DISCUSSION FORUM: ATOMIC FREQUENCY STANDARDS

CESIUM

C. C. Costain, National Research Council of Canada

I am not sure how this panel was picked, but I expect it was for our objectivity. I will therefore try to be objective on the subject of cesium standards. They are certainly important to us in the standards laboratories because, I think, they will remain as the defined basis for time and frequency for at least the next twenty years.

I am not going to say much about commercial cesium standards. They are widely used and well known. They are normally within specifications, and most of us are annoyed if they do not perform an order of magnitude better than specifed. The entry of the Frequency and Time Systems into the field is important, and our measurements, and I think others, show the FTS performance is between the HP and HP high-performance option. My only question with respect to commercial standards would be as to whether too much lifetime is sacrificed in attaining short-term stability.

I am now going to go directly to a discussion of our primary cesium standards at NRC. I have a particular reason for doing so, which will become obvious. CsV has been operating continuously since May 1, 1975, and has undergone six full evaluations in that time. If it is assumed that TAI has been decreasing in frequency by 8×10^{-14}/year, with this one-parameter fit, the standard deviation between TAI and CsV, from the BIH circular D, is less than 0.4 μs. We do not know what the flicker floor of CsV is because we have nothing as good to measure it.

Al Mungall and Herman Daams have completed the three new standards, CsVI, A, B and C. The next two figures show part of the construction. Figure 1 shows the inner C field structure, and the six coils to measure the LF resonances. Figure 2 shows the three standards completed. They have been operating as clocks for a few weeks, but they have not been evaluated. This will take most of a year, but the resonances are beautifully symmetric out to the $m = -3$ and $m = +3$, with a symmetry which would delight any physicist.

But the stability to date has been disappointing. The Allan σ approaches 1×10^{-14}, and then after maybe 24 hours, a frequency change of up to 1×10^{-13} occurs. The culprit is the C field. Al Mungall has found by measuring the low frequency resonances that the change in frequency is the result of a change in the C field. Sometimes one, two or three of the coils show a change. It is the residual magnetism in the shields which is changing. Better degaussing is expected to reduce the effects, and work is proceeding on this feature.

Mungall has suggested that the magnetic shields could well be the limiting factor in the stability of atomic standards. The same effects occur in CsV, where changes of parts in 10^{15} are seen in the biweekly C field measurements. But the field of a dipole is dependent on the cube of the distance, and as CsVI is nearly a factor of 2 smaller diameter, the effects are nearly an order of magnitude larger. It is likely that the residual magnetism will have a much greater effect on the frequency than the distributed phase shift when the beam position is changed.

Perhaps in H-masers, when a dielectric cavity reduces the size by a factor of 3, magnetic effects which are now 3×10^{-15} could become one or two orders of magnitude larger. Certainly at this level of precision one must expect the unexpected, and it becomes increasingly difficult to convert dreams into reality.

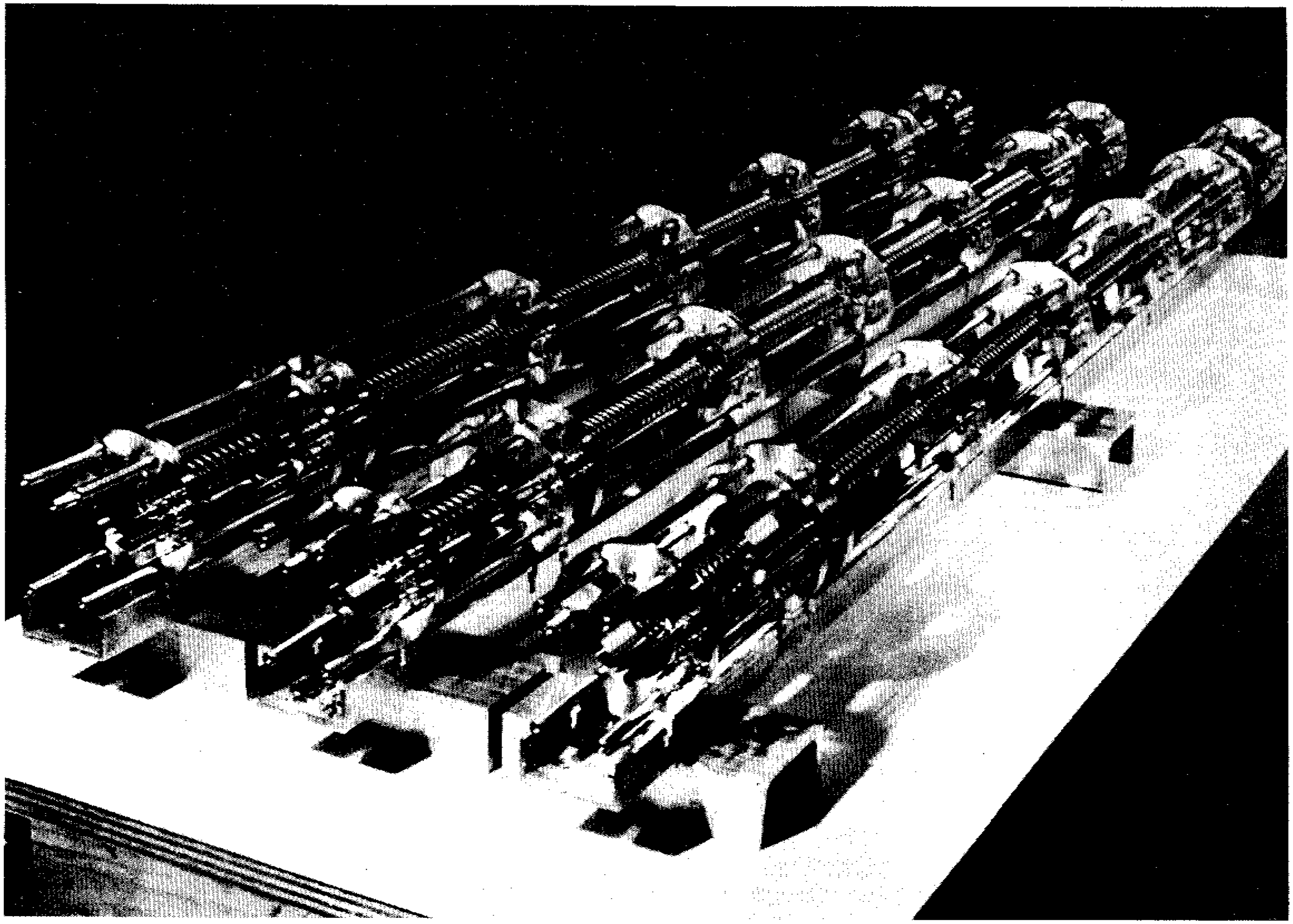


Figure 1. The C field structure of the three CSVI standards. The C field current in the four rods produces the transverse C field. The LF coils measure the C field outside each end of the cavity as well as in the drift space.

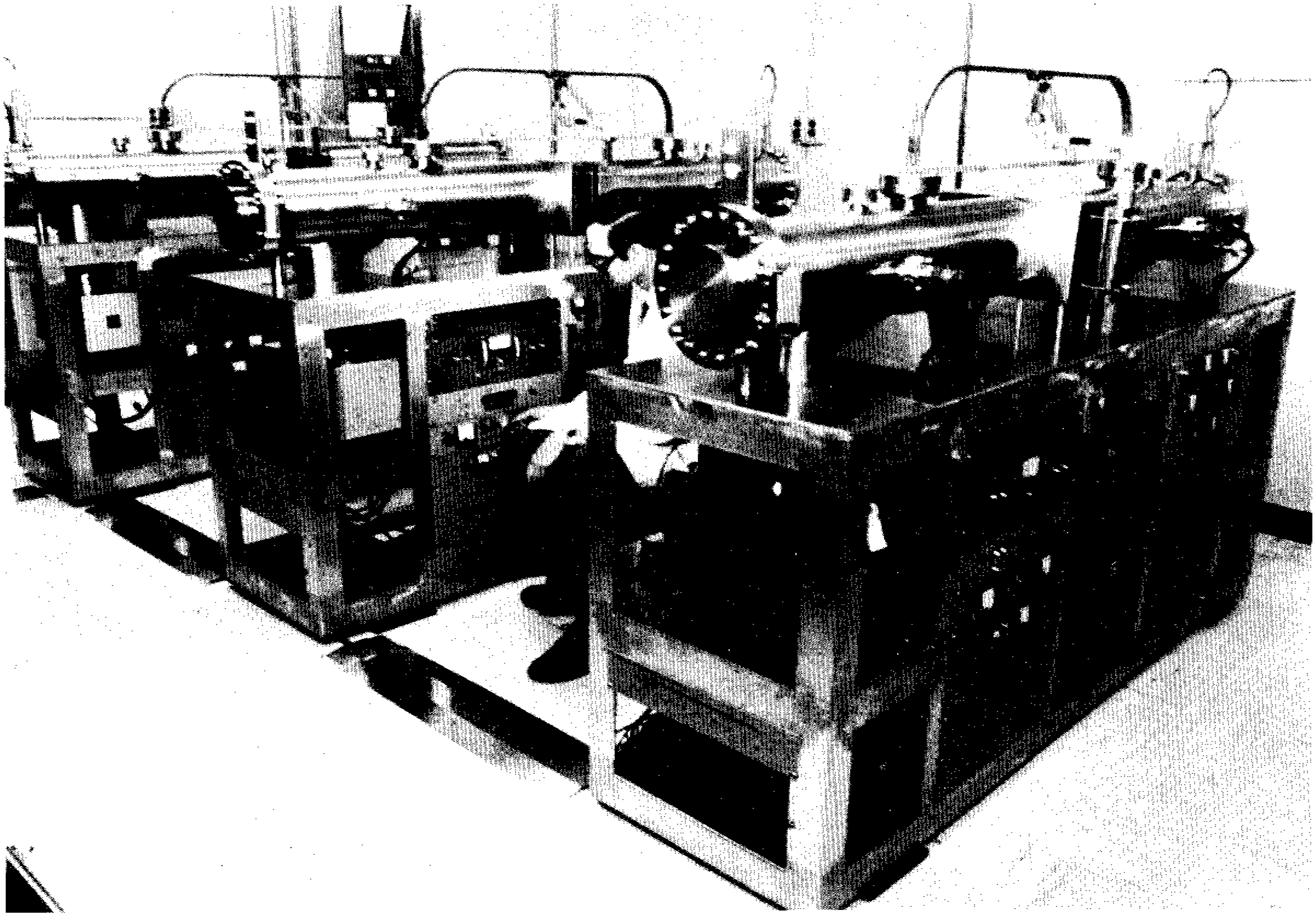


Figure 2. Dr. Mungall with the three CsVI primary clocks.

DISCUSSION FORUM: ATOMIC FREQUENCY STANDARDS

RUBIDIUM

Thomas C. English
Efratom Systems Corporation

INTRODUCTION

The purpose of this presentation is to point out the advantages of rubidium gas cell frequency standards relative to both quartz oscillators and other atomic standards. We also consider how these advantages determine the types of applications that are suitable for rubidium devices, and what improvements can be expected in the future.

MAJOR ADVANTAGES OF RB RELATIVE TO QUARTZ

We begin this presentation by enumerating the advantages of commercial rubidium frequency standards relative to commercial quartz oscillators. See Table 1. In the first column, the characteristic to be compared is listed. In the second column, values of these characteristics are given for a small commercial rubidium standard. All of the parameter values given in this column are realized simultaneously in a single, commercial device. In the third column, state-of-the-art parameter values are listed for presently available commercial quartz oscillators (developmental devices are not included!). It is important to point out here that these parameter values cannot be simultaneously realized in a single commercial quartz device, and that the values for a typical high quality commerical quartz oscillator are usually about an order of magnitude worse than shown here. For example, a typical, high quality commercial quartz oscillator will have drift rate of about 1×10^{-10}/day. The value of $< 2 \times 10^{-11}$/day indicated in Table 1 can be realized in a currently available quartz device, but the price tag is rather high, of the order of \$15k. On the other hand, a long-term drift rate of less than 1×10^{-11}/month is readily available from a rubidium device. This is about a factor of 60 better than the table value of 2×10^{-11}/day for the best commercial quartz.

