silica and some other (unknown) material. A brief search suggested that the non-volatile (at 1,700° C.) constituents of ordinary shale would form a suitable 'unknown' material, and in Table 1 we give the chemical composition resulting from such a mixing process with a quartz : shale ratio of 1 : 3. Column 2 of the table must be compared with column 3, which gives the average tektite figures. The agreement is seen to be excellent, and it seems evident that a hypothesis that tektites are derived from a shale–quartz mix will explain the major element compositions of tektites. Shale and quartz are both extremely common terrestrial materials, and lack of availability will present no problem. The question of the mechanism of the mixing process remains. In this connexion we can present no evidence, though the Urey comet hypothesis[2] still seems to us to be a promising theory.

Table 1. COMPARISON OF COMPOSITION OF TEKTITES WITH THAT OF A MIXTURE OF SiO_2 WITH THE NON-VOLATILE (AT 1,700° C.) CONSTITUENTS OF SHALES

	1	2	3
SiO_2	64·32	73·24	73·73
TiO_2	0·72	0·54	0·86
Al_2O_3	17·05	12·79	12·47
FeO	6·72	5·04	4·92
MgO	2·70	2·03	2·12
CaO	3·44	2·58	2·50
Na_2O	1·44	1·08	1·32
K_2O	3·59	2·69	2·32
Total	99·98	99·99	100·24

Column 1. Composition of average shale from Pettijohn[3] (Table 61, p. 344) recalculated to 100 per cent following removal of water, carbon dioxide, SO_3 and organic matter.

Column 2. Composition of a mixture of three parts of column 1 with one part of silica.

Column 3. Average composition of 61 tektites from Barnes[4]. The analyses of Darwin glass and Libyan Desert glass quoted by Barnes[4] are excluded from this average.

The above results will be published in greater detail elsewhere, and discussed more fully.

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PHYSICS

A Comparison of Atomic Beam Frequency Standards

STANDARD frequencies obtained from various cæsium atomic beam frequency standards have been compared in a number of instances[1–4]. The results of Holloway *et al.*[1] showed agreement to about 2×10^{-10} between the commercial beam standards developed and manufactured by the National Company and the atomic standard at the National Physical Laboratory, Teddington, England[4].

Two dissimilar beam standards at the National Bureau of Standards have been compared over the past several months. Their frequencies agree to within $\pm 1 \cdot 5 \times 10^{-11}$ (standard deviation of the mean for the comparisons and estimated uncertainty due to effects of pertinent parameters).

These machines employ Ramsey-type excitation, the separation of the oscillating fields being 55 cm. in one case and 164 cm. in the other. Beam dimensions are 0·003 in. × 0·100 in. and 0·015 in. × 0·187 in., respectively. The hot wire detectors (20 per cent iridium–platinum alloy) are used in conjunction with conventional electrometer circuits. Typical signal-to-noise ratios range between 100 and 400. The uniform magnetic C field in the transition region is produced by passing a d.c. current of about 1 amp. through a conducting section of a cylindrical brass tube contained within a magnetic shield. A double shield is used on the longer machine and a single shield on the shorter.

There are a number of uncertainties in absolute frequency measurements introduced by the measuring devices themselves. Those effects contributing most significantly to the overall uncertainty of the measurements are: (*a*) the magnitude and non-uniformity of the C field; (*b*) a phase difference between the two oscillating electromagnetic field regions; (*c*) a lack of purity of the electromagnetic field exciting the atomic transition.

The magnitude of the C field was determined in four different ways: by calculation from the known geometry of the conducting strip and the current used; by direct measurement using a rotating-coil fluxmeter sensitive to 0·002 oersted; by measurement of the low-frequency $\Delta F = 0$, $\Delta m_F = \pm 1$ transitions which are strongly dependent on the magnitude of the field; and by measurement of other microwave transitions, such as the $(F = 4, m_F = 1) \leftrightarrow (F = 3, m_F = 1)$ transition, which are more sensitive to the field than the standard frequency transition. The uniformity of the C field was determined by measuring the low-frequency transitions, utilizing small coils located at each end of the resonant cavity and at the centre of the transition region. These localized field measurements indicate that the maximum C field variation along its length is $\pm 0 \cdot 002$ oersted. This non-uniformity can introduce at most an uncertainty of 4×10^{-12} in the measured frequency. At the time of the initial comparisons of the two standards the values of the C field magnitude as measured by the different methods agreed to within the precision of the measurements ($\pm 0 \cdot 002$ oersted) for both machines. Since that time, however, the shielding properties of the mumetal shields have deteriorated to some extent, accompanied in the case of the longer machine by a discrepancy among the various types of field measurements of about 0·004 oersted at a field of 0·080 oersted. In order to reduce the resulting uncertainty in the frequency measurements to below 1×10^{-11}, smaller C fields (about 0·020 oersted) have been used in the more recent comparisons. Possible frequency shifts arising from the nearness of other transitions at these low fields have been calculated and found to be well below 1×10^{-11} for the degree of symmetry of position and amplitude observed for the nearby transitions.

