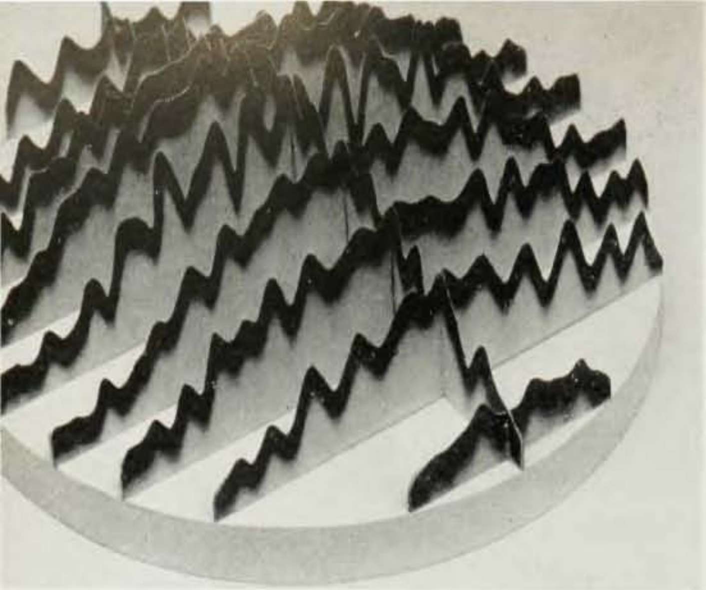

rain model of a circular quartz crystal plate vibrating in its ındamental thickness shear mode at 3 mc. Height of the patrn is indication of strain amplitude existing in that particular cation. Model by H. Fukuyo.

# FREQUENCY CONTROL SYMPOSIUM

*A Report by* ***G. K. Guttwein*** *and* ***H. H. Plotkin***

ON May 12, 13, and 14, 1959, the Thirteenth Annual Frequency Control Symposium sponsored by the Frequency Control Division of the US Army Signal Research and Development Laboratory was held at Asbury Park, New Jersey. Besides 700 participants of industrial, educational, and governmental organizations from the US, the Symposium was attended by a sizeable number of engineers and physicists from foreign countries, many of them participating actively in the discussions. Representatives of Canada, England, the Netherlands, West Germany, and Japan also presented papers. The Symposium covered the physical and technical aspects of frequency control with a high degree of completeness. Subjects under discussion ranged from a consideration of how the aging of the universe may affect gravitational and atomic time scales to a report on a mechanized plant for producing quartz crystals.

The two methods generally employed for obtaining precision frequency control today are use of mechanical resonators and use of atomic or molecular transitions. The latter method is more recent and in general of more interest to the physicist. In previous issues of this magazine (June 1956, December 1958), therefore, the reporting on the Frequency Control Symposium was restricted to this phase. The mechanical resonator, however, and particularly the old work horse of frequency control, the quartz crystal, is still of greatest practical importance, and not completely without its share of intriguing unanswered physical questions.

Since crystals have been used for approximately forty years, the opinion is common that all physical and engineering problems connected with them must have been solved by now. This is not true. The continuously stiffening requirements on the precision of frequency control elements to be used in modern communication and navigation systems and in space probes present a variety of such problems and require a much better understanding of basic phenomena whose study had been neglected in the past. An active research program is now being carried out by many laboratories in connection with quartz crystals, their basic properties, and their application. This program is supplemented by development and production activities. All these different phases were covered in the meetings; however, only some of those topics which are of particular interest to the physicist will be mentioned here.

In present-day applications, two types of quartz crystals are used, the naturally quarried and the synthetically made. The quartz synthesis program was originated by the Signal Corps in 1946 to create domestic sources for a strategically important material. The program has now reached a state at which synthetic quartz is competitive with the natural material. It can be expected that it will be used in steadily increasing quantities in the future. This was pointed out in the papers by R. A. Laudise of Bell Telephone Laboratories and C. B. Sawyer of Sawyer Research Products. Laudise has conducted a systematic study of quartz growth rates which enables him to grow quartz under a variety of conditions either for meeting production requirements or for scientific studies.

