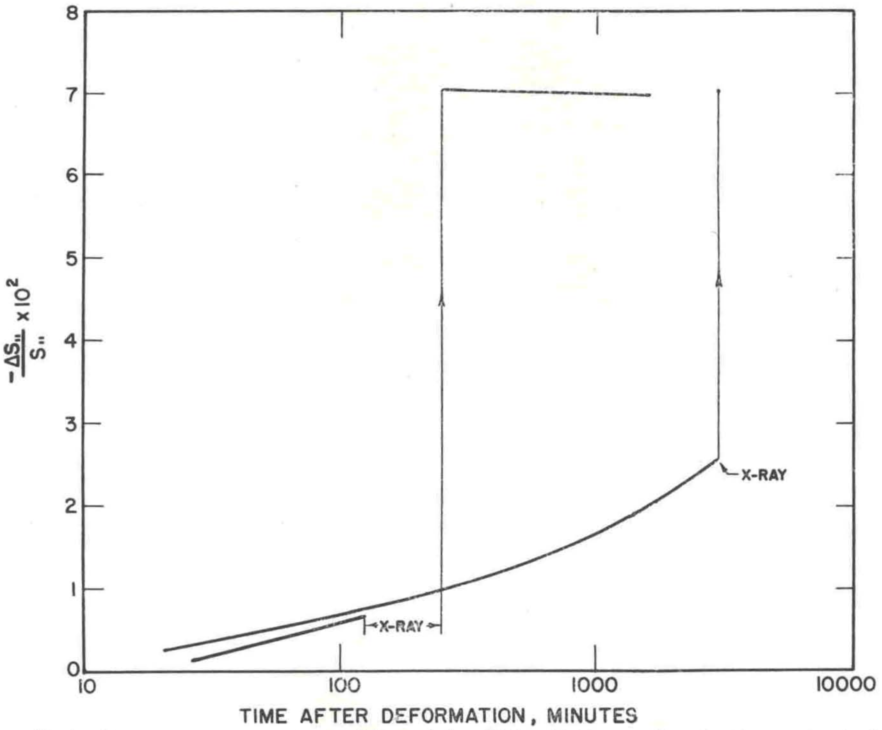

FIG. 4. The effect of spontaneous recovery followed by X-irradiation on the elastic constant of two crystals (Nos. 12 and 13). Specimens were subjected to X-irradiation for 2 h at the times indicated.

in such a way that they can be shifted into coincidence by a translation along the log-time axis.

Effect of Irradiation Temperature

Crystal No. 9 was irradiated at a temperature of 42°C instead of room temperature. As is evident from Fig. 5, irradiation at this slightly elevated temperature does not change the form of the modulus defect vs. dose curve.

Measurements *at room temperature* were also made on crystals irradiated at low temperatures. In view of the fact that Frankl$^{(7)}$ reported a decrease in damping for crystals irradiated at a low temperature and warmed in the dark, but not for crystals irradiated and optically bleached at low temperature, it seemed desirable to carry out similar experiments on the modulus changes. Accordingly, some of the crystals were subjected to strong illumination after low-temperature irradiation, while the others were warmed up to room temperature in the dark. The results of these experiments are given in Table 3. In this Table, Δf_s (obs) is the total change in resonant frequency

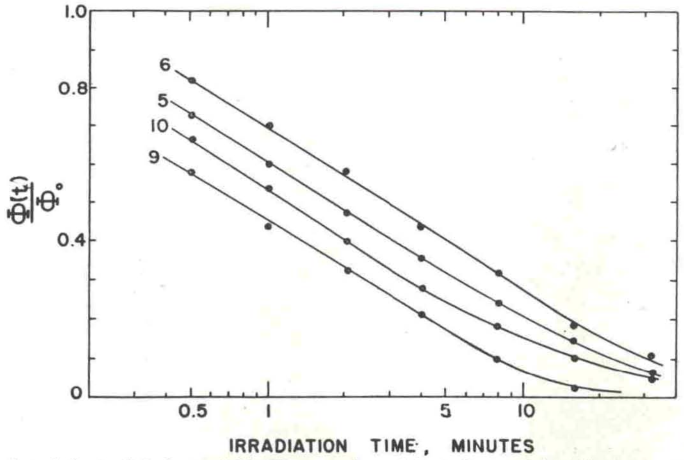

FIG. 5. Relative modulus defect of deformed NaCl crystals subjected to X-irradiation. Each curve is numbered with the identification number of the crystal measured. Data for crystal No. 4 superimposes on that for crystal No. 9.

