the diffraction pattern (Fig. 1a), Bragg's law is best rewritten in terms of photon energy E:

$$E = hc/\lambda = 12.398/\lambda \quad (3)$$

if E is expressed in kiloelectron volts and λ is in angstroms, which leads to

$$d(hkl) = (6.199/\sin\theta) \cdot (1/E) \quad (4a)$$

or

$$|\mathbf{k}| = 1/d = (\sin\theta/6.199)\,E \quad (4b)$$

This form demonstrates clearly the proportionality of the magnitude $|\mathbf{k}|$ of the reciprocal lattice vector to the energy E of the diffraction peak.

In this experiment the uncertainty of determination of the lattice parameter a_0 is about 0.18 percent. The fractional error, $\Delta d/d$, equals $\Delta E/E$ after errors in θ are minimized by proper alignment of the diffractometer. Although the FWHM of the photopeaks is about 0.7 kev, centroids of the peaks can be determined within 0.1 kev over the entire energy range. Thus the most accurate determinations of a_0 are those based on d-values from the diffraction peaks observed at the highest energies: for example, $\Delta d/d$ for the (422) and (333/511) reflections is about $0.1/40 = 0.25$ percent.

Combination of information from both these peaks drops the uncertainty to 0.18 percent, which corresponds to $\Delta a_0 = 0.007$ Å for Pt. While this error value is about ten times that obtainable with a conventional lattice-parameter determination of fair quality, it can be significantly improved by use of more reflections and by shifting of the diffraction pattern to higher energies by suitable choice of $\sin\theta$. The shift can be achieved with a higher tube voltage and by use of a Ge(Li) detector rather than the Si(Li) detector, with resultant decrease in $\Delta E/E$ by a factor of at least 2; this decrease is possible because $P_a(E)$ does not decrease as fast, with increase in E, for Ge as for Si (*3*). Appropriate choice of $\sin\theta$ also is needed to avoid superimposition of the fluorescent radiation excited in the sample or target, or both, over important parts of the diffraction pattern.

Although the pattern in Fig. 1a was obtained by counting for 1.5 hours to give good statistics, fair patterns of all materials named above were obtained with 5- to 10-minute exposures. These materials include Re, which is hcp (A3 type) and thus yields a diffraction pattern with more-closely spaced lines than those of the fcc (A1-type) metals. The first 13 lines up to (203) (which occurred at 33.4 kev for the chosen $\sin\theta$ setting) were resolved or clearly detectable. By taking all available values into account we obtained an axial ratio $c{:}a = 1.617 \pm 0.003$, in excellent agreement with the literature value, $c{:}a = 1.615_4$ (*5*).

Compared to the conventional x-ray powder diffraction technique, the new method, which may be suitably termed powder-diffraction spectrography, gathers information about the reciprocal lattice at a rate greater by two to three orders of magnitude; thus very short observation times are possible, especially with certain experimental modifications. The present arrangement yielded recognizable diffraction patterns in 15 seconds; by use of a W-target tube, with higher emission and a correspondingly higher tube voltage and current, the intensity $I_{cont}(E)$ may be easily increased by a factor of 10. Use of a rotating anode tube with about 6 kw may further shorten the time by a factor of 5. As we have noted $P_a(E)$ can be increased at higher energies by use of Ge(Li) instead of Si(Li) for the detector. With these improvements, recognizable diffraction patterns are probably possible within 0.3 second; such brief exposure is valuable during transient or extreme conditions such as the rapid transformation of metastable phases or very high pressures. In order to follow rapid transitions one must take successive spectra; this we did by storing the spectra in the various quadrants of the analyzer memory or by recording them on magnetic tape.

The new method may be especially applicable for x-ray determinations of crystal structures under high pressure for another reason: only one beam-exit port is required, which can be chosen at a convenient angle θ, rather than a port permitting the range of θ values that is necessary in the conventional powder method. The new x-ray method represents the formal analogy to powder patterns taken by neutron spectroscopy, such as by use of the time-of-flight method (*6*). Powder diffraction spectrography should be applicable in instances in which some resolution can be sacrificed for great reduction in exposure time.

