Since the size of the X-ray beam was too small to irradiate the specimen uniformly over its length, the composite resonator was mounted so that it could be translated vertically in front of the tube. The translational motion was obtained from a cam follower running on a motor-driven cam. The cam was cut so that the resonator moved up and down with a constant velocity, its period being about 15 sec. In this way the specimen could be irradiated uniformly without removing it from the composite resonator.

The resonator assembly was mounted in a light-tight, air-tight box containing a drying agent. X-rays were admitted through an aluminum-foil window. It was demonstrated that the presence of this window in no way influenced the formation of color centers in the specimen upon irradiation.

It was not possible to make resonant-frequency measurements during the course of irradiation because of the changing capacitance between the leads to the resonator and the light-tight box during the translation of the resonator. This capacitance change caused erratic readings on the vacuum-tube voltmeter connected to the gage electrodes. It was therefore necessary to turn off the X-rays and stop the translation of the resonator before each reading. Measurements of resonant frequency showed that the irradiation slightly perturbed the thermal equilibrium of the resonator, but that equilibrium was generally restored within a minute or two after the X-rays were turned off.

In order to irradiate a specimen at low temperature it was necessary to remove it from the resonator. The specimen was surrounded on three sides by coolant by placing it in a re-entrant cavity formed on the side of the copper box containing the coolant. This box had a volume of about one quart, and the cavity projected into the box about one inch. The coolant used was either liquid air or crushed dry ice. Radiation was admitted through an aluminum-foil window placed over the mouth of the cavity, the window serving to exclude both light and moisture.

For bleaching experiments a 4.5-amp carbon arc lamp was used as the light-source. A pair of glass condenser lenses and a water-cell heat-filter were included in the optical path. For bleaching at room temperature the specimen remained attached to the composite resonator, and the aluminum window of the dry box was replaced by a lucite one. No window was used to protect the crystal in the low-temperature box during illumination at low temperature; all water-vapor condensed at the mouth of the re-entrant cavity leaving the specimen completely dry.

3. EXPERIMENTAL RESULTS

General Character of the Radiation Effects

The effect of X-irradiation is to increase the modulus and to decrease the internal friction of NaCl crystals. The magnitude of the total change in modulus or in damping produced by irradiation is sensitive to the history of the individual specimen under investigation. Regardless of magnitude, however, both these properties respond to irradiation in the manner shown in Fig. 1. Here the modulus change is reported in terms of the change Δf_s in the resonant frequency of the specimen, and the internal friction as the decrement Δ_s. The resonant frequency generally decreases with increasing strain amplitude of vibration.* The frequency measurements reported in Fig. 1 (and throughout the rest of this paper), however, are measured at *low-strain amplitudes* where frequency is independent of amplitude. Fig. 1 shows that at the beginning of irradiation the changes in frequency and decrement are very rapid, but with larger X-ray doses the rate of change decreases, and eventually "saturation" values are reached. The decrement at large strain amplitudes is decreased by irradiation to the same final value as the decrement observed at small strain amplitudes, i.e. the damping becomes independent of strain amplitude, as was observed by Frankl.

The frequency and decrement changes resulting from X-irradiation are permanent at room temperature; after irradiation to saturation, neither of these quantities shows any tendency to return to its preirradiation value. Illuminating a crystal with white light after irradiation likewise has no effect on either the frequency or the decrement, in spite of the fact that such illumination bleaches out all of the coloration in the crystal.

The effects of irradiation on both the frequency and the damping represent changes throughout the volume of the crystal (in contrast to the hardness increase[6] which occurs only in a thin layer near the surface where soft X-rays are heavily absorbed). This is evident in the case of the damping merely from the fact that irradiation on one face of the specimen destroys all of the amplitude-dependent part of the damping. That the modulus increase is a volume effect is demonstrated by irradiating a crystal on one face until the frequency change is nearly complete, and then irradiating on the reverse face. For one of the NaCl specimens (No. 4) it was found, for example, that Δf_s after irradiating on one face for

* These changes are usually small compared to the change in frequency (at a given amplitude) produced by irradiation.