In summary, Table 1 shows that rubidium is one to two orders of magnitude better in each parameter listed, with the possible exception of short-term stability over periods of minutes to hours. Moreover, all parameter values given here are simultaneously realized in a small

TABLE 1

MAJOR ADVANTAGES OF RUBIDIUM RELATIVE TO

QUARTZ OSCILLATORS

CHARACTERISTIC	SMALL COMMERCIAL RUBIDIUM	STATE-OF-THE-ART PARAMETERS COMMERCIAL QUARTZ[A]
SHORT-TERM STABILITY (MINUTES TO HOURS)	PARTS IN 10^{13}	NOT USUALLY SPECIFIED
LONG-TERM DRIFT	$< 1 \times 10^{-11}$/<u>MONTH</u>	$< 2 \times 10^{-11}$/<u>DAY</u>
WARMUP TIME (25 °C AMBIENT)	10 MIN TO $< 2 \times 10^{-10}$	30 MIN TO 1×10^{-9}
RETRACE (ON-OFF 24 HRS-ON)	$< 2 \times 10^{-11}$	1×10^{-9}
ACCELERATION SENSITIVITY	$< 8 \times 10^{-12}$/G	8×10^{-10}/G

[A] THESE PARAMETERS ARE NOT SIMULTANEOUSLY AVAILABLE IN A SINGLE DEVICE.

commercial rubidium, whereas this is not the case for commercial quartz.

MAJOR ADVANTAGES OF RB RELATIVE TO OTHER ATOMIC STANDARDS

The main advantages of rubidium relative to other atomic standards are listed in Table 2. These advantages include small size, light weight, low power consumption and low cost.

PHOTOGRAPH OF SMALL COMMERCIAL RB

Figure 1 shows the size of a small commercial rubidium frequency standard. It is a cube that is 4 inches on a side. The pocket watch serves to give one a gut feel for the small size of this device.

PHYSICAL CHARACTERISTICS OF COMMERCIAL RB & CS STDS

The first two lines of Table 3 compare small commercial rubidium and cesium devices. These are the basic, no-frills units. Note that rubidium is 8 times smaller, 7 times lighter, uses ½ as much power and costs from 1/3 to 1/5 as much.

The last two lines of Table 3 are for those persons who are interested in a bench or rack mount unit, including an AC power supply and a standby battery pack for uninterrupted operation in the event of a powerline failure. In this case, small size, weight and power consumption are not of major concern, so no effort has been made to minimize these characteristics.

By the way, hydrogen devices have not been included in this comparison because we are concerned here only with commercially available atomic standards; to the best of our knowledge, there are no commercially available hydrogen devices.

SIZE COMPARISON OF TWO COMMERCIAL ATOMIC STANDARDS

Figure 2 allows a direct comparison of the relative sizes of a small commercial rubidium and a small commercial cesium. For many years I did physics research in the area of atomic and molecular beams, with big, long, machines that filled up most of a room. For this reason, it is always amazing to me to see that it has been possible to make cesium standards as small as they are today. But, of course, the same is also true for present-day rubidium devices. In any case, it

TABLE 2

MAJOR ADVANTAGES OF RUBIDIUM RELATIVE TO OTHER ATOMIC STANDARDS

- SMALL SIZE
- LIGHTWEIGHT
- LOW POWER CONSUMPTION
- GOOD SHORT-TERM STABILITY
- LOW PHASE NOISE
- POTENTIALLY FASTER WARMUP
- LOW COST

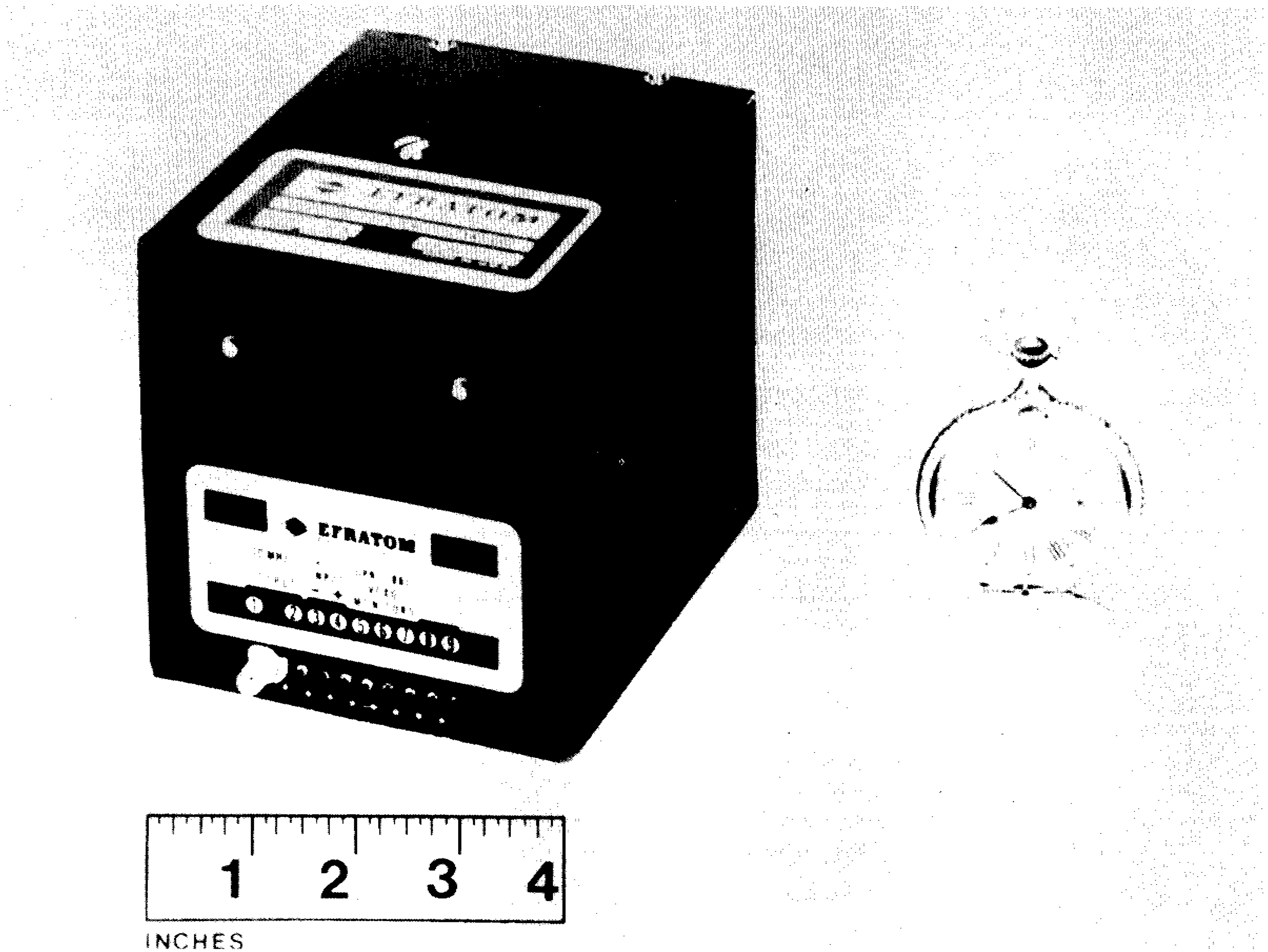


Figure 1. Small commercial rubidium frequency standard.

TABLE 3

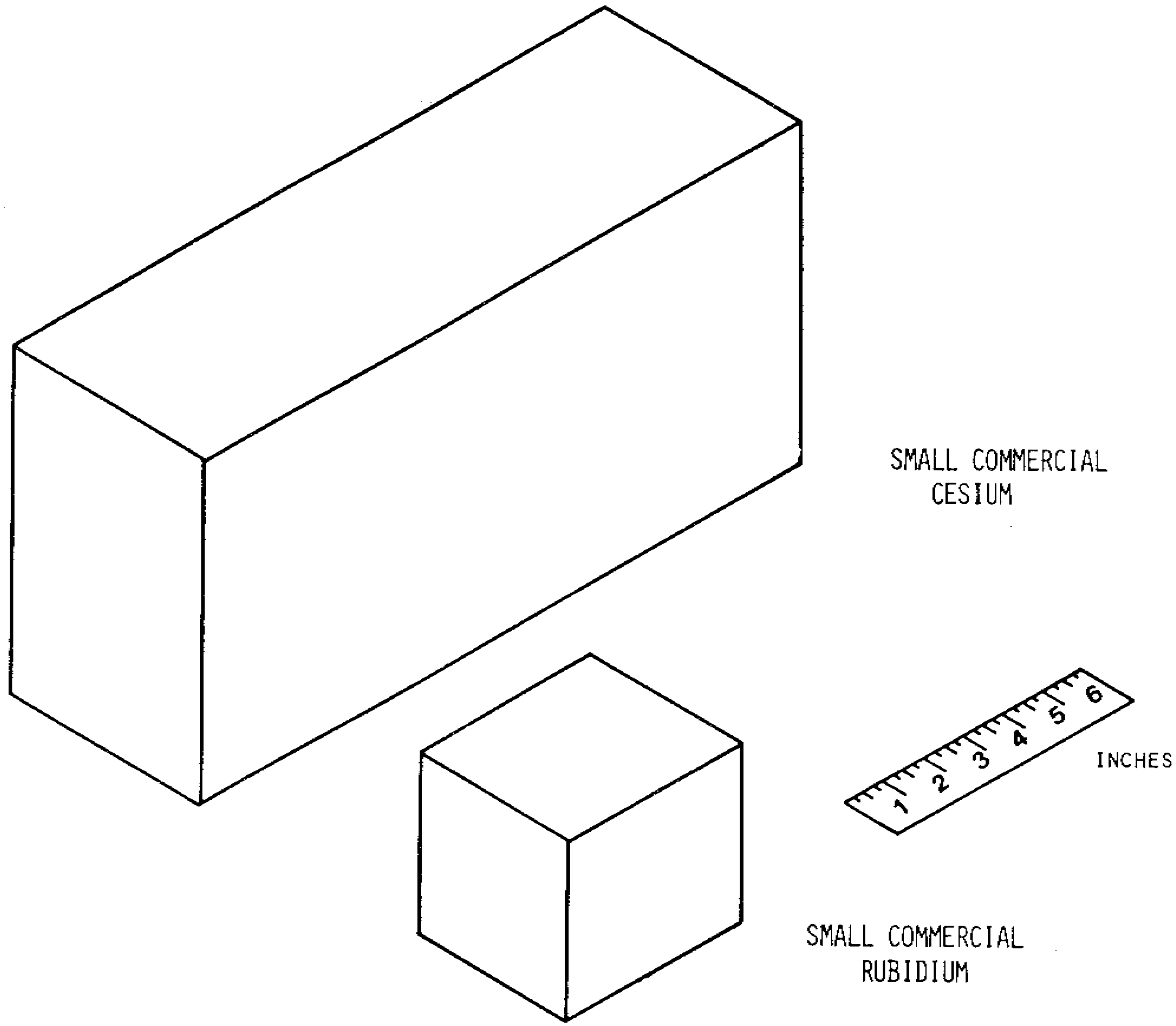
PHYSICAL CHARACTERISTICS OF COMMERCIAL RUBIDIUM AND CESIUM FREQUENCY STANDARDS

DEVICE	SIZE (CU IN)	WEIGHT (LBS)	DC POWER (W)	COST[B] (K$)
SMALL COMMERCIAL RUBIDIUM	67	3	13	4 - 6
SMALL COMMERCIAL CESIUM	560	22	24	19
RUBIDIUM/CESIUM	x 1/8	x 1/7	x 1/2	x 1/3 - 1/5
COMMERCIAL RUBIDIUM [A]	900 - 1400	27 - 38	---	7 - 10
COMMERCIAL CESIUM [A]	1600 - 2400	57 - 75	---	20 - 25

[A] INCLUDES AC POWER SUPPLY & STANDBY BATTERY PACK.

[B] SINGLE QUANTITIES.

FIGURE 2. SIZE COMPARISON OF TWO COMMERCIAL ATOMIC STANDARDS



is evident from Figure 2 that the small size of rubidium devices is one of their major advantages.

MEASUREMENT TIME REQ'D TO REALIZE A FREQUENCY ACCURACY OF 1×10^{-12}

Figure 3 shows the time required to make a frequency measurement to 1 part in 10^{12} using commercially available atomic frequency standards. In plotting these curves, we have assumed that the performance of the frequency standard used as the measuring device is the limiting factor. For each curve, the measuring device is specified to the right of the curve; for example, the measuring device for the uppermost curve is a commercial cesium.

In general, it should be obvious that the measurement time will depend on how good the short-term stability of the measuring device is; the better the short-term stability, the shorter the measurement time that is required. Because of the excellent short-term stability of rubidium standards, the measurement time required to attain 1×10^{-12} accuracy with them is very short.