TABLE 3. Change in resonant frequency, measured at room temperature, resulting from 1-h irradiations at various temperatures. (All crystals deformed approximately 1.5% and allowed to recover about 800 min before irradiation)

Crystal No.	Irradiation temperature (°K)	Illumination	Δf_s (obs)	Δf_s (corr)
18	298	none	235	241
19	180	none	250	256
20	180	at 180°K	403	310
21	78	none	261	266
22	78	at 78°K	187	214
23	78	during warm-up	45	48

upon irradiation, obtained by direct measurement; the Δf_s (corr) values are obtained by correcting the observed values to a standard deformation of 1.50%, under the assumption of a direct proportionality between the total frequency change and the amount of deformation. This correction is generally quite small.

In view of the difficulty in obtaining exactly the same modulus change in two different crystals, even for the same per cent deformation, it cannot be claimed that there are any significant differences between the modulus changes observed for crystals Nos. 18–22. It should be noted that, in contrast to the results reported by Frankl, there is no substantial difference between a crystal irradiated at liquid-nitrogen temperature and then warmed up in the dark (No. 21) and one irradiated and strongly illuminated at liquid-nitrogen temperature before warming (No. 22). The smaller modulus change in specimen No. 23 must, however, be regarded as significantly different. This crystal was irradiated in the usual way, but during illumination with the arc lamp the water-cell heat-filter was removed and the liquid air in the low-temperature box allowed to boil away. In this way the crystal was slowly warmed up to a temperature somewhat less than room temperature over the course of an hour while it was simultaneously subjected to strong illumination.

It was observed that very much less color is produced by the same X-ray dose when a crystal is arribiated at 78°K instead of at 180°K or room temperature. Furthermore, the color produced at either 180°K or 78°K cannot be bleached appreciably at the temperature of irradiation even under prolonged exposure to strong illumination. Among the crystals listed in Table 3, bleaching was effected only on crystal No. 23.

Other Alkali Halides

In addition to the work on NaCl, modulus and damping measurements were also made during irradiation of KCl and LiF crystals. The observed response of the modulus and damping of KCl to X-irradiation was similar in all respects to that of NaCl. The decrement of plastically deformed LiF, however, is substantially less than that of NaCl and KCl, while the response of both its modulus and damping to X-irradiation is much slower. The resulting damping change is also small, as is to be expected in view of the fact that plastic deformation produces only a small increase in damping. Nevertheless, the magnitude of the modulus change upon irradiation seems to be comparable with that observed in both NaCl and KCl.

4. DISCUSSION

The modulus measurements on cold-worked crystals show clearly that the modulus increase produced by irradiating NaCl crystals with X-rays corresponds exactly to the elimination of the modulus decrease (Köster effect) produced by plastic deformation. The Köster effect is known to be due to the presence of mobile dislocation loops produced during deformation,(7) i.e. to the effect described by equation (1). The radiation-induced modulus increase must then result from the restraint of the motion of these dislocation loops, either through regrouping of the loops in the dislocation network into more stable configurations or by the pinning down of the loops at a finite number of points by the products of irradiation. Since X-irradiation does not result in any appreciable gross heating of the crystal structure, it is difficult to see how the irradiation can produce a regrouping of dislocations. Consequently the modulus increase may be most reasonably ascribed to the formation of pinning points along dislocation loops; it may be that these pinning points are vacancies or clusters of vacancies located along the dislocations.

An attempt will now be made to calculate the shape of the curves of modulus vs. radiation dose with the aid of a number of simplifying assumptions. Let ϕ be the fractional decrease in modulus (i.e. the modulus defect) in any given element of volume of the crystal due to the oscillating dislocation loops. Correspondingly, Φ will designate the modulus defect of the crystal, resulting from the dislocations. (This definition is then consistent with equation 4.) Let P represent the total number of pinning points per unit volume created by irradiation, n be the number of pinning points per unit length of dislocation line (assumed for simplicity to be equally spaced), N be the total length of dislocation line per unit volume, and x represent depth below the irradiated surface. Since the number of pinning points is, presumably,