The oscillating fields exciting the $(F = 4, m_F = 0) \leftrightarrow (F = 3, m_F = 0)$ transition are produced at the two ends of a single resonant U-shaped rectangular cavity operating in the $TE_{0,1,60}$ mode for the shorter machine and in the $TE_{0,1,100}$ mode for the longer machine. The cavities were precisely electroformed for symmetry about the coupling hole to the microwave transmission line from the frequency multiplier chain. The atomic beam grazes the shorted end walls of the U-shaped cavity. Provision for tuning the cavities in the event of large room-temperature changes is provided by a tuning plunger opposite the coupling hole.

Frequency uncertainties introduced by a phase difference between the two ends of the cavity were investigated by rotating the cavity 180°, that is, by interchanging the two oscillating field regions. No frequency shift was measurable under this operation for either machine.

If the electromagnetic field exciting the transition is not pure, that is, if this signal is frequency modulated, rather large frequency uncertainties are possible in the measurements. The exciting radiation is ordinarily produced by frequency multiplication by a factor of 1836 from a stable quartz crystal oscillator. Side-bands in the power spectrum introduced in the oscillator or first stages of the frequency multiplier chain are enhanced significantly by the multiplication process. What is worse, side-bands resulting from frequency modulation are not, in general, symmetrically placed about the 'primary' signal. The power spectrum of the exciting radiation for the Bureau standards was examined using an ammonia maser stabilized frequency multiplier chain as a spectrum analyser[5]. The signal was found to have a bandwidth of about 6 c./s. at 9,000 Mc./s., was symmetrical and contained no observable side-bands. Any shift introduced from this source would be much less than the precision of measurement. In general, however, side-bands will be present to some extent. In one experiment where side-bands were deliberately introduced, the measured frequency was shifted by 3×10^{-9}.

The effects discussed above are those that we consider to contribute most significantly to the uncertainty of absolute frequency measurements if adequate care is not taken in construction and testing. We have found it possible to reduce these uncertainties to a level below 1×10^{-11}.

Initial comparisons of the two standards were made during a ten-day period with each daily comparison consisting of an average of from 15 to 25 measurements with each standard. If $\Delta\nu_i$ denotes the zero-field frequency difference between the two machines for the ith day, then the measured average difference for the ten-day period was:

$$<\Delta\nu>_{av} = \frac{1}{n}\sum_{i=1}^{n} \Delta\nu_i = 0, \text{ where } n = 10$$

The standard deviation of the mean for this particular test was:

$$\sigma_M = \frac{1}{\nu}\left[\frac{\sum\limits_{i=1}^{n} (\Delta\nu_i - <\Delta\nu>_{av})^2}{n(n-1)}\right]^{1/2} = \pm 1{\cdot}6 \times 10^{-11}$$

The estimated uncertainties introduced by the effects discussed above fall within this precision. During later tests on the standards a more complete set of comparisons was obtained consisting of 18 separate comparisons taken over a period of one month. The average zero-field frequency difference for this period was 9×10^{-12} with a standard deviation of the mean of 6×10^{-12}. To this standard deviation was added the maximum uncertainty in frequency contributed by the C field (9×10^{-12}), giving $\pm 1{\cdot}5 \times 10^{-11}$ as the limits quoted for the agreement of the two machines. The uncertainty introduced by the discrepancy in the C field measurements noted above was reduced to less than 1×10^{-11} by using low fields. Since this discrepancy seems to be associated with a noticeable deterioration of the C field shielding, it is likely that for most precise results the shields will have to be exchanged periodically for newly annealed ones.

One indication of the reproducibility of measurements made with the longer machine was obtained by comparing eight separate sets of measurements of 'Atomichron 106' during an 8-hr. period. Each set or sub-group consisted of 15 measurements taken in a period of about 15 min. The standard deviation of the mean for each sub-group was 1×10^{-11}, while the standard deviation of the mean for the average of all the results was 5×10^{-12}. A similar experiment was conducted in which an extremely low-drift crystal oscillator with its crystal immersed in liquid helium was measured instead of the 'Atomichron'. These measurements gave 7×10^{-12} as the standard deviation of the mean for each sub-group and 2×10^{-12} as the standard deviation of the mean for the average of all the results taken during the period of several hours. The various parameters affecting the frequency measurements, then, are sufficiently constant that measurements can be made to a precision of 2×10^{-12} in periods of several hours or longer; however, uncertainty in the exact values of some of the parameters limits the accuracy to about $1{\cdot}5 \times 10^{-11}$.

The longer of the two machines is the present United States Frequency Standard. The shorter machine is an alternate standard[3]. The frequency assumed for the $(F = 4, m_F = 0) \leftrightarrow (F = 3, m_F = 0)$ transition of cæsium in zero field is 9192631770·0 c.p.s. The best comparison between cæsium and Ephemeris Time at present is that given by Markowitz, Hall, Essen and Parry as 9192631770 ± 20 c.p.s.[6].

Corrections for the 60 kc./s. standard frequency broadcasts of Station *WWVB* (formerly *KK2XEI*), Boulder, Colorado, are made each week and are available upon request.

We believe that the experiments demonstrate that with adequate care in construction and testing, atomic beam standards can be expected to agree in frequency without special recipes in design, and indeed they behave precisely as one would predict from theory—one need only know the values of the pertinent parameters to sufficient accuracy. This information must be obtained from appropriate tests.

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