Although the synthetic material is perfectly adequate for 99 percent of all resonator applications, the interesting fact remains that synthetic quartz is still inferior for use in the highest precision frequency standards

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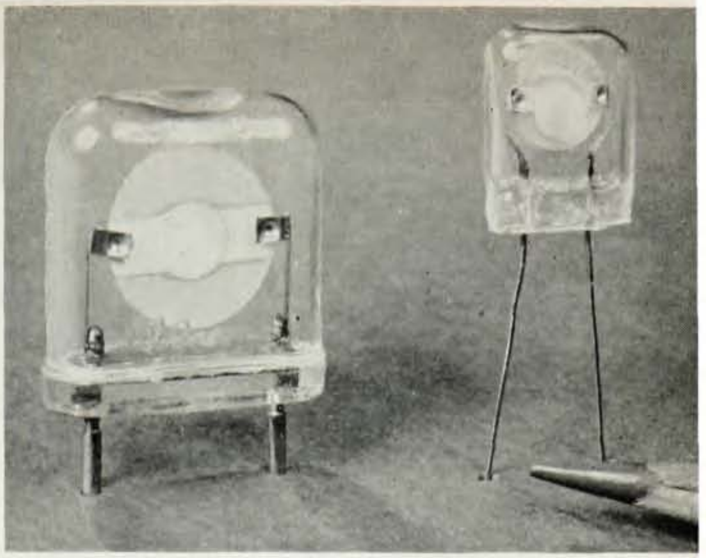
because of greater internal friction and a higher aging rate. The reasonable thought that synthetic material grown under carefully controlled laboratory conditions ought to be more "perfect" than its counterpart grown under the variation of conditions offered by nature is obviously too simple to cover the actual facts.

The difference in the behavior of natural and synthetic quartz is probably related to defects in the crystal structure. Two papers on that topic were presented. R. A. Weeks of Oak Ridge National Laboratory investigated the defects in neutron irradiated quartz by means of electron spin resonance. J. C. King of Bell Telephone Laboratories is studying the nature of imperfections by analyzing the anelastic processes induced by such imperfections. To determine the internal friction, he measures the quality factor ($Q$) of carefully prepared resonator samples. He reported on mechanical relaxation losses occurring at temperatures down to liquid helium in different specimens of synthetic and natural quartz. Some of his samples had been subjected to x-ray irradiation, others to a static electric field at elevated temperatures.

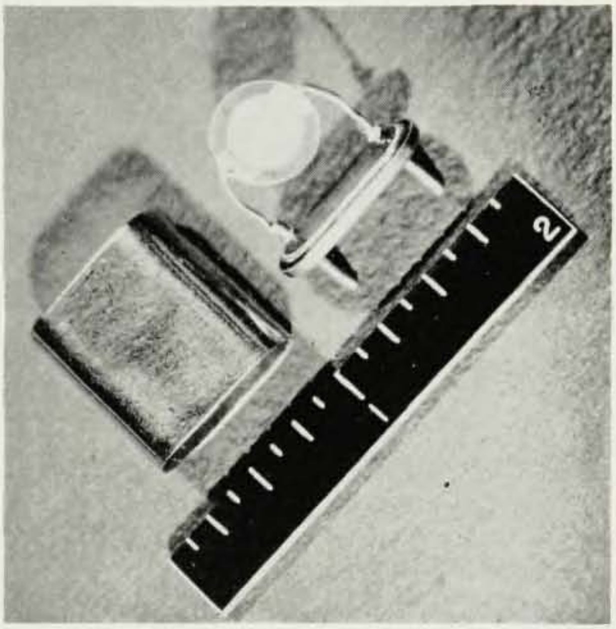
In frequency control applications, the quartz crystal is used as a mechanical resonator, the motion of which is extremely complex. In spite of this, many attempts have been made to describe it analytically. The most important resonator shape is the circular plate since that shape is the one most frequently used. A solution of the equations of motion for an infinite isotropic plate was published by Rayleigh in 1889. To extend that to finite anisotropic plates presents formidable mathematical difficulties. R. D. Mindlin of Columbia University is working on this and associated problems. He was able to obtain solutions for the extensional vibrations of circular quartz plates for four distinct crystal cuts. That these cuts are of little practical use does not restrict the value of Mindlin's analysis. It can be expected that he will be able to find solutions for the more commonly used crystal cuts by a modification of his method in the not too distant future.