In discussing measurement time, it is important to understand that we are really dealing with frequency fluctuations over a given period of time, and that these fluctuations are statistical in nature. For this reason, it is necessary to make multiple measurements in order to reduce the statistical uncertainty. For example, 19 measurements are required to specify an accuracy of 1×10^{-12} to within $\pm$ 20 %. For the commercial rubidium having the best available short-term stablity, this will require a total measurement time of 8 minutes. For the small commercial rubidium, 32 minutes will be required. When we look at the measurement times for the cesiums, we can see how good the rubidium times really are. One commercial cesium, a very commonly used one, requires a total measurement time of 1 day! A small commercial cesium is available that requires only about half this amount of time, but this is still quite long when compared to the rubidium figures.

Now, you will look at this graph and say, "but hey, wait, you forgot one of the cesiums!--the high performance cesium." Yes, you are right, the high performance cesium has good short-term stability -- it is comparable to that of the rubidiums, but it is obtained at a price. It is obtained by increasing the cesium beam intensity by more than an order of magnitude, and this reduces the life of the beam tube. This reduced lifetime is reflected in the manufacturer's warranty for the beam tube. For most commercial cesiums, the warranty is 3 years, but for the high performance cesium, the warranty is only 14 months. Here again, the cost factor enters: in general,

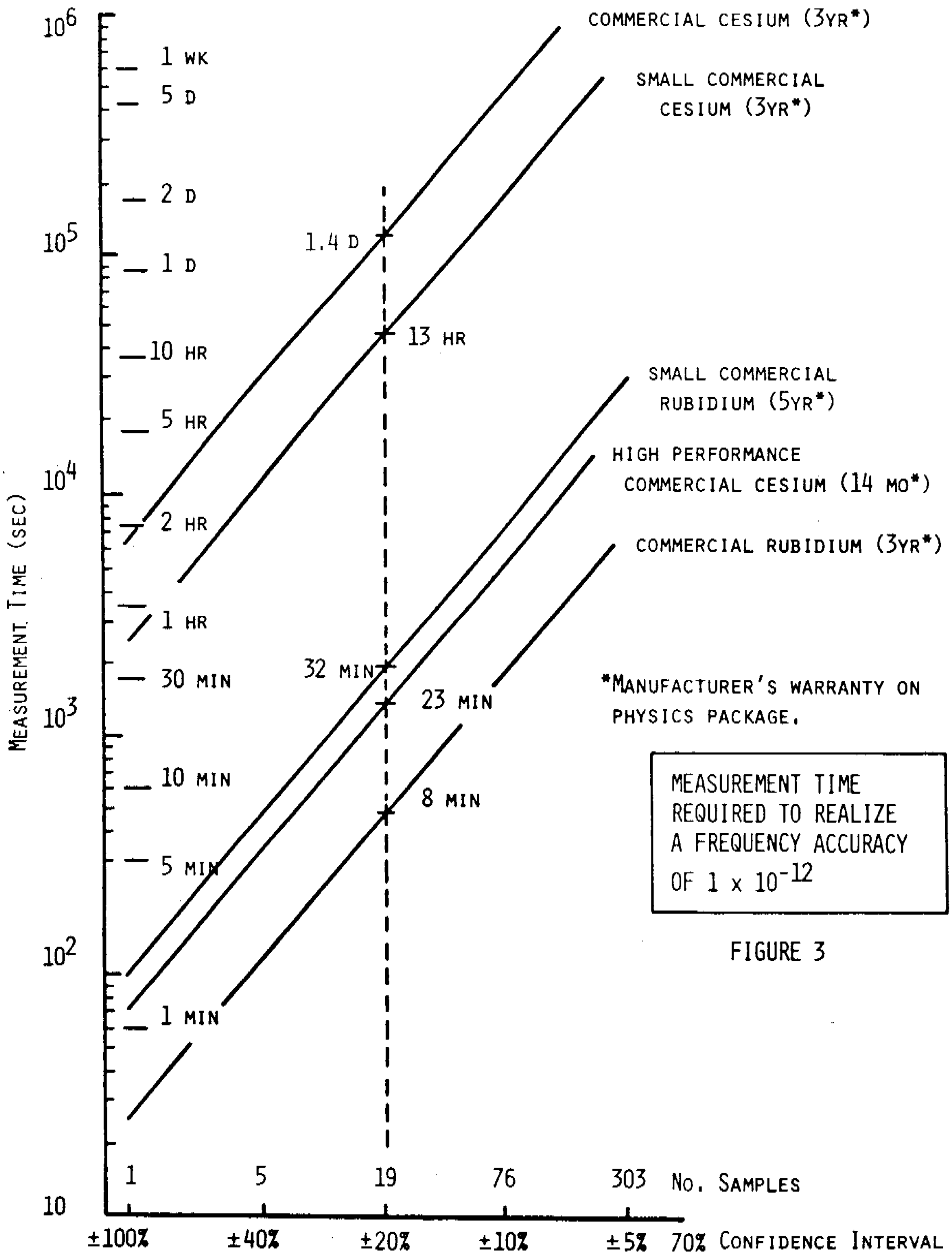

COMMERCIAL CESIUM (3YR*)
SMALL COMMERCIAL CESIUM (3YR*)
SMALL COMMERCIAL RUBIDIUM (5YR*)
HIGH PERFORMANCE COMMERCIAL CESIUM (14 MO*)
COMMERCIAL RUBIDIUM (3YR*)
1.4 D
13 HR
32 MIN
23 MIN
8 MIN
1 WK
5 D
2 D
1 D
10 HR
5 HR
2 HR
1 HR
30 MIN
10 MIN
5 MIN
1 MIN
10^6
10^5
10^4
10^3
10^2
10
MEASUREMENT TIME (SEC)
1
5
19
76
303
NO. SAMPLES
±100%
±40%
±20%
±10%
±5%
70% CONFIDENCE INTERVAL
*MANUFACTURER'S WARRANTY ON PHYSICS PACKAGE.
MEASUREMENT TIME REQUIRED TO REALIZE A FREQUENCY ACCURACY OF 1×10^{-12}

FIGURE 3

the beam tube replacement costs for any cesium are on the order of, or greater than the purchase price of a complete rubidium frequency standard. In the rubidium devices, the component in the physics package that is most likely to fail is the rubidium lamp whose replacement cost is only a few hundred dollars. Moreover, the manufacturers' warranties vary from 3 to 5 years on the physics package, which includes the lamp.

To summarize, conventional cesiums require long measurement times to attain frequency accuracies of 1 part in 10^{12}. It is possible to buy cesiums that allow short measurement times, but they suffer from the disadvantage of reduced beam tube life and high replacement costs. Rubidium standards, on the other hand, do not suffer from these disadvantages.

RUBIDIUM PHASE NOISE SPECIFICATION

Figure 4 shows the phase noise specification for a small commercial rubidium. Low phase noise is important when multiplying signals in the MHz region up into the GHz region and beyond because the noise power increases by n^2 for a frequency multiplication by a factor of n. The specification shows that the single sideband phase noise is down by 92 dB one Hz away from the carrier, and decreases as $1/f^3$ until the white phase modulation floor of -155 dB is reached at a Fourier frequency of 100 Hz. To the best of my knowledge, the phase noise spec shown here is better than that of any commercial cesium.

EFFECT OF NUCLEAR RADIATION ON AN OPERATING RB STD

One topic, about which not much information seems to be available, is the effect of nuclear radiation on atomic frequency standards. Data are now available for the effects of dose rate and total dose on rubidium frequency standards, and we present some of these data here.

Table 4 shows the result of a recently conducted test to determine the effect of dose rate on an operating rubidium frequency standard. The unit tested is one of the Rockwell engineering models for the GPS satellite program. This unit uses an Efratom small rubidium physics package. The unit was exposed to flash x-ray radiation at a dose rate of about 4×10^8 rads/sec while operating. This dose rate was the maximum dose rate that could be obtained from the flash x-ray facility. There are two main results from this experiment. First, the radiation had a negligible effect on the physics package. Second, the accumulated phase error due to the radiation was $<$ 1 nsec.

FIGURE 4
PHASE NOISE
SMALL COMMERCIAL RUBIDIUM

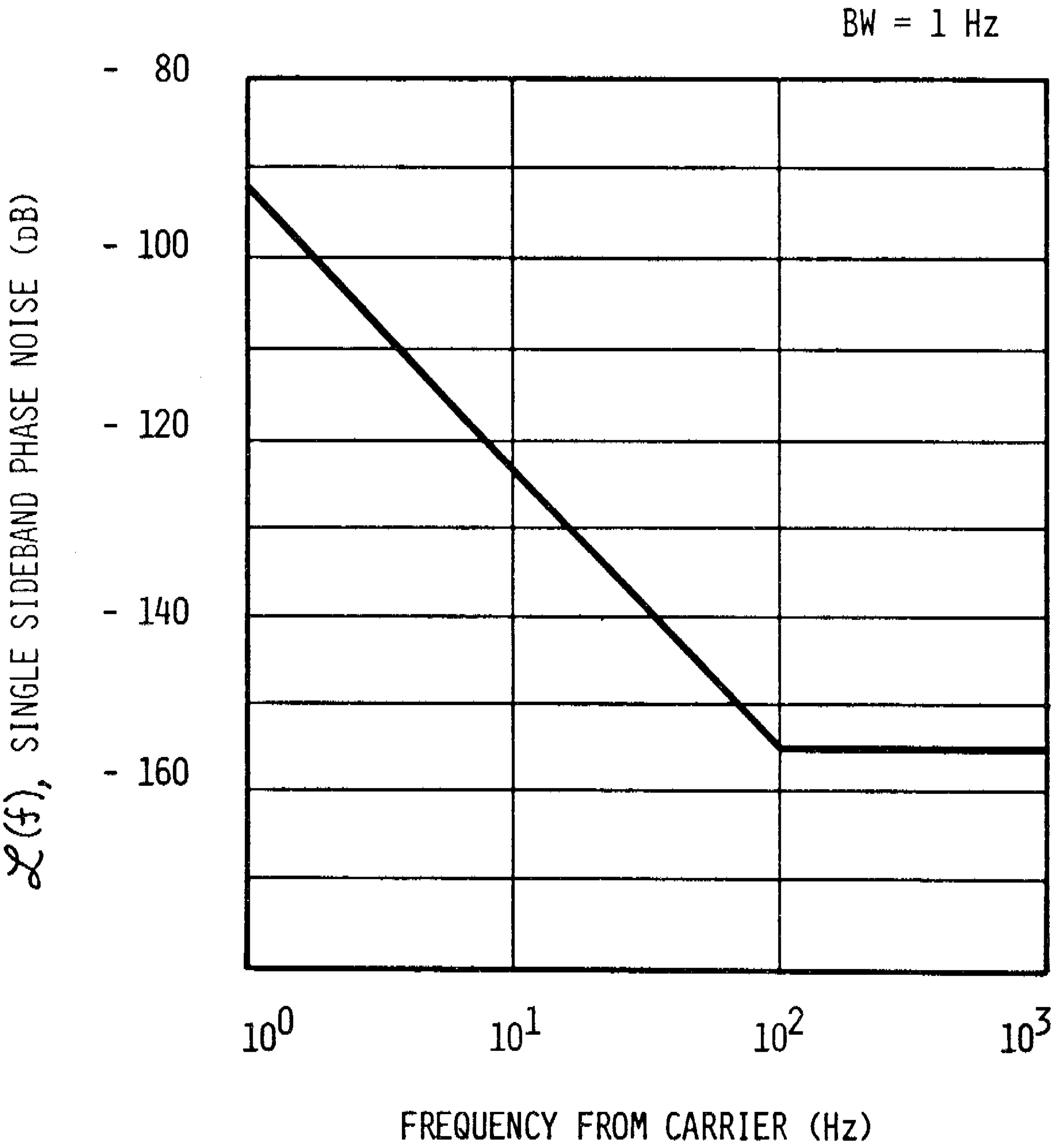


TABLE 4

EFFECT OF NUCLEAR RADIATION (DOSE RATE) ON AN OPERATING RUBIDIUM FREQUENCY STANDARD

DEVICE TESTED : UNSHIELDED GPS PHASE I RUBIDIUM SPACE CLOCK (EM3)

LOCATION OF TEST : ROCKWELL INTERNATIONAL, AUTONETICS DIVISION,
FLASH X-RAY FACILITY

DOSE RATE : $> 3.8 \times 10^8$ RAD (Si)/SEC (MAX ATTAINABLE RATE)

RESULTS

- EFFECT OF RADIATION ON PHYSICS PACKAGE: NEGLIGIBLE
- ACCUMULATED PHASE ERROR: <1 NSEC

ACCUMULATED PHASE ERROR FOR MOST SENSITIVE DIRECTION

The engineering model tested contained two radiation-hardened crystal oscillators (VCXO's). The first VCXO was used in the primary loop and was locked to the rubidium resonance with a loop time constant of < 0.1 sec. The second VCXO was used in a secondary 10.23 MHz loop that was locked to the first loop with a time constant of 21 sec. The main effect of the radiation is to alter the properties of the radiation-hardened VCXO's. This results in VCXO frequency changes which are subsequently servoed out by the control loops (each VCXO is locked, in effect, to the rubidium resonance). However, accumulated phase changes will result if the VCXO frequency changes occur in times short compared to the loop time constant; i.e., transient effects are responsible for the accumulated phase errors.