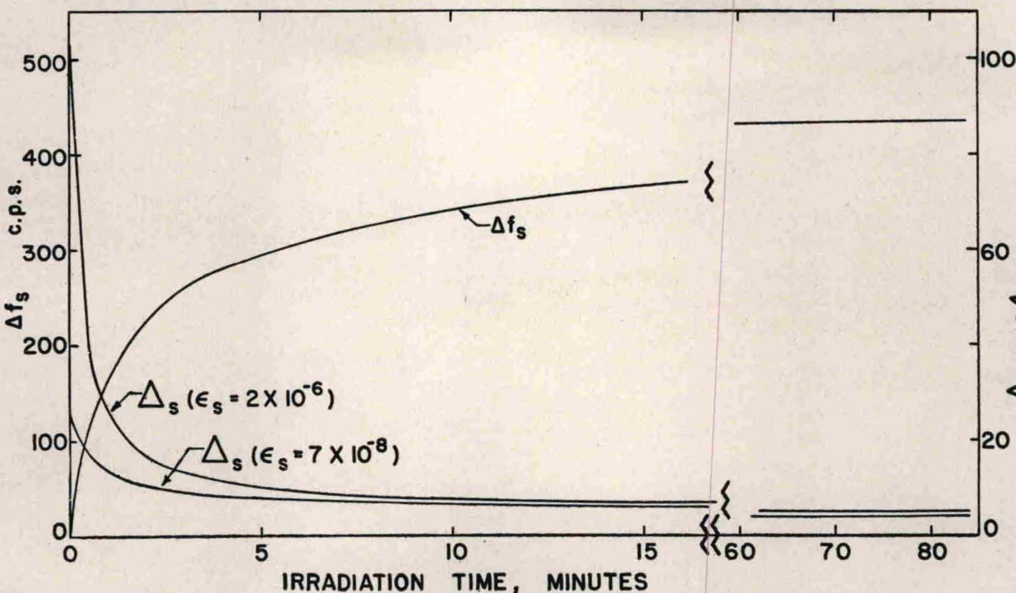

FIG. 1. Changes in resonant frequency, and in the decrement at two different strain amplitudes, of an NaCl crystal (No. 5) exposed to 39 kV X-rays. Experimental points were taken at time-intervals in geometric progression (viz. at 0.5, 1, 2, · · · min) and lie on the curves shown to within the thickness of the pen line.

50 min was 175 c.p.s., while irradiation on the back face to saturation produced an additional change of only 10 c.p.s. Further irradiation with higher-energy X-rays has no additional effect on the modulus, after saturation has been achieved with lower-energy radiation.

Additional evidence on this point is supplied by an experiment in which a crystal was irradiated through a thin NaCl filter. The filter crystal, 0.030 cm thick, was interposed in the X-ray beam in front of the specimen, and the resonant frequency and decrement measured as a function of dose. The filter is thick enough to absorb a substantial fraction of the incident X-ray intensity (particularly in the long-wavelength region). Nevertheless, the modulus and damping curves so obtained are completely equivalent to those obtained without a filter. This result shows that the changes in modulus and damping are produced throughout the volume of the crystal by the more penetrating (short wavelength) X-rays.

It is known that X-irradiation increases the length[12] and decreases the density[13] of rock-salt crystals, so that some question may arise as to whether the changes in resonant frequency observed in these experiments can be wholly attributed to modulus changes. First it should be noted that, for the present radiation dosages, the density and dimensional changes are most probably confined to the layer less than 0.01 cm thick at the front of the crystal, where the majority of the incident radiant energy is absorbed,[6] whereas the resonant-frequency change resulting from irradiation has been shown to be a volume effect. Second, the magnitude of the dimensional and density changes produced by the relatively short irradiations used in these experiments are too small to account for changes in resonant frequency of the magnitudes found here. For example, the increase in length of about 2 parts in 10^5 found by Sakaguchi and Suita[12] in irradiated NaCl would cause a resonant-frequency change of only 1 c.p.s. at 85 kc, which is within the experimental error of the present measurements. It is concluded that the resonant-frequency changes observed upon irradiation must be due entirely to changes in modulus.

The modulus and damping changes resulting from irradiation have been measured in specimens of NaCl from four different lots of Harshaw crystals and from one natural crystal. The nature of the radiation effects produced in all these crystals was found to be the same; only the magnitude of the effects differed from crystal to crystal.

Effects of Deformation and Recovery

A crystal which has been annealed at 500°C for 1 h and subsequently handled with care is characterized by a decrement which is almost amplitude-independent and by a modulus which is unaffected by X-irradiation. Curve *A* in Fig. 2 shows the decrement of a carefully annealed crystal as a function of strain amplitude.

Crystals quenched from temperatures of the order of 500°C show a somewhat higher decrement than the annealed crystals (equivalent to Curve *B*, Fig. 2),