Experimental studies of the modes of vibration of quartz resonators have also been conducted by a number of investigators. I. Koga and H. Fukuyo at the University of Tokyo have developed semiautomatic equipment for obtaining records for the spectral response and the distribution of polarization of vibrating quartz plates. Fukuyo is at present at the Georgia Institute of Technology and is using his equipment there. A. E. Rhodes of Georgia Tech described the equipment and showed mode and polarization patterns of circular quartz plates. The particular feature of this equipment is its high resolution. The pick-up probe has a diameter of only 0.3 millimeter.

One of the problems that has bothered the crystal physicist for a long time is the question of aging. All quartz crystals change their frequency with time. Although for the highest precision standards these changes can be made extremely small—fractional variations on the order of $10^{-10}$ per month have been achieved recently by Bell Telephone Laboratories—aging is still



Two glass-enclosed crystal units of standard and mini[a] size. This design will gradually replace the units in metal




A 54-mc ruggedized crystal unit of the type used in the Explorer satellites.

there and, according to the nature of things, is usually unpredictable. The great advantage which the atomic standards have is that they are free from this deficiency. Since practical atomic standards are now available and can be used in most applications for which extreme constancy of frequency or time is required, the question could be asked, "Why bother with the quartz standard at all?". There are several reasons why quartz oscillators are necessary. Most of the atomic standards need a quartz standard as a "flywheel". Furthermore, when only moderate precision is needed, no atomic standard can compete in terms of cost, simplicity, and size with a simple crystal oscillator which, if necessary, can be condensed to the volume of a book of matches. Such oscillators have been used and will be used in large quantities in many types of equipment. The equipment engineers, however, are continuously asking for a better frequency stability. This requires improvement of the aging behavior of the standard crystal units.

It was shown in two papers by R. B. Belser of Georgia Institute of Technology and P. E. Mulvihill of the Signal Corps, that the metal cans used in the present-day standardized crystals are largely responsible for the high aging rate of these units. An equal number of identical crystal plates was put in metal cans and in evacuated glass holders. It was shown that the glass-enclosed crystals had a much lower and more predictable aging characteristic. It can be expected that future standardized military crystals will be glass enclosed and that an aging rate of better than five parts per million per year can be achieved for mass produced units.

In addition to improving the standardized military units, investigations are also underway to reduce the aging rate of the highest precision crystals. Experience shows that increasing the temperature accelerates aging; cooling the crystal then should reduce it. Investigations on the aging of crystals at liquid nitrogen and liquid helium temperatures were reported by P. E. Simpson of the Boulder Laboratories of the National Bureau of Standards. Aging seems greatly reduced at low temperatures. Further observations and refinements of the system, however, are necessary before definite conclusions can be drawn. An interesting observation was reported in regard to short-time stability. A 5-mc crystal oscillator with the crystal operating at liquid helium temperature gave the best short-time stability ever observed with a crystal oscillator at the NBS Laboratory. The tests were made by comparing the crystal oscillator with a maser which has an extremely good short-time stability.

The reasons for the better short-time behavior could be that the $Q$ of the crystal is higher at liquid helium temperature and that the thermal noise generated in the equivalent crystal resistance is much reduced. The question as to what factors contribute to short-time instability of crystal oscillators is wide open and calls for a systematic investigation. More questions on this topic were asked in the discussion than could be answered.