Figure 5 shows the accumulated phase error for the secondary loop. The radiation burst occurred at $t = 0$ while the unit was operating. After about 1 minute the phase stabilized with an accumulated phase error of about 22 nsec. Under the same conditions, the accumulated phase error for the primary loop was < 1 nsec. This difference may be attributed mostly to the smaller time constant for the primary loop and the fact that the rubidium resonance is essentially unaffected by the radiation. Here the important results are those for the primary loop. Secondary loops are rarely used, and in any event can be considered as a loop that is external to the actual rubidium device, whereas the primary loop is part of the rubidium device.

EFFECT OF 10^4 RADS ON AN OPERATING, UNMODIFIED SMALL COMMERCIAL RUBIDIUM STANDARD.

Figure 6 shows the effect of total radiation dose from a cobalt 60 source on an operating, unmodified, small commercial rubidium standard, essentially an Efratom Model FRK with high reliability electronic components. That is, the device was unmodified in any essential respect as far as its capacity to resist radiation was concerned. The total dose of 10^4 rads was accumulated at a steady rate over a 1 hour period.

As a result of the irradiation, the frequency of the unit increased by about 6 parts in 10^{11}. This frequency change resulted from a change in the characteristics of the electronics in the servo loop. The photocell voltage, here labelled "Rb lamp voltage," changed by less than 1 %. This shows that the rubidium lamp and the physics package optics were essentially unaffected by the radiation. On the other hand, the VCXO control voltage changed by 6 volts, indicating that the VCXO characteristics had been altered by the radiation.

FIGURE 5
ACCUMULATED PHASE ERROR FOR MOST
SENSITIVE DIRECTION

SECONDARY 10.23 MHz LOOP, τ = 21 SEC
$>3.8 \times 10^8$ RAD (Si)/SEC

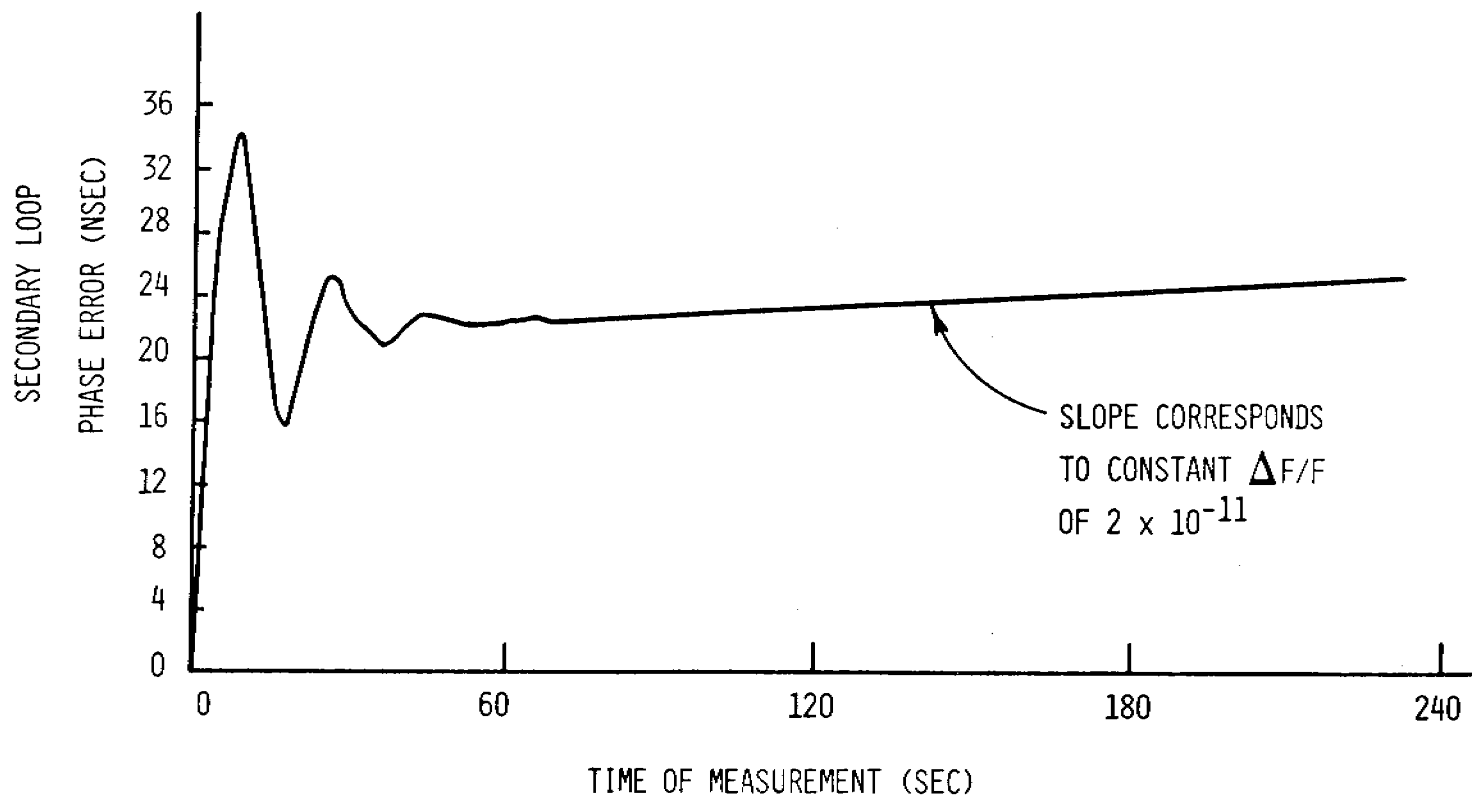
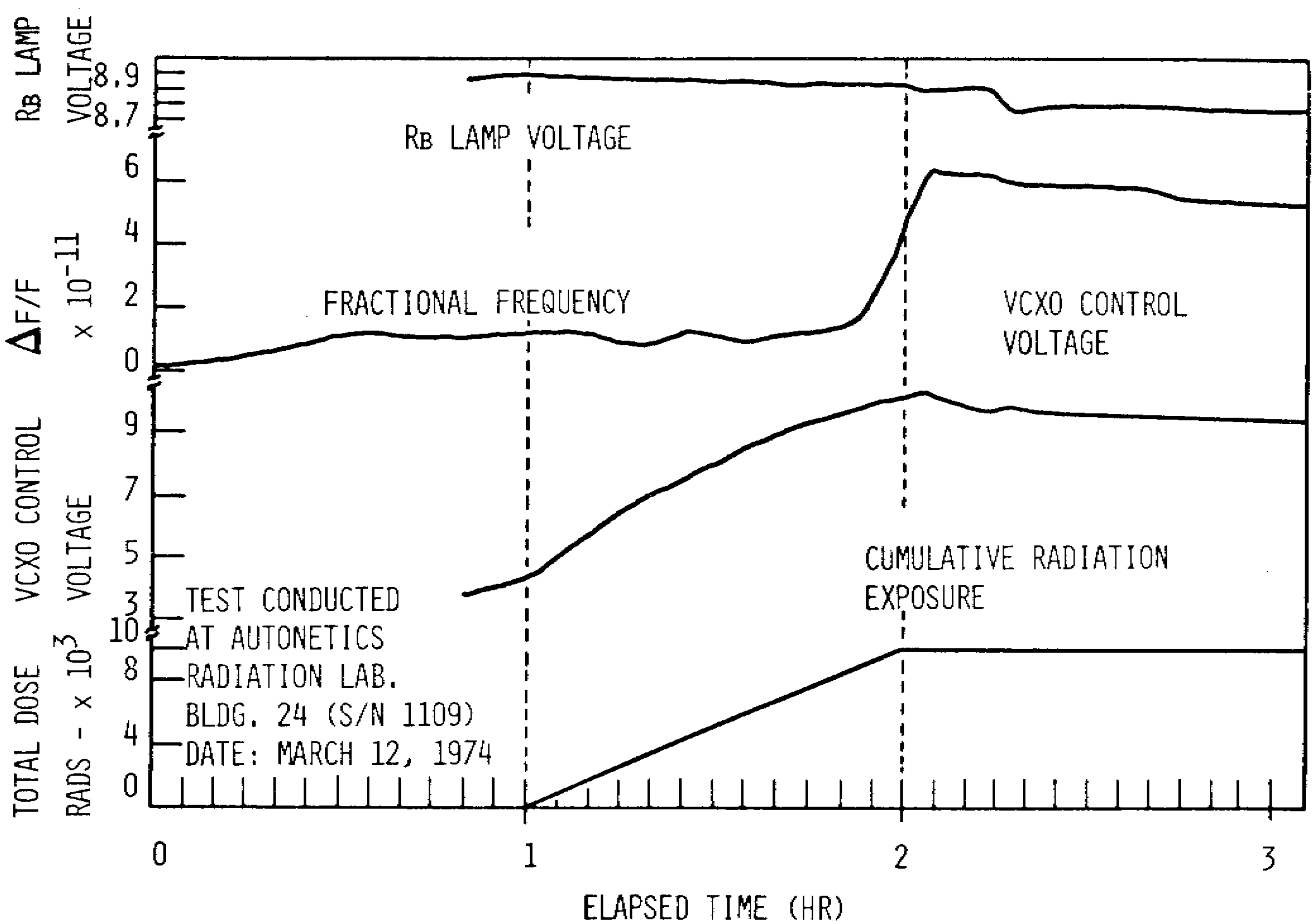


FIGURE 6. EFFECT OF 10^4 RADS (Co^{60}) ON AN OPERATING, UNMODIFIED, SMALL COMMERCIAL RUBIDIUM STANDARD



This was not surprising, however, since the VCXO crystal was not designed or selected to withstand radiation effects.

In summary: The physics package of a small commercial rubidium frequency standard was essentially unaffected by a radiation dose rate of 4×10^8 rads/sec, and a total dose of 10^4 rads, in independent tests. For the dose rate of 4×10^8 rads/sec, the accumulated phase error was < 1 nsec, and this occurred within 60 sec after the radiation burst. For the experiment where the total dose was 10^4 rads, there was a frequency shift of about 6 parts in 10^{11} due to the irradiation. However, since this was due to a change in the electronics rather than to any changes in the physics package, and since the electronics in this case were not radiation hardened, this frequency shift could be eliminated in a carefully designed device.

APPLICATIONS ESPECIALLY SUITED FOR SMALL, LOW-COST RB STDS

Most of the applications for rubidium frequency standards utilize one or both of the two basic techniques listed in Table 5, namely, timekeeping, usually in the sense of measuring precise time and time intervals over periods up to about 10 hours, and also the generation of spectrally pure and stable microwave frequencies having high signal-to-noise ratios using the method of frequency multiplication from high quality low frequency signals.

Most of the applications peculiar to rubidium, as opposed to cesium, utilize the small size and weight, the low power consumption, and the low cost that rubidium provides. By far the largest application for ribidium at the present time is the use of these standards for navigation purposes in light and medium aircraft. We discuss this in some detail below. A related application is the use of these standards for positioning and geodetic survey purposes. An example of a positioning application would be locating the correct position at which to place an offshore oil and gas drilling platform.

