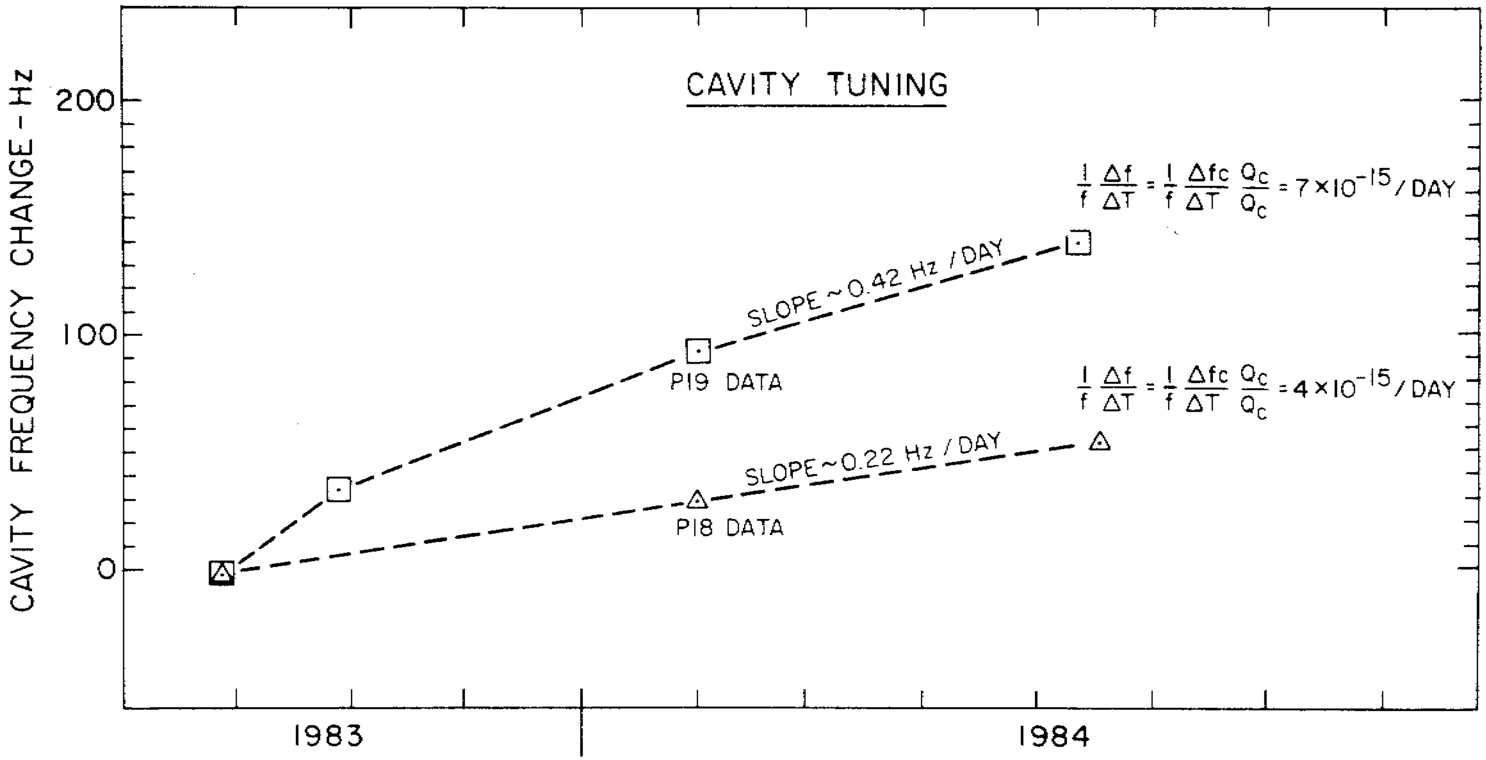
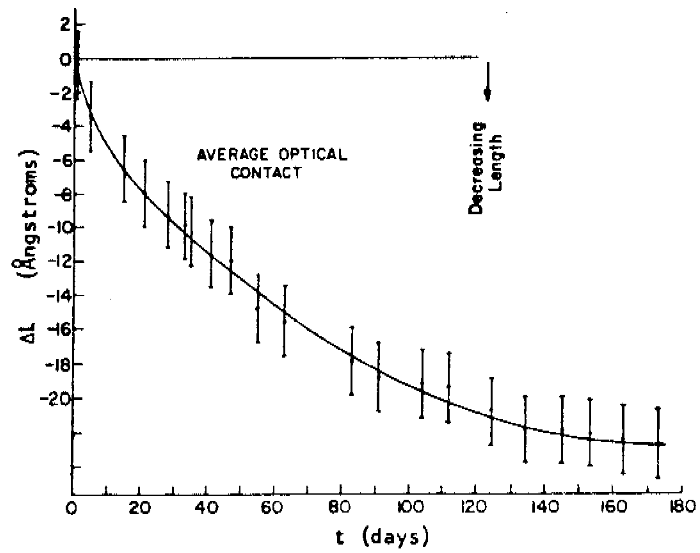

CAVITY TUNING
CAVITY FREQUENCY CHANGE - Hz
200
100
0
1983
1984
SLOPE ~ 0.42 Hz / DAY
P19 DATA
SLOPE ~ 0.22 Hz / DAY
P18 DATA
$\frac{1}{f}\frac{\Delta f}{\Delta T} = \frac{1}{f}\frac{\Delta fc}{\Delta T}\frac{Q_c}{Q_c} = 7\times10^{-15}$ / DAY
$\frac{1}{f}\frac{\Delta f}{\Delta T} = \frac{1}{f}\frac{\Delta fc}{\Delta T}\frac{Q_c}{Q_c} = 4\times10^{-15}$ / DAY

FIGURE 3



2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
ΔL (Ångstroms)
AVERAGE OPTICAL
CONTACT
Decreasing
Length
0
20
40
60
80
100
120
140
160
180
t (days)

FIGURE 4

QUESTIONS AND ANSWERS

JACQUES VANIER, NATIONAL RESEARCH COUNCIL: What was the line Q that you observed in the VLG-11?

MR. MATTISON: The line Q that we used to get was on the order of 1.1 to 1.3 times ten to the ninth. More recently we have been getting values on the order of 1.8 to 1.9 times ten to the ninth.

MR. VANIER: I believe that there is a large gain to be made there. Simply a redesign of the bulb and of the collimator, so that you can increase that by a factor of three or four. Then the drift that you were talking about before, due to the creeping of the cavity, would be diminished dramatically. That would be fantastic.

MR. MATTISON: You are referring to changing the design of the collimator?

MR. VANIER: Yes. Because you can make it for a very long time constant, and it will still work very beautifully, so that you would be limited by the wall then.

MR. MATTISON: I does get limited by the wall. That increase in line Q that you observed has been due to our method of applying the teflon. We haven't changed the design at all.

MR. McCOUBREY: My impression is that with the advances you are making, there is going to be more and more interest in the actual structure and morphology of those surfaces. Maybe some of the polymer scientists would have to play a role in this, because I would expect that whatever happens with this teflon, and how it rearranges itself is something that they have looked into, and probably understand fairly well these days.

MR. MATTISON: Our method of applying teflon has changed. It is essentially a black art. All we know is that there is a recipe, and we apply it according to the recipe, and it works. If we do it a different way, it may work better.

MR. McCOUBREY: It sounds like there are some really interesting possibilities.