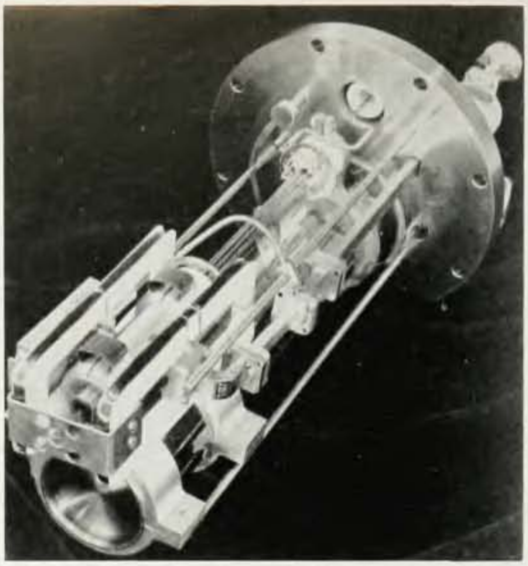
ANOTHER field in which new and stiffer requirements make further investigation mandatory is the area of vibration and acceleration stability of crystal oscillators. The Frequency Control Division was able to design, mostly on an empirical basis, a ruggedly mounted crystal unit for satellite applications which has been used successfully in all the Explorer satellites. The main feature of this design is its vibration resistance. The problem of making the crystal less susceptible to static accelerations is under study by A. W. Warner of Bell Telephone Laboratories who gave a report on highly stable crystal oscillators for missile applications. By using a stiff crystal plate in a rugged mount, he was able to keep mechanical deformation due to external forces small. To balance the body forces, the crystal plate was made as symmetrical as possible. The acceleration dependency of frequency was studied in a centrifuge under accelerations as high as 60 $g$'s. The frequency acceleration coefficient of Warner's best crystal was $2 \times 10^{-10}$ per $g$ or better for all orientations in the plane of the crystal plate and $3 \times 10^{-10}$ per $g$ for directions of acceleration perpendicular to the crystal plate.

Although these experimental studies are essential for serving urgent practical needs, they must be supported by more fundamental theoretical investigations as to the reasons that a vibrating crystal plate changes its frequency under the influence of external mechanical forces. A first approach in that direction was presented by L. Dick of James Knights Company who had conducted an analytical investigation in collaboration with P. Cheo. Their analysis is based on the fact that an externally generated stress will change the thickness and the density of the crystal plate. This then must result in a change of its resonant frequency. It is felt that the next step in advancing the theory should be a more general approach which will also assume a change of the elastic moduli due to externally induced strain.

The technical aspects of developing, producing, and measuring the higher precision crystal units required by today's stiffened specifications were discussed in detail by a number of speakers. From J. C. B. Missel's report (N. V. Philips Company, Eindhoven, Netherlands) it became apparent that Western Europe is confronted with about the same technical problems and has developed similar, however not identical, methods for solving them.

Among the papers dealing with future trends in research and development, the one written by W. Victor of the Caltech Jet Propulsion Laboratory considered the frequency control requirements necessary in future communications systems for space vehicles. If the available transmitter power, antenna gain, and noise temperature are given, the communication range can only be increased by reducing the receiver bandwidth. To cover the range of our solar system, as far as Pluto, the JPL calculations require a bandwidth of 10 cycles per second. If communication to the nearest star over a distance of four and a half light years should be attempted, the JPL design calls for a bandwidth of 1/1000 cps. This would require both a short- and long-time frequency stability of $10^{-12}$ which seems beyond the state of the art of either quartz crystals or atomic standards and presents a challenge to the frequency control field. It can be assumed, however, that the frequency control experts will not lose much sleep because of this. Tremendous technical problems in other fields must be solved before a space probe towards Alpha Centauri can be launched.

The thoughts of trips to outer space, while fascinating, therefore do not constitute the only immediate impetus to research and development work on atomic frequency standards. As the techniques have developed, so have the many earthly applications: narrow-band communications, precise tracking and navigation sys-



The working parts of a Signal Corps experimental ammonia maser showing quartz cavity and magnetic coils used for setting the cavity to the ammonia frequency.

tems, synchronization of clocks, etc. The number of papers devoted to this subject was such that one and a half days were spent in discussion of various aspects of atomic timekeeping.