Another class of applications is the use of these devices for secure communications systems; i.e., for military communications systems. This is an application that is just getting started and of which we will see quite a bit in the comming years. The area of secure communications can be divided into two groups: The first is message modulation and synchronous demodulation which uses the timekeeping capability of rubidium devices. The second is the use of spread spectrum techniques such as frequency hopping and pseudo random noise phase modulation that require spectrally pure and stable microwave frequencies with low phase noise, which is the second technique listed above. Again, the small size and weight, low power consump-

TABLE 5

APPLICATIONS ESPECIALLY SUITED FOR SMALL, LOW-COST RUBIDIUM FREQUENCY STANDARDS

BASIC TECHNIQUES:

- TIMEKEEPING (PTTI)
- GENERATION OF SPECTRALLY PURE & STABLE MICROWAVE FREQUENCIES (USING FREQUENCY MULTIPLICATION)

APPLICATIONS:

- NAVIGATION (SMALL-MEDIUM AIRCRAFT)
- POSITIONING & GEODETIC SURVEY
- SECURE COMMUNICATIONS
  - MESSAGE MODULATION & SYNCHRONOUS DEMODULATION
  - SPREAD SPECTRUM (E.G., FREQUENCY HOPPING; PRN PHASE MODULATION)
- DIGITAL NETWORK SYNCHRONIZATION & MULTIPLEXING
- FREQUENCY CONTROL & CALIBRATION
- TIMEKEEPING PER SE (CLOCKS)

tion, and low cost make rubidium more suitable for applications of this type which require portability, such as in moveable field stations and military aircraft.

A somewhat related application is the use of rubidium standards for the synchronization of digital networks. This includes civilian, as well as military uses. An example of this is the Datran commercial communication system which uses rubidium standards for timing purposes (R. L. Mitchell, "Survey of Timing/Synchronization of Operating Wideband Digital Communications Networks," Paper 11, Session IV, this conference (10th PTTI)) . The last two applications in Table 5 are not especially suited to rubidium, except inasmuch as cost is a factor. In any case, these two applications are two of the more conventional ones as regards atomic standards.

NAVIGATION APPLICATION--RADIO NAVIGATION (VLF - OMEGA)

In Table 6 we are talking about the use of rubidium frequency standards in VLF & Omega navigation systems. The users here are owners and operators of light-medium aircraft. This includes both Lear jets and helicopters. In this application, price is a very important consideration. These types of radio navigation systems are typically priced in the range of $40,000 to $50,000. By way of comparison, inertial navigation systems sell for more than $100,000 and up. It is worth noting that it is obviously impractical to use a cesium standard costing about $20,000 in a radio navigation system that sells for $40,000. For this reason, the small commercial rubidium standard is the clear choice for this application.

A conventional VLF-Omega navigation system, which does not use an atomic standard, uses the hyperbolic method of locating position. In this method, a minimum of 3 VLF and/or Omega stations is required. Sometimes, radio conditions are such that it is not possible to receive as many as three stations. In this case, the accuracy of the system is greatly degraded. Even if three stations can be received, it may not be possible to obtain an accurate position determination. This depends on the geometical positions of the stations relative to the aircraft and the signal-to-noise ratios of the received signals.

A VLF-Omega navigation system that uses a rubidium standard does not suffer from these disadvantages. The inclusion of the atomic standard in the plane's navigation system allows the rho-rho navigation method to be used instead of, or in addition to, the hyperbolic system. The main advantages of the rho-rho system are that it is simpler to implement and is more accurate under adverse conditions.

TABLE 6

NAVIGATION APPLICATION

RADIO NAVIGATION (VLF - OMEGA)

USERS: LIGHT - MEDIUM AIRCRAFT, INCLUDING HELICOPTERS

NO RUBIDIUM STANDARD: HYPERBOLIC, <u>MINIMUM</u> OF 3 STATIONS REQ'D

WITH RUBIDIUM STANDARD: RHO - RHO, ONLY 2 STATIONS REQ'D

<u>NAVIGATION ACCURACY</u>

$$\Delta X = C \cdot \Delta T$$

DISTANCE ERROR = 1 FT/NSEC x TIME ERROR

CLOCK OFFSET OF 4×10^{-10} GIVES:

$$\left.\begin{array}{l}\text{TIME ERROR} = 6\ \mu\text{SEC} \\ \text{DISTANCE ERROR} = 1\ \text{MILE}\end{array}\right\}\ \text{IN 4 HOURS}$$

COMPARE WITH INERTIAL NAVIGATION ERROR OF ~4 MILES IN 4 HOURS!

In the rho-rho method, the distance to a radio navigation station having known position is determined by measuring the time T that it takes for the radio signal to travel from the radio station to the aircraft. The distance X from the station to the plane is then given by $X = C \cdot T$, where C is the speed of light. The distance of the aircraft from the radio station defines a line of position (or locus) that is a circle of radius X with its center at the station. If the distances from two such radio stations are known, then we will have two such circles, one centered on each radio station. The aircraft is then located at one of the two points of intersection of the two circles. In this method, the distance error, delta X, is related to the time error, delta T, by the equation shown in Table 6, where C is the speed of light. In this equation the time error, delta T, is the accumulated time error of the atomic clock since the aircraft left its point of origin (point of clock synchronization).

Even if the atomic clock has a large average frequency offset, the navigational accuracy is still quite good. For example, suppose the average frequency offset of the clock were as large as 4×10^{-10}. Then the accumulated time error over a 4 hour period would amount to approximately 6 microseconds, and this would give a distance error of only about 1 mile. It is interesting to compare this navigational accuracy with that attainable by inertial navigation. For inertial navigation, the error would typically be about 1 mile for every hour of flight time, or about 4 miles in 4 hours! The rho-rho method is therefore capable of greater navigational accuracy at considerably lower cost.

FUTURE IMPROVEMENTS IN SMALL RUBIDIUM STANDARDS

Table 7 shows some of the improvements that can be expected in rubidium frequency standards in the future. We can expect the size to decrease by about a factor of two from the present small rubidium size of 1 liter. This will be accompanied by a weight reduction of about 40 % and a power reduction of about a factor of 2. In addition, we can expect warmup times to decrease further, by about a factor of five for a room temperature ambient. At -55 $^{\circ}$C ambient, warmup times of less than 5 minutes should be easily possible.

The temperature sensitivity will be less by at least a factor of 4. At the same time, it should be possible to reduce the sensitivity to changes in barometric pressure by about an order of magnitude. As quantities increase and manufacturing techniques improve, the price will decrease at the same time. It is difficult to predict this with much accuracy, but a price decrease of approximately a factor of 2 is reasonable to expect.

TABLE 7

FUTURE IMPROVEMENTS IN SMALL RUBIDIUM STANDARDS

CHARACTERISTIC	PRESENT	FUTURE	IMPROVEMENT
SIZE (CU IN)	67	34	x 2
WEIGHT (LBS)	3	1.8	x 1.7
POWER CONSUMPTION (W)	13	7	x 2
WARMUP TIME (25 °C AMBIENT)	10 MIN TO $< 2 \times 10^{-10}$	< 2 MIN TO 5×10^{-10}	$\sim$ x 5
TEMPERATURE EFFECT (-55 °C AMB. TO + 71 °C B.P.)	4×10^{-10}	$\sim 1 \times 10^{-10}$	$\sim$ x 4
ATMOSPHERIC PRESSURE EFFECT (SEA LEVEL TO 40,000 FT)	8×10^{-11}	$\sim 1 \times 10^{-11}$	$\sim$ x 8
COST (K$)	4 - 6	2 - 5	$\sim$ x 2

To summarize: The main improvements will be in the areas of size, weight, power consumption, warmup time, and environmental sensitivity. Other characteristics will either also improve, or else remain about the same as they are now. This should result in a wider range of aplications and concomitant lower prices.

DISCUSSION FORUM: ATOMIC FREQUENCY STANDARDS

HYDROGEN

Harry Peters, Sigma Tau Corporation

The things that I would like to compare hydrogen to, today, are not NBS-5 or 6 or the latest basic standard or NRC absolute standards, which are in great array here now; but with respect to present and future commercial cesium and rubidium because this is what I think is missing as far as hydrogen devices are concerned as has been pointed out today: they need to be available before they are going to be useful.

All the hydrogen masers today either originate in government laboratories, are government built, lent, or supplied, or are carefully tended antiques. And there are many examples of people desperately using hydrogen masers today. But there are lots of data to substantiate the performance on operating characteristics, to document their performance, present and potential, and improvements that may occur.

I am going to show two viewgraphs now to illustrate a couple of additional points. Now this viewgraph is rather a rough one. I apologize for it. It illustrates the rubidium and cesium passive standard systems and hydrogen maser active system.

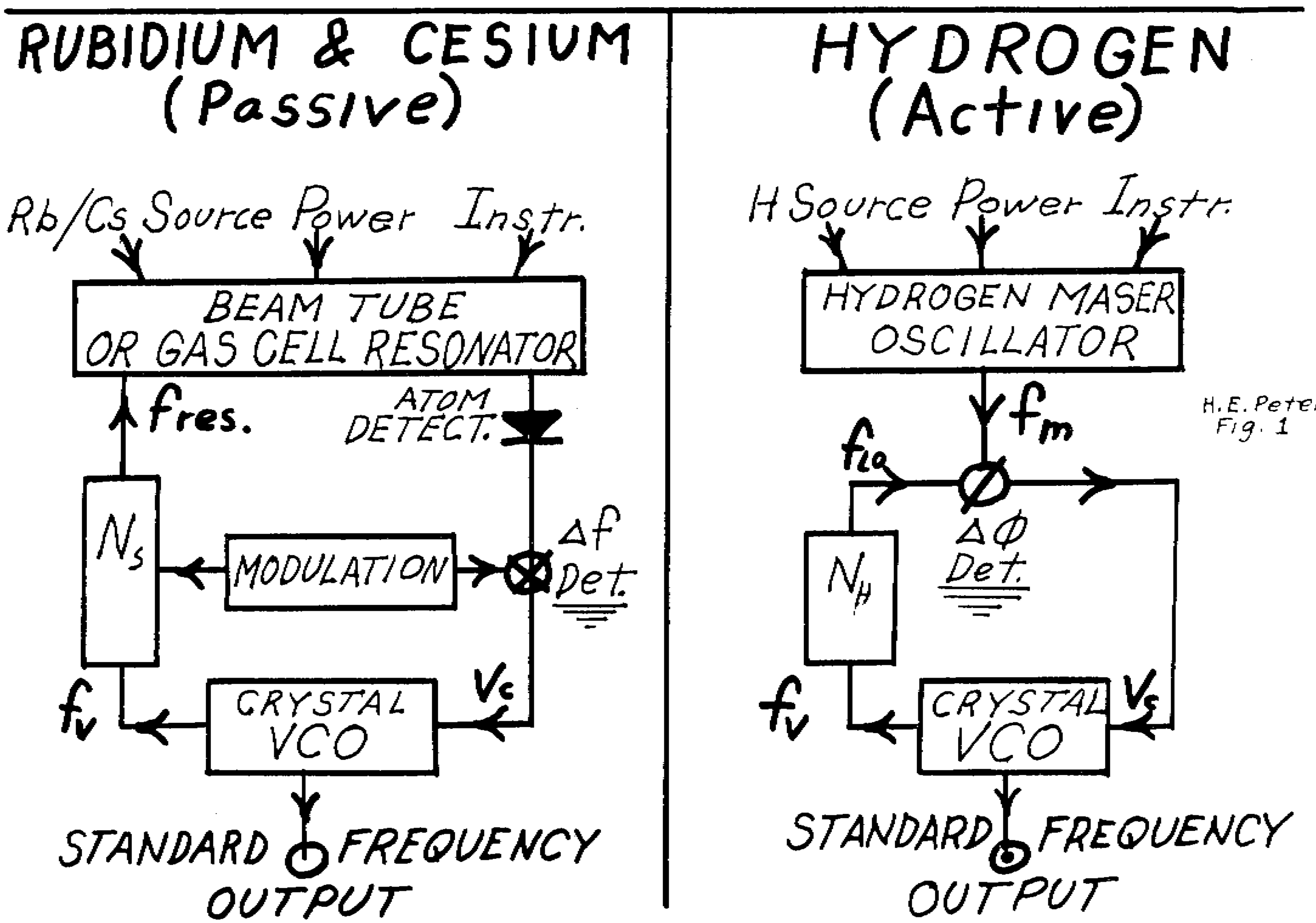
I am only showing them--not for a course on how beam tubes work and masers oscillate, but rather to illustrate the relative complexity of the systems. And for this purpose, both rubidium and cesium are well known to be resonant devices. But each of these devices needs a source of atoms. You have power input and instrumentation.

Then you have a crystal oscillator, which is multiplied up, if you are using a synthesizer system, to the resonant frequency. And you sweep the resonance by using a modulation frequency. You detect it synchronously and lock the crystal on.

Now let us look at the active hydrogen. You have a similar source, power input, instrumentation. You have an active maser oscillator, so it is a case of having a good low noise receiver to lock on to a coherent output. You have again the crystal oscillator and a number synthesizer to get the local oscillator. And you lock on the crystal using a VCO, and you have again the standard frequency output.