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References and Notes

1. R. W. James, *The Optical Principles of the Diffraction of X-rays* (Bell, London, 1962), p. 6.
2. B. C. Giessen, in *Proc. Sagamore Army Materials Res. Conf. 12th*, J. J. Burke, N. L. Reed, V. Weiss, Eds. (Syracuse Univ. Press, Syracuse, N.Y., 1966), p. 273; ———, M. Morris, N. J. Grant, *Trans. Met. Soc. AIME* **239**, 883 (1967); P. Duwez, *Progr. Solid State Chem.* **3**, 377 (1966).
3. H. R. Bowman, E. K. Hyde, S. G. Thompson, R. C. Jared, *Science* **151**, 562 (1966).
4. Technical Measurement Corp., North Haven, Conn.
5. *International Tables for X-ray Crystallography* (Kynoch Press, Birmingham, England, 1962), vol. 3, p. 281.
6. R. M. Brugger, in *Thermal Neutron Scattering*, P. A. Egelstaff, Ed. (Academic Press, London, 1965), p. 53.
7. Aided by the AEC [contract AT(30-1) 905] and by the U.S. Army Research Office, Durham, N.C. (contract DA 31-124-ARO-D). We thank William Zoller for help and Robert Ogilvie and Roy Kaplow for lending equipment.

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Cavitation in Liquids Demonstrated by Ultrashort-Exposure Radiography

Abstract. *Using a field-emission x-ray tube, giving a much shorter pulse of rays than does conventional apparatus, we have demonstrated around a water jet the presence of a toroidal cavity that could not be detected visually. One advantage of this method of demonstrating cavitation is that it may be used with fluids and vessels that are opaque to light.*

For experimental purposes the presence of cavitation in a liquid is usually detected visually in specially prepared models. Occasionally, ultrasound-reflection and sound-detection devices are employed, but these merely indicate the occurrence of cavitation and do not demonstrate the extent and distribution of the phenomenon. For visual detection, abundant light is required (*1*), which enables direct observation or cinephotography in clear fluids. In

opaque liquids, such as blood, direct observation is not practicable because of both the opacity of the fluid and the wall of the containing vessel.

Radiographic techniques offer a means of circumventing this difficulty; hitherto, however, the long x-ray exposure required, relative to the speed and lifetime of the bubbles, has kept this method of detection from practical use, because the sharpness of a radiographic image is a function of the ratio between the amount of movement of the object, during the exposure, and its size. Furthermore, the lifetime of cavitation bubbles is probably so short that several generations are present, in slightly different situations, during a standard radiographic exposure lasting 1/60 second or longer.

X-ray exposures that are very short, even in relation to the lifetime of a single cavitation bubble, can be produced by a pulsed-field emission unit (*2*); the 30-nsec exposure available also offers a means of avoiding blurring by motion.

This technique has been applied to demonstration of cavity formation in water. By use of a plexiglass block containing a circular channel of 12.5-mm diameter, cavitation was produced by a constriction having a central lumen of 4-mm diameter. The inlet and outlet of the stenosis were shaped as shown (Fig. 1A); with flows of tap water of about 15 liter/min (corresponding to a Reynolds number in the main channel of 22,000), fairly strong cavitation was produced (Fig. 1B).

X-ray exposures of 30 nsec were made by use of kilovoltages across the x-ray tube of about 160, at a film-source distance of 25 cm, with the radiographic film contained in a metal cassette supported directly against the plastic block. The film used was Kodak Blue Brand (Medical); the intensifying screens were DuPont Par-Speed, LG.

The radiographic evidence of cavitation consisted of an oval shadow (5 by 1.5 mm), with circular areas of increased density at its outer ends—the radiographic image of a toroid (doughnut) viewed from its side. The shadow was situated axially in the flow expansion at the junction of the constriction and the main channel, the indication being that cavitation was occurring within a toroid vortex in this situation (Fig. 1C).

This cavity could not be detected visually, however, because of the extensive effervescence around the jet. This effervescence originated within the throat of the constriction and occupied a fan-shaped area, 1 to 2 cm downstream from the constriction, surrounding the jet (Fig. 1B). The inability to detect this large fan-shaped area radiographically is attributed partly to the small size of the individual bubbles relative to the grain of the emulsion of the film, and also to the low inherent contrast caused by their small volume compared with that of the surrounding water.