In the interval since our last report, the Signal Corps was able to subject the existing commercial cesium beam standard to some fairly grueling tests. For example, in a report by G. Winkler the integrated outputs of several independent standards were compared with a differential clock in order to observe the differences in accumulated phase over longish periods. In the best of these runs, two "Atomichrons", whose rates had been adjusted to be as equal as possible, were found to have deviated at no time by more than 1 microsecond after 63 hours. This discrepancy is a fraction of a part in $10^{11}$ of the measured time interval! The general experience has been that little understood excursions in frequency occur, amounting to parts in $10^{11}$ when averaged over times on the order of one minute, but these are mostly random and may average out to less than that over runs hours long.

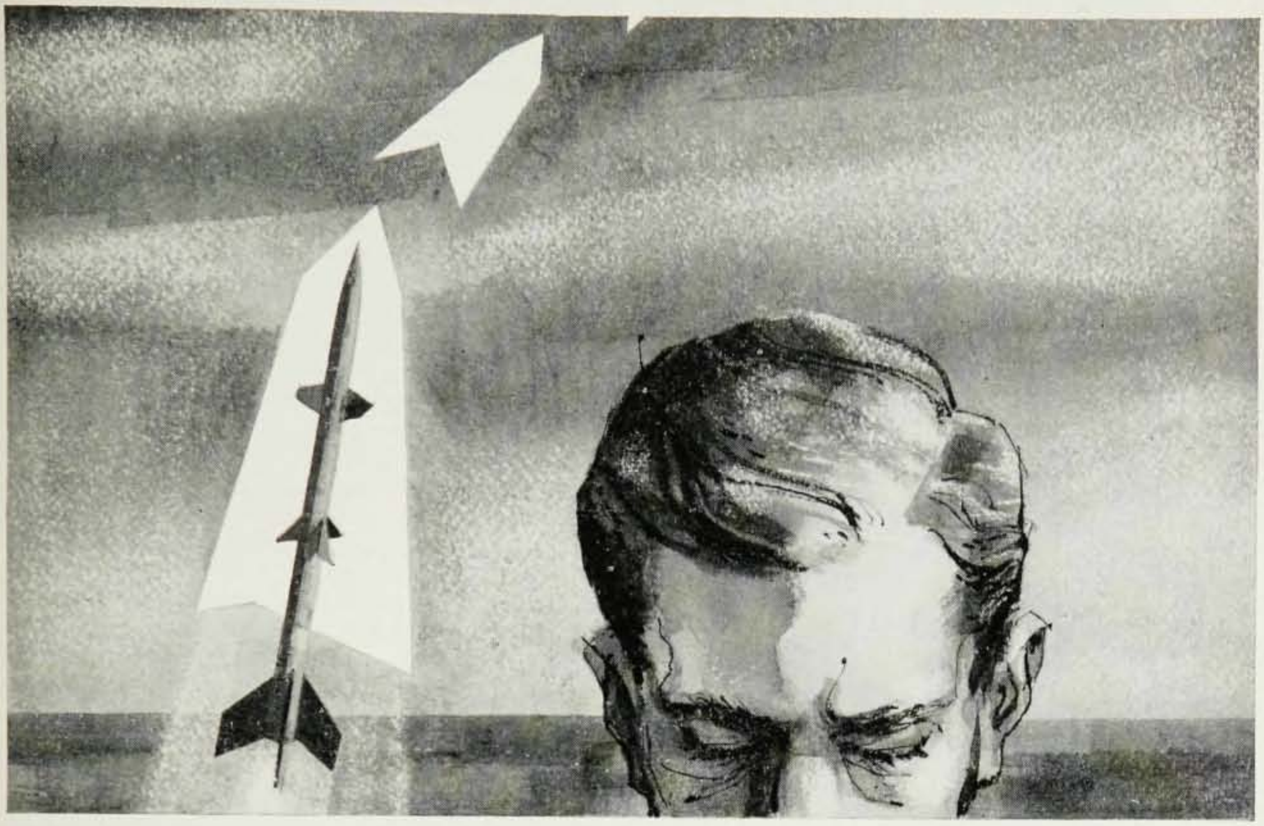
To improve the reliability and performance of atomic beam frequency standards, National Company is continuing their development as described by A. McCoubrey. The geometry of the microwave structure has been changed so as to present to the flying atoms an interaction field free of asymmetries, likely to change with time, and the microwave source has been simplified for greater reliability and reduction of sidebands which also tend to distort the resonance. Both National Company and R. Daly of Technical Research Group described miniaturized airborne atomic beam standards. L. Essen of England's National Physical Laboratory reported that his laboratory is putting into operation a beam with an effective length of four meters, to give a resonance line width of 50 cycles/sec and corresponding increase in precision.