Now all of these electronic systems are really becoming very simple today, and electronics and instrumentation and power are of comparable magnitude, cost-wise, complexity-wise, and so forth. So they should not be large factors in future availability.

ATOMIC STANDARD SYSTEMS



H.E. Peters
Fig. 1

They are now because hydrogens have not been commercially developed. They have not gone through a large production run, and there has not been a lot of reliability work done. Most of them have been built by scientists in laboratories.

Let me carry on with the next viewgraph please. This viewgraph gives my own opinion, and I hope others, of the particular features of the hydrogen maser. I have just listed them. These are the only two viewgraphs that I will show.

First, it has the obvious stability characteristics, which for a long-term operating device are really outstanding and fundamental. Their reproducibility is exceptional. Now I intend this to illustrate it is better than any other device of the two types which I am comparing with. And basic accuracy: It is well known that hydrogen masers reproduce the cesium frequency to a factor of five or ten better than commercial cesiums, and in that sense they are a better basic standard.

This partly arises because of intrinsic reproducibility of the hydrogen frequency. If you look at the cost of the hydrogen maser per part in 10^{15}, you will find that it is several orders of magnitude less expensive than other standards where you need them.

The same is true of cost per year. The amount of hydrogen used today in a maser is trivial. The pumps last for decades, and you don't necessarily have to take them apart and replace the insides if the cesium becomes depleted or contaminates the tube.

They are simply active oscillators, and they can be made passive incidentally. There is work going on today in at least two laboratories, successful work with passive masers. But we all have our enthusiasms in this regard.

Reliability and longevity have been shown by papers which have been published. We don't have as much information as we would like because they aren't available in great numbers and for the reasons I mentioned. They are technically well developed.

The last point, I think, is quite obvious. They are not commercially available, so it is sort of unfair of me to compare hydrogen masers with commercially available rubidium and cesium. However, I hope perhaps you can say I am comparing them as future ones.

Let me go right on into applications. I am not going to go into detail. I think that a lot of this detail has been gone over today, and everyone knows where you can use parts in 10^{14}, 10^{15}, etc. and perhaps where it isn't needed.

FEATURES OF HYDROGEN MASER

- STABILITY
- REPRODUCIBILITY
- BASIC ACCURACY
- COST Per PP/10^{15}
- COST Per YEAR (CS Ens.)
- Simple Active Oscillator (Or Passive)
- Reliability
- Longevity
- Technically Well Developed

O NOT COMMERCIALLY AVAILABLE!

H.E. Peters
Fig. 2

We need them of all places, obviously, where rubidium or cesium are not less costly, or are not adequate for the application. For example, a very important application is that a given hydrogen maser--you might want two actually for redundancy--can replace a very large cesium ensemble in principle in basic timekeeping systems. Of course, you have military and NASA ground stations, navigation and communication stations, time and frequency calibration labs, astronomy, VLBI, geodessy, and other scientific and military uses.

Next I would just mention a couple of words about future performance. We have at least three laboratories that are either at or pushing into the parts in 10^{16} region for certain averaging times. And I would like to point out that some of this work is being done with masers which have aluminum cavities, and other masers have dielectric cavities with a similar performance.

Now, with regard to the types that I have been using, I am not really an advocate of aluminum basically; however, it is not clear that the instabilities are due to temperature in many cases. I would point out that in the future I expect in the aluminum type, by using subsidiary dielectric materials, that you can easily get a factor of 50 in principle and you get down into the part in 10^{16} region in stability just due to the further lack of pulling, due to cavity pulling.

As to size, there are new approaches available. They have to be proven in the laboratory, and most of you know about these attempts. But the best standard is, in principle, the largest standard, and that is all I will say about that.

The future availability depends entirely, of course, upon getting well-known state of the art into private industry. You cannot sell, distribute, support, or go around in the field and have people to maintain or have wide usefulness in a hydrogen maser standard if they are built in specific scientific laboratories and don't go through the disciplines of the production cycle.

Just one more point I should make. There is one place in the world today with significant private investment to achieve both active and passive hydrogen maser frequency standards. It is not in the United States. It is a well-known company in Switzerland, Ebauches. And if there are any further questions regarding the work there, I would refer you to Dr. Busca, who is present today.

I think that we will see hydrogen masers in the future in the United States. I personally think that, unless we can get some way to stimulate availability of commercial standards in the United States, there is a high probability that we will have Volkswagon hydrogen masers, Le Car hydrogen masers, Toyota hydrogen masers, etc. It doesn't appear that we are going to have any Ford, General Motors, or Hewlett-Packard hydrogen masers in the near future.

OPEN DISCUSSION: FORUM ON ATOMIC FREQUENCY STANDARDS

DR. HELMUT HELLWIG, National Bureau of Standards:

I would like to thank all of the speakers. Before we open the discussion, Raymond (Besson), could you join us. You know, we have sort of competing standards concepts, and that is the purpose of this panel.

Let me first ask simply, does anyone here agree, disagree, or have comments on what anyone else has said? Raymond, you are first.

DR. RAYMOND BESSON, E.N.S.C.M., Besancon, France:

Immediately I have a comment. I will say to Dr. English that I perfectly agree with his positive statement about the rubidium. And I really enjoyed the talk and the work in this area. But I do not agree with his negative statement about quartz.

You say you do not have available data about short-term stability. Well, if you don't, measure it. You should also take into account the last results, at least the last commercially available results. You say I don't have the numbers. You pointed out....

DR. THOMAS ENGLISH, Efratom California:

Why don't I just put it on the viewgraph. It is right here.

DR. BESSON:

Okay. On short-term stability, I would like to see some figure, whatever it is. Okay. Long-term drift, I would say I agree with the commercially available number.

MR. ERNST JECHART, Efratom California:

It is important. It means only commercially available.

DR. BESSON:

Yes. Okay. But you know I simply would not like to make a too partial point. I would like simply to see some figures for the short-term stability. Warmup time can be discussed. But, for instance, for acceleration sensitivity, I just stepped out here during the session and saw companies just giving some sensitivity data which is not 8×10^{-10}/g. So I think I would like some of those numbers, you see, to take into account the last data.

Also about the compensation, Don Emmons pointed out some results and compensation devices that are also available in France. It has been three years since Valdois did his work. And really I don't believe we come out with this terrible acceleration sensitivity right now, at least in France.

DR. ENGLISH:

This was based on commercial quartz oscillators that are available right now and represent, I felt, the state-of-the-art parameters. Now I don't promise you that I have the exact correct value in every case. I really honestly tried to give good values here. Now if the acceleration sensitivity is too high, I would appreciate it if you would correct me.

But these are commercial units. I am not talking about the state of the art for quartz in laboratories.

DR. BESSON:

Oh, naturally, but you should, I think, give a number for short-term stability because this is available on commercial units.

DR. ENGLISH:

Well, I did mention that usually the best I knew was parts in 10^{13} when it was specified. Usually it is not specified over 100 seconds. See, I have over here short-term stability, minutes to hours. I know it is usually specified out to 100 seconds. Beyond that I don't know.

DR. BESSON:

You know the point--it is always very difficult to make such comparisons because it can always be discussed. It is, rather, a feeling. Negative statements always lead people to drop some effort, and I believe, like I said in my talk, that there are many routes available. Don't make the people throw away the quartz oscillators.

DR. ENGLISH:

Well, I don't think we are going to throw away quartz oscillators because they obviously have advantages. But this was supposed to be a parochial presentation.

MR. JECHART:

Tom, I would also like to say that it is not fair to compare a commercial rubidium unit with a crystal that is in a laboratory. If we reverse this we can make a much better statement for rubidium. What we have done is....

DR. BESSON: I perfectly understand, but....

MR. JECHART:

Yes, but you said it was a negative statement. I don't believe....

DR. BESSON: Negative, yes.

MR. JECHART:

It is not negative. It is what you call negative. Please tell me one company that produces crystals on the market with a better value than 8×10^{-10}/g? One company? I don't know of one with a better value because we said commercially available.

DR. HELLWIG:

Maybe we should reduce the discussion at this point from what could be done in the future to what is available now.

DR. C. C. COSTAIN, National Research Council of Canada:

I just want to take one crack at Harry Peters here. We promised each other that. And this again is not connected with commercially available units, but with bringing things out into the open. Since I came into this business six years ago, Dr. Guinot and others have been pleading to have hydrogen maser clock measurements reported to the Bureau International de l'Heure (BIH) so that some evaluation against the international standards can be made. I would hope--we haven't seen it yet--that next year, three or four masers will have made ten months of reports (because they always come back 60 days late) and that at the next PTTI, we can have results on these masers that have been reported to the BIH so that some evaluation can be looked at.

MR. HARRY PETERS, Sigma Tau Corp.:

That is terrific, yes. I would like to see that also. However, the people that have been making hydrogen masers have been very few. And the evaluation and distribution of these standards to organizations makes it almost impossible.

Actually, I am not in a position to help with such a thing. I think there is some discussion of the possibility of Goddard masers being compared with TAI and so forth. Now, as to whether hydrogen masers have been observed, they have been observed for months, eight months or up to nine months, and for three months at a time in comparison with cesium ensembles, and have done remarkably well.

It is very difficult to confirm whether a great number of cesium clocks have been stable or hydrogen masers have been stable. So there is no doubt in my mind that there are a lot of data, both maser to maser and also internal data. It is done in our laboratory, of course, and it would be preferable to have everybody in the world look over the data. However, I believe in it, and they are as stable as theory predicts.

There is no opportunity to do what you say until we have several units which have gone through the discipline of being produced and have the support, and other people can do it. Because the people who develop these, make them, invent them, cannot possibly take up the whole job of your organization, and compare them with TAI. It is an impossible burden, and I hope others will do that when and if they ever get masers.

Now, could I continue on to comment since Dr. Costain has opened the door.

MR. PETERS:

I want to thank you particularly for predicting presently unobserved effects in hydrogen masers due to magnetic effects. Actually, our holes get smaller as the size of the shields get smaller, and they are smaller than some have told about in magnetic shielding calculations and some of the later designs of masers, such as a spacecraft maser and another design which has been proposed. They are only about 0.4 inch.

Typically, these designs have been approached rather carefully, and we are already down to inches for bulb state selector distances, for example.

DR. COSTAIN:

It is not the holes. It is the material I am concerned about.

MR. PETERS:

No, no. I am going to relate to that in just a moment. As a matter of fact, you can easily evaluate the inhomogeneity shift in hydrogen masers through several well-known techniques. They have been published, and the effects do not create either an inaccuracy or a resetability problem.

I don't anticipate that we are going to make hydrogen masers an order of magnitude smaller than they are now, so it is not going to be an order of magnitude change.

I would like to make one last comment since I still have the opportunity. I wish you could have put your enthusiasm and your talents and your opinions originally into hydrogen because I think we would be much further ahead in hydrogen technology than we are today.

DR. COSTAIN:

We have a couple of the ancient masers that you referred to in Ottawa, vintage 1965.

MR. PETERS:

I have pictures of them.

DR. COSTAIN:

When the cesium program is finished, we fully intend to see if we can do better in hydrogen masers.

DR. HELLWIG:

Maybe I should make a comment here and conclude this part of the discussion. It is, I think, a perennial battle within every lab. I saw it go on at NRC, PTB, NBS, and, I think, in a derived way, at some, say, non-standards labs as well. You have certain tasks you have to do and that causes you to order priorities. And you are not always doing what from a purely technical viewpoint is the best choice. I think that goes for almost any decision we are making.

Let me change the topic slightly. It is very close to what we have started on. In many peoples' minds, again back to the systems designer, the user, etc., there is always a ranking of standards. Sometimes the ranking goes hydrogen, cesium, rubidium, crystal. Sometimes the ranking goes in reverse. It depends upon your requirements and how you look at them.

We, I think, have not fully addressed that yet in the formal presentations or in this discussion. Where are the actual niches for present day hydrogen, rubidium, cesium, crystal? And where are the potential niches? I'll ask Harry first.

Hydrogen definitely produces the best numbers. There is no question in terms of stability. What in your experience are the present customers, and what are you seeing as customers, either based totally on this exceptional stability performance of hydrogen or maybe on other qualities of hydrogen as you see them? In a nutshell, who needs hydrogen, now and in the future?

MR. PETERS:

I think that the answer lies in the fact that you don't absolutely need it, but it would be more economical to use it, and you would have a better system if you used it, and it would take fewer computers and fewer people if you used it. You would have better navigation. Maybe you don't quite need it, but it has many practical advantages.