Existence of a central cavity as large as the one mentioned is surprising when one considers the small size of the bubbles in the visible area of cavitation. We suggest that a radiographic technique using very short exposures, such as the one described, is a useful complementary technique for investigation of the presence and extent of cavities in clear fluids. The occurrence of cavitation in blood has often been postulated (*3*), but the difficulty in demonstrating cavities in vivo has retarded acceptance of the concept (*4*). As this technique for demonstration is applicable to a light-opaque fluid, it should be able to confirm the presence of cavities within blood in physiological circumstances, provided that the cavities are large relative to the grain of the film emulsion.

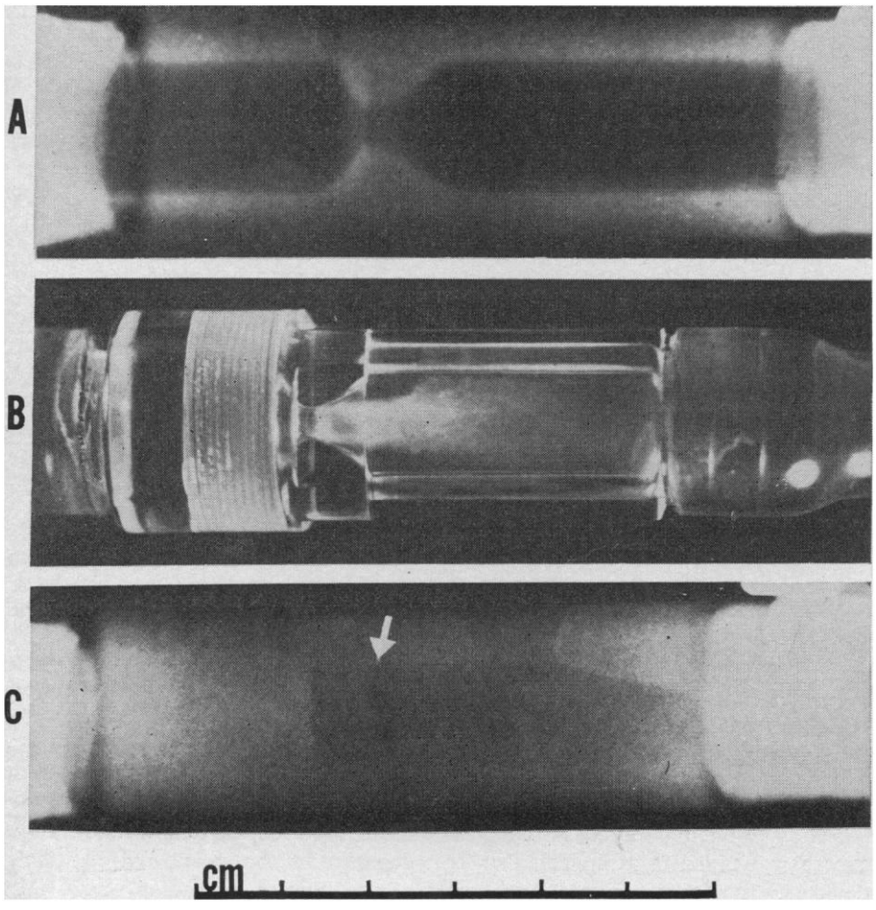

Fig. 1. (A) Radiograph of plastic block, containing air only. (B) Photograph of block, showing position and extent of visible cavitation. (C) Radiograph of block containing cavitating flow; arrow indicates the shadow cast by the toroidal cavity.

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References and Notes

1. A. F. Lehman, in *Cavitation Research Facilities and Techniques* (American Society of Mechanical Engineers, 1964), p. 31.
2. Fexitron 180-kv flash x-ray unit, model 730-2722; Field Emission Corp., McMinniville, Oregon 97128.
3. J. E. Malcolm, *Blood Pressure Sounds and Their Meanings* (Heinemann, London, 1957); A. E. Hugh and J. A. Fox, *Lancet* **1963-II**, 717 (1963).
4. R. F. Rushmer, in *Pulsatile Blood Flow*, E. O. Attinger, Ed. (McGraw-Hill, New York, 1964).
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