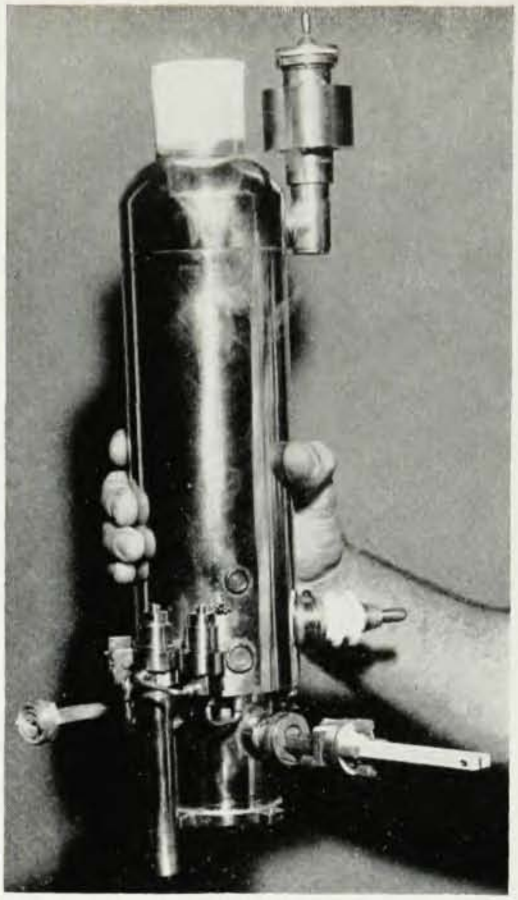
A different approach to higher precision in atomic beams is being followed in N. Ramsey's laboratory at Harvard University in the "broken atomic beam experiment" reported on by D. Kleppner. Instead of lengthening the beam to increase the microwave interaction time, the idea here is to store the atoms in a box midway through the interaction structure. The walls with which the atoms collide must be inert with respect to relaxing the hyperfine states. The results that were reported on teflon and polyethylene indicated that a narrowing of the resonance line could indeed be found, but not as much as was expected, accompanied by a shift in the center frequency of the resonance, the origin of which is unknown.

As announced by W. M. Markowitz, a very flattering degree of respectability was accorded to atomic frequency standards when, on January 1, 1959, the US Naval Observatory placed in operation a system of Atomic Time, denoted A.1. This was done after carefully measuring, in terms of a second of Ephemeris Time, the mean cesium frequency given by a number of standards in the United States and England. The value is 9 192 631 770 $\pm$20 cycles per second (of E.T.). The designation A.1 allows for a future redetermination of this number. A system of Atomic Time, denoted TA.1, has also been placed in operation in Switzerland, based upon an ammonia maser oscillator at Neuchâtel whose particular frequency is assumed to be 23 870 128 870 cycles per second (of E.T.).

Masers have also achieved prominence in quite another way. It has been calculated that a Doppler shift in the frequency of the oscillator should occur if the maser is moving with respect to an ether. A sort of Michelson-Morley experiment was repeated at IBM's Watson Laboratory by J. Cedarholm in which two masers with oppositely directed beams were compared, and turned with respect to the earth's motion. From the absence of changes greater than 1/50 cps in the frequency, it was concluded that the maximum ether drift, if any, is less than 1/1000 of the earth's orbital velocity.