I think the users are obviously time and frequency organizations such as your own, and also international timekeeping organizations where it has been cited by others that it would be desirable to have a comparison standard for the present cesium ensembles. Perhaps it is more clear now since we have got better accuracy than we had before. But actually, absolute accuracy is what determines our long-term knowledge of our frequency drift of any group of standards. It is not an ensemble of commercial devices which are not in themselves absolute in the sense that they can be evaluated.

So we have that application. I think that for certain navigation systems, Loran-C, Omega, they may develop needs as the capabilities of timing and frequency and communication systems evolve into the future.

Certainly, many applications of which I can't possibly be aware, military, mobile, and so forth, are possibilities. All of the NASA tracking stations, many of them, particularly DSN.

Incidentally, I think 75% of the hydrogen masers being used today, such as our old H-10's and many of the laboratory devices such as those Dr. Costain referred to, should be replaced with something that is a little more modern. And I am sure he agrees with me. I think I could go on. I think many university labs....

DR. HELLWIG:

Do you have a rough guess as to how many hydrogen masers are not only in existence but actually being used?

MR. PETERS:

I'm sure that if we counted carefully and not only in the Western countries, we would find 50 or 100 of them, something on that order. And there are more in the Eastern countries because they started out with more enthusiasm in this direction, I believe, than we did. At least, in Russia, their basic standards were originally hydrogen, and now they have come over to cesium.

Then there is geodesy and astronomy, and VLBI of course. Any system that needs phase coherence, where you have to resolve to 10^{10} cycles, one radian or a small fraction of a radian, really needs this type of standard. And if you can maintain this over a day's time, of course, and over long periods of time, you don't need to resynchronize.

I'm sorry. I've gotten away from customers into performance again. Did I answer....

DR. HELLWIG:

Yes, you really answered that question.

MR. JECHART:

What do you think is the price if it is available for commercial use?

MR. PETERS:

I think the electronics will basically be the same price as the electronics for your rubidium cell, almost.

MR. JECHART: Really?

MR. PETERS:

We have synthesizers on one board; they are operating and work beautifully. You have shown all your beautiful electronics. There is so much large scale integration. Temperature controls are a couple of very inexpensive IC's, for example. Power supplies are commercially available. They have just been put together by high-priced scientists in the past. Basically, the electronics part is not expensive. The large parts are made of aluminum, and if they are made in production, they will come down by a factor of who knows--two, three, five, ten, depending on how many. We are never going to make them like automobiles, of course.

MR. JECHART:

Do I understand you correctly, that you can make it much cheaper than cesiums?

MR. PETERS:

I think we can make the price comparable. I think we would probably put into the hydrogen things that cesium doesn't have because it (hydrogen) is inherently more reproducible and also has higher resolution on the C field. And you would want to, with the short-term stability, have much greater resolution on the synthesizer.

So we have put in a couple of little things that really make it this much more useful than the cesium would be because of its (cesium's) high-shot noise.

I think you can bring it down significantly in price, but with the fluctuation of the dollar and so forth, I don't want to say what it is going to be.

DR. HELLWIG:

I wanted to ask the same question about rubidium. Who needs rubidium now and who will need it in the future? But I think Tom English answered that question to a large degree, so I will modify it. Please answer this question with a special twist of thinking of either simpler or higher performing rubidiums, which I think Tom did not really address. So sub-question "a," is: Can rubidium be so much improved that it really competes on the level of present day cesium, maybe even hydrogen? Then, I think, the answers would be the same as those given by Harry for hydrogen, and you would have direct competition between the standards.

MR. JECHART:

I would say it is not a simple question.

DR. HELLWIG:

Sub-question "b" is: Could you even further simplify the rubidium to the degree that applications open up where, as I tried to point out this morning, at the present time, you have difficulties in coming up with standards at all. What is your answer?

MR. JECHART:

The answer to the first question is yes. We have experimental data that were not discussed here. And the data show that we can go close to cesium. This is what I believe, what my experience shows.

DR. HELLWIG:

At no great increase in complexity?

MR. JECHART:

No. The answer to the other question is yes because with modern electronics, you can make it much cheaper and smaller, as you can do with everything. But because the rubidium physics package alone is already so small, it makes sense to make an electronics package much smaller. Tom showed, on the last graph, what we believe is possible in this area.

DR. ENGLISH: Factor of two or so.

MR. JECHART:

Yes, and this is really what your second question was, I think; and of course much cheaper.

DR. HELLWIG:

Let me repeat what I think was an important point with regard to rubidium. As contrasted to hydrogen and cesium, the electronics is the bulk of the size at this point. So that gives a totally different attack angle for the designer of the clock.

MR. JECHART: Yes.

DR. HELLWIG:

Cecil, the same question. Where is cesium used, where will it be used, and where do you think fundamental improvements could be made?

DR. COSTAIN:

Well, I think in any of the standards that any step in accuracy that can be achieved is immediately saleable. I don't think there is any question there, and it is just a question of commercial viability.

In cesium, certainly, there are going to be limitations. I think it is almost inevitable if you reduce the size, you are going to reduce the accuracy.

We thought we'd see if we could put one in a watch one day, but we didn't get very far. The magnets might go in a watch, but the microwave source is a little difficult. But perhaps you could come down in size and not sacrifice the accuracy totally.

What we have done in the lab is perhaps an experiment in practicality. We don't know yet. We will hopefully know next year if you can match, in one device, what you can do by averaging 100 commercial units. In that case, there might be requirements in ground navigation, or you might say absolute indexing, although I think it is more fun doing the indexing by satellites, and I hope we can discuss that on Thursday.

DR. HELLWIG:

Thanks, and finally, Dr. Besson, you get your chance. Crystals. You should not talk about commercial crystal but about some fancy devices of the future. Will they wipe out atomic standards? If so, how?

DR. BESSON:

First, I would still go back to normal units and point out that quartz crystals are still the work horse in frequency and time measurement systems, since almost any device has a good quartz crystal. That would be my first point. I should have said it sooner.

DR. HELLWIG:

Excuse me. That means if the world is populated exclusively by atomic standards, which I think is nonsense, that there would be at least an equal number of crystals?

DR. BESSON:

Yes. That is exactly what I mean.

MR. JECHART:

I don't know if atomic standards always need a crystal.

DR. BESSON:

Yes. So that would be my first point. Second, it is always very difficult to speak about the future because one has a tendency to be optimistic. But I believe in some qualities of the quartz oscillator. It is a low-cost unit. It is low volume and can be operated with low power. At that point, I very strongly believe that the g sensitivity will remain a problem for quartz units.

It all depends to what extent. I would say that down to some parts in $10^{-11}/g$, I don't see any problem right now. And it is a very important point because some years ago, this was still a problem which was not solved at all. And it is a very difficult one because you do need theoretical stuff of high level. And you do need to realize it experimentally; it is not enough to make nice calculations.

So I can tell that we solved the question in France. We made our first low-g-sensitivity resonator, very low-g, one year ago. This is done, and you can reproduce it very well. Of course, if you would like some g sensitivity down to 10^{-12}, that is another step.

So the next question, "Will it be a huge market or not?" I don't believe I can answer. I am working in a research lab. But I believe that those numbers could certainly bring some customers.

MR. JECHART:

I feel what is important here is not what you say you can do, but if you do it. Of course, I am sure you can, but if you compare later on what is important for a customer, it is really the price also.

DR. BESSON:

Okay, I already said that the price of the unit we are evaluating right now should range, at least for as far as I can see, from a factor of 1.1 to 1.7 of the price of regular units. But we don't believe there will be a large increase in price.

DR. HELLWIG:

Excuse me. Less than a factor of two increase in the complexity of manufacturing, right? As compared to normal?

DR. BESSON:

Yes. And also you do have to know some features--I am speaking now about the new crystal--which are very nice, like frequency adjustment, which allows you actually to get rid of, to a certain extent, the series capacitor. It is too soon to say things now, but I believe that there is some kind of hope for the very near future.

DR. HELLWIG: Questions?

DR. VIG:

As a quartz crystal man, I was very happy to hear Raymond Besson defend quartz crystals. And I think also he is being much too modest as to what the future holds for quartz.

Those numbers that you mentioned before for commercially available crystals were all numbers for singly-rotated, either AT or BT cut crystals. For those of you who are atomic and molecular frequency standards people, there is a revolution taking place in quartz crystals in that the double-rotated cuts, in particular the SC cut, are known to be much less sensitive to stresses than the AT cut. And this has produced improvements in short-term stability, which was reported already at the Frequency Control Symposium last year. And also this morning, it was mentioned that stabilities of 10^{-14} per 100-second averaging time, I believe, were achieved already.

I would also like to point out that the crystals that were mentioned, as far as being commercially available, are usually manufactured using technologies which are 10 to 20 years old. And there are some technologies that have come along in crystal fabrication, such as in cleaning and packaging, which again will probably produce orders of magnitude improvements in long-term stability.

I would also like to mention that even though the long-term stability mentioned in that chart and in the HP catalog, for instance, is like 4 or 5 parts in 10^{10} per day, it was mentioned by Jack Kusters at the last symposium, for instance, that the actual crystals are aging in parts in 10^{12} per day. Even though they are not going to guarantee that in their catalog, the actual units do age parts in 10^{12} per day, and that is still for a singly-rotated crystal, where most likely the dominant aging mechanism is in the stress relief.

If you can use the most modern fabrication techniques for eliminating contamination plus use the SC cut for eliminating stress effects, there is every reason to believe that orders of magnitude improvements in long-term stability will result.

DR. HELLWIG: Is there any comment from the panel?

DR. BESSON:

Well, as a fact right now, I think we know very well a way of making SC crystals; for instance, their g sensitivity would be less than 5×10^{-11}. And that is not one crystal. That is a lot of them. And then you can compensate if you don't like this 5×10^{-11}. And I do believe that more improvement can be made.

I think that the quartz business is really at a turning point. I pointed that out in my talk. For 20 years, for some reason, there were some kind of asymptotic performance that caused people to maybe be less interested in quartz. But I believe this is going to change.

DR. HELLWIG:

I think I know the reason for the 20 years. I can quote correctly, I believe, Don Hammond of Hewlett-Packard, telling me that the advent of atomic standards stunted further scientific and advanced engineering development of crystals. That was 20 years ago.

DR. BESSON:

I really think that this is true, for instance, when I think about the techniques that John Vig has developed right now. There is an incredible amount of work that is being done now, and we are just ready to gather the benefits from that. And there is this technique of John's where the packaging of crystals can really bring much in the result and stability and drift per day. And one day I think we will put all those techniques together. We would like to use more of your new packaging or chemical etching and things like this. I believe it is time to do it, and I believe that the results will be surprising. So I perfectly agree with John.

DR. KAHAN:

I would like to argue that same area that John Vig and Dr. Besson are arguing. Personally, I see rubidium becoming obsolete very shortly.

We have to understand that the standards are competing against a moving target. Now what you have heard today or at the previous symposium is tremendous development both in quartz oscillators and resonators, and performance. In terms of cesium standards, what we have heard the last few years is not so much development in terms of performance, but development in terms of operational parameters, cost, size, and system limitations.

From what we have heard in Tom English's first paper, which is a complete contradiction to his second paper, for example, is that in one case he is concentrating on taking on the cesium market. And yet his last slide in the second paper is the possible improvements that can be done in rubidium, which doesn't mention long-term stability at all. What he mentions very properly is weight, power, and warm-up in terms of airborne navigation. And in that respect, I think that market will disappear as soon as the quartz oscillators become available.

I think that in that respect, cesium is moving ahead and quartz is moving ahead, but I haven't heard anything either today or at the Frequency Control Symposium which makes me believe that rubidium will soon be a valuable standard a few years from now.

MR. PETERS: Could I give a word for rubidium?

DR. HELLWIG: Yes, I need a word for rubidium right now.

MR. PETERS:

It is probably not well known, but some of my first work in graduate school was with rubidium cells and spin exchange. So you are forewarned.

Actually, it seems to me that quartz crystals are very good when you need them. They are never going to disappear. It seems to me also that for the very long term, atomic standards are always going to be better than mechanical standards.

MR. JECHART:

You say that right. It is a mechanical resonator, and I feel that this is a limitation you don't really have in an atomic standard.

I'm not sure you said the aging was much better. So of course, you can find the same thing in rubidium. We have rubidium standards that don't age, but the important thing is what you can tell a customer you can guarantee--and here I feel is the limitation.

What I heard regarding crystals is fine because you now use a new technique and you can make improvements. But first, what is the price? Is it economical compared to rubidium, and what is the advantage? I feel we here in this room should really discuss this fairly in a technical way. And I think this is possible.

Back to the crystal: Of course, for me, the limitation is the mechanical resonator. This is what I believe.

DR. BESSON:

I would not like to make any negative statement about rubidium standards. The first question is, what do we need and what do we want? And we ought to know what is available.

I really find once more that, you know, one should not make any negative statement. I think it would stop progress for a while. The same thing is true if you say, "Well, bulk devices, that is okay, but you have got saw devices now, and bulk devices are going to die."

MR. JECHART: Look, what I am saying is.....

DR. BESSON: You may be wrong.

MR. JECHART:

I am sure it can be much better with the new technique. On the other hand, look at the rubidium field. It was also the same way. Nobody really spent money in this field, and nobody worked on this (basic advances). And I am sure the rubidium situation could be the same as you are doing now with crystals. You can always make improvements. I feel it (rubidium) is not limited. This is what I would like to say.

DR. HELLWIG:

Well, we have come back to the old point, I think, of having a need for something, and only then will it be produced in adequate numbers with adequate performance characteristics. It will be produced if it can fulfill a need which the other devices cannot fulfill under the same conditions of, say, size, power, performance, warm-up, cost, and so on.

I think the question, put differently, is that some people here think that crystals can assume certain characteristics which were not possible before and were only available at a reasonable price from rubidium standards. But I think it is probably too simplistic to think that that makes rubidium unnecessary, for reasons which were stated already. And I think the same is true for cesium and hydrogen......

MR. JECHART: Yes, every one has a place.

DR. HELLWIG: Andy Chi has a comment.

MR. ANDREW CHI, NASA Goddard Space Flight Center:

I would like to first commend the panel members. That is, the presentations were parochial and also very interesting. However, one should realize the different types of atomic standards, including crystal oscillators as oscillators, which are competing, are not really the same. They have a certain amount of common characteristics. It is hard to believe that one can be substituted for another if a sophisticated user has genuine need for a particular type of standard with particular specifications. Most likely, he would be dictated to use one type, perhaps two. But they are not all the same, which is the impression that is given.

The other point I would like to make is the fact that in the applications, it is very hard to identify a particular application for a particular type of standard unless one can specify the requirement needed for the application.

One can conjecture and guess. This almost brings back to mind when cesium standards were developed. The estimated number of potential sales was 50. And you can see that now the number of sales of cesium is more than 50. And of course the same would apply to hydrogen masers.

Now rubidium by itself has its own use. In short, I am not sure it would be replaced by a crystal ocillator. In the same way, crystal oscillators will never be replaced by atomic oscillators.

DR. WINKLER:

I think Mr. Chi has stated a very important point. I think one can make a case that, at the moment, about ten hydrogen masers are being built and sold per year, about 100 cesium standards, about 1,000 rubidium standards, about 10,000 quartz crystal oscillators of the quality which goes into a frequency counter or similar type of instrument, about 100,000 low-quality quartz crystals per year, and possibly a million going into the quartz crystal watch industry.

So, why are these standards or these oscillators being used in these almost decades of orders or quantities? I think there is a very good reason for that, and that is that each one of them has certain performances which attract a certain clientele.

I am very pleased to hear that, in all of these devices, very interesting and most promising progress is being achieved. Now if I may add a few other comments, going back to some of the other things that have been said before, I think there is one misconception in regard to the lifetime of the high-performance cesium beam tube.

It is true that there has been a higher failure rate of those than the regular ones. But I believe that it cannot be an intrinsic great difference in lifetime because we have several of those standards performing very well after five and six years. And so I think we have to distinguish manufacturing and quality control problems which seem to have existed from intrinsic problems because the first ones eventually get straightened out. The second ones require a different design or engineering approach.

Regarding the magnetic comments of Dr. Costain, I really wonder whether you are talking about final limitations coming from the shields or coming from the random remagnetizations, random magnetic reorientations of the total material in your transition regions.

DR. COSTAIN:

Yes, the total material, of which I think the shields are the most important. But speaking really not of the shielding but of the shields themselves, we have found, by monitoring along the length of the tube, really unexpected changes in the field.

DR. WINKLER:

But then I think we have arrived at the paradox that, if I assume your numbers are parts in 10^{15} for the long standard and parts in 10^{14} for a two-meter beam, a normal so-called commercial standard ought to be not better than parts in 10^{12}. And this is a little bit difficult to conceive.

I also think that these effects are not borne out by the experience with hydrogen masers, as I think Harry Peters has already hinted at. I feel there may be something else or a different kind of manufacturing.

Incidentally, that brings me to that question of terminology. Wouldn't it be better to not distinguish oscillators or clocks by the particular way in which their development has been financed, but by the difference in manufacturing. Here we talk about a laboratory device or industry-produced device, which I think is a more significant difference than to talk about commercial and .... I don't know what you would call the other one. I think the distinction is one that has to do with which way do you manufacture them because there are some individually built devices in an industrial environment that have performed exceedingly well. In fact, one-half of NBS-4 actually originated this way (by industry-production). Isn't that true, Dr. Hellwig?

DR. HELLWIG: (Nods affirmatively)

DR. WINKLER:

So I don't know. Regarding the contribution to the BIH, Dr. Costain does not read carefully enough the bulletins of the BIH because there is a hydrogen maser contributing to the BIH. And, believe it or not, it is at the Naval Observatory--with some interruptions, I must agree.

Regarding the phase noise curve that has been shown by you, Dr. English, isn't it true that all phase noise contributions coming from about the breaking point of your servo loop really are the crystal's and have no bearing whatsoever on whether this is a rubidium reference or cesium reference or hydrogen reference? Am I correct?

DR. ENGLISH:

Could I make a comment on it? You are correct. I think the problem is to do it in such a way that you don't add to the cost of the unit. And if you look at the rubidium, the cost that it adds to achieve that phase noise is pretty minimal.

DR. WINKLER:

Yes, but the industrially-produced cesium beam standards have a very good crystal oscillator also. The trouble is you don't see it because it is shielded so much by buffer stages for the purpose of avoiding external interference signals going into the transition region; and this would indicate to me that your rubidium does not have this kind of buffering.

MR. PETERS:

Could I just comment on one thing? I just wanted to mention there is one little difference in crystals in a hydrogen maser rather than the passive device. A passive device that gets a glitch in phase on the crystal will not recover because it is a passive resonance. A hydrogen maser has an active lock on a crystal and it will recover in an infinitesimal amount of time any phase lost. So there will be a difference in the statistics of your results.

MR. JECHART:

Dr. Winkler, about your comments on phase noise in cesium devices. Perhaps I do not understand what you are saying because the servo loop time constant is much larger for cesium than for rubidium. For example, our rubidium has a loop time constant of 100 milliseconds. This means that for times shorter than 100 milliseconds the stability is due to the crystal, and for longer times it is due to the rubidium. And in cesium I know that the loop time constant is selectable, either 1 second or 50. So even if you use a very good crystal, you still have an influence from the cesium tube, and this is the reason why it is . . . .

DR. WINKLER:

Exactly, but I was talking in the frequency domain and talking about frequency offsets larger than 10 Hz or 100 Hz.

MR. JECHART: Yes, this is the crystal....of course.

DR. COSTAIN:

Just one final word on the magnetic domains. I think in the industrially-produced standards, you certainly do have effects that are a part in 10^{12} or larger if they are not very carefully degaussed. And I was pointing out that this scale factor is a cubic one and that you can run into trouble awfully quickly if you don't expect it. You have got to be much more careful in the degaussing and, in fact, in the construction of your shields, which might be easier in one type of device than another, and determine if a weld or riveting or seals might seriously influence the device once it gets small. If you are a foot away, it doesn't matter.

DR. HELLWIG:

Yes, I was just reporting one result on NBS-4, which is half a meter long, a little shorter than your present CsVI, A,B,&C. If I remember right, our magnetic field limitations are below the 10^{-14} level in that device. We know that from measured data. Are there any more questions, comments?

MR. SAM WARD, Jet Propulsion Lab:

I have two questions and one comment. In listening to the relative performance there, it appears to me that with hydrogen masers and cesium, it's think big, and for rubidium and crystal, small. So, based on relative performance, per unit volume, the rubidium is the clear winner.

Now for the question. Has anyone for the crystals considered using the separate cuts of crystals in a mixed device, using a crystal that is most favorable for the long-term performance to slave to a device that has the good short-term?

And the second question, addressed to Harry Peters, that those of us using hydrogen masers in a widely dispersed net have a great need for better accuracy because the cost of establishing synchronization is really a heavy burden.

DR. BESSON:

Well, I think that the answer to the question for quartz crystal is that this possibility has been demonstrated. That is at least what we can say. For instance, by just using the crystal that was driven at--that was some years ago--low power for long-term stability and run one at higher power for short-term. But now we do have some better things to do with two crystals. And I think it has been demonstrated; you simply have to make it in a very smart way.

DR. HELLWIG: Harry, do you have a comment?

MR. PETERS:

Well, I think certainly hydrogen masers at deep space networks and so forth, systems like that, will make a contribution to the basic reproducibility of the frequency at the stations. Of course, we still have to establish epoch, but you won't have to resynchronize so often. I thank you for your comment on the need for hydrogen masers.

DR. HELLWIG:

Maybe I should insert a comment here. There is a need for, as I call it, syntonization. It means equal frequency, and we normally assure equal frequency by electromagnetic signals or by portable clocks, which are really time difference measurements over time intervals. And I think we are coming to grips with the possibility of establishing from scratch a frequency with very high accuracy. And I think the hydrogen maser may be the first choice, at the moment at least, to carry frequency around. Not with an operating device: turn it off, ship it, turn it on, and it is within certain narrow limits, I think. What would you say the limits may be? Turning it off and then on again; that is, reproducibility?

MR. PETERS:

Oh, I think we have basic intrinsic reproducibility in principle. It depends on whether you have an autotuned device or one without all the sophistication you might want to put into it.

DR. HELLWIG: What is technically feasible? What is the number?

MR. PETERS:

Oh, I think our hydrogen masers will reproduce in the range of at least parts in 10^{13}.

DR. HELLWIG: That is very conservative, I think.

MR. PETERS:

Well, I don't want to take any biased or unconservative stand. Thank you.

MR. WARD: What I meant was absolute accuracy.

MR. PETERS:

Oh, it depends upon whether we are talking about intrinsic reproducibility or reproducibility like we compare the frequency here and then we compare it after it is turned on. And that might be better than the one I gave.

DR. HELLWIG: Excuse me. How do you define absolute accuracy?

MR. WARD: In traceability, for instance, to A1.

DR. HELLWIG: You mean in terms of time or frequency?

MR. WARD: Frequency, syntonization.

DR. HELLWIG:

Okay, but you mean in reference to some established standard, in which case reproducibility would be sufficient?

MR. WARD:

Yes. For instance, in our net we have to maintain so many parts accuracy. And the length of time over which we have to maintain this is longer than we can keep a single unit working. And so when we bring in a replacement unit, we have to go through the arduous process of resyntonizing, which takes weeks.

DR. HELLWIG:

But would you agree that essentially a reproducible device is adequate if it does over its lifetime basically the same thing (in frequency)?

MR. WARD: Yes. You expressed what I meant, but Harry didn't.

DR. JACQUES VANIER, Laval University:

I would like to make just a few comments here. We have heard about this progress going on in all these fields: quartz, rubidium, hydrogen, cesium. Now this depends somewhat on the scientific interest at the moment, and I was surprised to see today a paper on the rubidium gas cell. And it gave some new evidence that we could control things that people accepted in the past as uncontrollable. They all said, "Well, we have a light shift and that is it. We live with it." And now we see somebody who comes out with the ideas or maybe applies ideas that were old. They were coming from 1960 and we come back to it.

Now the same thing in quartz. These things are all going in parallel and all going further. And it depends quite a lot on the scientific interest of a person like Dr. English, like Dr. Besson, and like Harry Peters for hydrogen masers.

Now let me say something about hydrogen masers. About more than ten years ago, I heard statements like the one you made. The statement: If we had put at the time, ten or twelve years ago, the amount of effort that they have been putting in cesium, you would see where we could have been now. Now where did we go wrong, Harry?

MR. PETERS:

I don't think the ball is in our hands as a matter of fact. As I recall, there were some statements in various meetings about the necessity of making a profit, and some of the research had to be done by selling devices. So whoever got devices at that time got research-built devices.

I don't know of any further enthusiasm in the private area for pursuing this. Now I don't know whether we went wrong. Perhaps some of us should get out of the laboratory; perhaps some of us should stay in it.

DR. HELLWIG:

I am getting signals that the bus is waiting and I apologize for discontinuing the discussion. I would like to thank the panel and the audience for this lively discussion.