The development of high-precision maser oscillators as frequency standards was reported by five laboratories. These instruments now seem capable of maintaining stabilities for a few hours to within several parts in $10^{11}$, as reported by R. Mockler of the Boulder Laboratories of the National Bureau of Standards, provided the cavity is very carefully temperature stabilized ($\pm$.001°C) and other parameters are controlled. A similar stability has been achieved by F. Vonbun at the Signal Corps over a wider temperature range ($\pm$2°C) by using a quartz cavity near a temperature for which the expansion coefficient goes through zero. A small portable package built at the Signal Corps to provide a missile tracking signal contains a 300-mc transmitter locked to a maser output, capable of operating continuously for several hours. It was shown in a paper by F. Reder that even under missile blast-off conditions, the frequency would be maintained to better than 5 parts in $10^{10}$. J. F. Lotspeich reported that





Prototype model of missile-borne maser oscillator at the Signal Corps Laboratories. Sealed off and self-contained, except for small power supply, it can provide clean $k$-band signal for several hours before requiring additional liquid nitrogen to maintain vacuum.

the Hughes Aircraft Company is considering the use of this type of device as timekeeper in a satellite designed to measure the gravitational "red shift". In this connection, J. R. Zacharias of MIT presented a stimulating discussion of his ideas concerning the synchronization of clocks on earth through the use of a satellite. He developed the thesis that the gravitational "red shift" could even be measured with a satellite transmitter controlled by a precise quartz crystal oscillator. The variation in the oscillator's rate when travelling in a highly eccentric orbit should be measurable over the normal drift rate of the crystal.

The National Bureau of Standards, on the other hand, is pursuing the development of a gas cell frequency standard for the "red shift" experiment. A considerable amount of work on gas cells has been done in several laboratories, employing either rubidium or cesium as the reference atom. In the gas cell, the alkali atoms are "optically pumped" preferentially into one of the ground state hyperfine levels by illuminating them with light from an alkali vapor discharge lamp. When the reference microwave transition occurs, the optical properties of the vapor change, offering a very convenient detection mechanism for the resonance. The vapor cell must also be filled to an "optimum" pressure with an "optimum" mixture of so-called buffer gases, such as the rare gases. These serve to increase the time of diffusion of the radiating atoms to the walls, increasing the effectiveness of optical pumping and reducing the resonance line width. E. C. Beaty reported that lines as narrow as 20 cps have been achieved for rubidium in a neon buffer at 1–10 cm Hg. The difficulty here is that through their collisions some of the buffer gases increase the resonance frequency of the alkali atom while others decrease it. This results in a dependence upon pressure and temperature which is most unwelcome in a frequency standard.

It seems, however, that by properly choosing and controlling the buffer gases, one can build a gas cell standard which will rival the present atomic beams in stability. At the ITT Laboratories a controlled oscillator has been built on this principle by M. Arditi and it shows an apparent long-time stability of 1 part in $10^{10}$. Thus, although the gas cell will probably be a secondary standard requiring calibration, its small size, ruggedness, and high stability will make it valuable. Only experience can make this statement a certainty. Many tests must be performed over extended periods to uncover possible slow drifts of the resonance frequency due to changes in the pressure and composition of the buffer gas.

With a continual narrowing of the available atomic resonance lines, we must very soon put our attention to developing microwave sources with even cleaner spectral purity with which to probe them. The observed line can obviously be no narrower than the spectrum of the field which is used to examine it. Considerable discussion was devoted to the noise created in crystal flywheel oscillators and in frequency multipliers. Advances in precision frequency control, therefore, continue to remain dependent upon an active research program in crystal physics.

The establishment of an atomic time scale alongside the astronomical ones naturally suggests the question as to whether or not one would expect them to diverge with time, and whether this could be observed. R. H. Dicke of Princeton University discussed this possibility. According to some arguments put forth by Dirac and others, the gravitational constant might vary inversely as the age of the universe. The rotation of the moon, planets, and artificial satellites, and therefore our gravitational time scale, would be expected to slow down with time. On the other hand, we do not expect the atomic constants which determine the hyperfine transition frequencies to depend in the same way on age. If these assumptions have some validity, then the period of a high-flying satellite, as measured with an atomic clock, should show a secular increase with time amounting to perhaps $10^{-10}$ per year, and in addition a small periodic term due to the orbital motion of the earth about the sun. Techniques of both satellites and atomic clocks should soon be at the point where some of these notions can be checked.