reading speeds in all modes but A.1. In the A.2 and B.2 modes there appeared to be about a 10 percent reduction in maximum reading speed as compared with the B.1 mode. Perhaps this is the result of the need to sweep back to the left margin after each line is read. Fair readers (100 to 150 words per minute) and poor readers (less than 100 words per minute) had even more pronounced preference for the B.1 mode than did the superior group, and, in fact, some of them achieved much higher rates with it than they did with the usual Braille text.

It thus appears that the B.1 mode, which we had considered desirable for engineering reasons, is preferred by readers. To substantiate our conclusions we asked each reader for comments on the B.1 mode. (Unfortunately, we revealed our prejudices for certain modes.) There was unanimous agreement that it was acceptable, and probably easy to adjust to. Several hoped that use of such a mode would improve their reading speeds (the B.1 mode has some features akin to those that are used in training for speed reading, and many thought that it might improve their reading comfort and enjoyment.

At this point we prepared the following set of criteria for a Braille-reading machine. (i) The machine should be conveniently portable. This implies at least an optional battery operation, and a weight of approximately 4.54 kg. (ii) The machine should be inexpensive. An estimated production cost of less than $500 should put it within the financial means of professionals. There are approximately 380,000 blind or severely visually handicapped people in the United States. Let us assume that one out of eight in this population reads Braille intensively when Braille reading material is more widely available. Free distribution of reading machines to those who need them would then entail expenditure of approximately $25 million—not an excessive amount by government or foundation standards. (iii) The machine should be durable, with simple and convenient controls, and should require standard supplies such as batteries. (iv) Presentation of material should be in the B.1 mode, and the characters should be erased after they have been read. (v) The machine should allow the magnetic tape to move quickly forward and backward, permitting the reader to locate any desired page or passage of text easily. (vi) The code used on the magnetic tape should be producible as direct computer output. It should include pagination, indexing, and cueing features for the reader. (vii) The tape (including box and reel) should contain at least 1000 words per cubic centimeter of space it occupies to make the system competitive with ink-print volumes. (viii) The maximum rate at which the machine presents characters should exceed 22 characters per second. (Three of our subjects routinely achieved this remarkable speed.)

In addition to these requirements, certain accessory features would be highly desirable with regard to the use of the machine for writing and annotating. With the addition of a device incorporating a Braille typewriter keyboard it should be possible to type directly onto magnetic tape. A blind author could then have his text translated into standard print by means of a computer. More commonly, it would simplify his letter writing and note taking, and would also be useful for making annotations in space provided on book tapes. Acoustic recording (perhaps on an extra channel provided in a multichannel book tape) would permit oral annotation. Further features may emerge as development of the machine proceeds.

ARNOLD P. GRUNWALD
Reactor Engineering Division, Argonne National Laboratory, Argonne, Illinois

References and Notes

1. The American Printing House for the Blind, in cooperation with IBM, has developed a method of translating Braille by means of standard punch cards for computer input. The Computer Science Laboratory and Honeywell have developed a similar system. The Mechanical Engineering Department of the Massachusetts Institute of Technology is working on computer translation bypassing the step of the punched card. [See also R. W. Mann, "Enhancing the Availability of Braille," *Proc., Int. Congr. Technol. Blindness*, vol. 1 (American Foundation for the Blind, New York, 1963).]
2. I thank E. Groh, T. Pienas, B. Burson, P. Grunwald, L. Wos, B. Spinrad, Mrs. Gretel Grunwald, and Mrs. Julian Levi for their valuable support.

6 June 1966

Turbulent-Gas Chromatography

Abstract. *Turbulent flow in gas chromatography was achieved and its effect was studied with high-speed, high-pressure equipment. A gas-solid capillary and several packed columns were used. The onset of turbulence was associated with abrupt decrease in peak width in the capillary and gradual leveling off and decrease in the packed columns. The existence of separation under turbulent conditions was shown. The potential of the method was demonstrated by its short elution times and rapid generation of theoretical plates.*

We now report the first experimental realization of fully developed turbulence in gas chromatography. With the aid of high-speed, high-pressure equipment, we have operated at Reynolds numbers (*Re*) to 16,000, 10^4-fold beyond conventional laboratory operation. Correspondingly, mean gas velocities exceeding 2000 cm/sec and outlet velocities near the sonic level have been reached, compared with the usual velocity range of 2 to 10 cm/sec. These extremes of velocity have revealed a clear maximum in the plate height (or peak dispersion)–velocity plots for both packed and capillary columns (*1*). This maximum is of particular interest for high-speed, high-resolution gas chromatography since, beyond the maximum, both separation speed and resolution increase simultaneously to rather high values; ordinarily one must sacrifice one in order to gain in the other.

The role and potential value of turbulence in gas chromatography has been discussed by several: Giddings and Robison (*2*) first pointed out that flow conditions frequently approach the threshold of turbulence; Sternberg and Poulson (*3*), adverting to increased mass-transport rates, were the first to draw attention to the unusual promise of turbulence. That "velocity equalization" in turbulent flow might be advantageous was suggested by Giddings (*4*); both he and Knox (*5*) have shown that turbulent and "coupling" effects overlap one another in high-velocity, packed columns. Turbulent effects have been treated mathematically by Pretorius and Smuts (*6*).

The transition from laminar to turbulent flow in packed columns is grad-

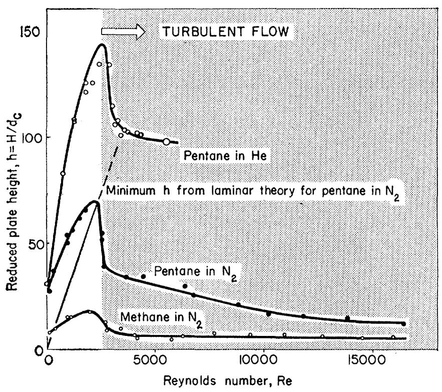

Fig. 1. Reduced plate height versus Reynolds number in 21.3-m "Schwartz" capillary at 0°C. Retention ratio for pentane is 0.88; for methane it is assumed to be unity.

ual, probably occurring between Re 1 and 100 (*4*). In capillary (open tubular) columns, turbulence is expected to begin suddenly at about Re 2100. Laboratory values in both cases range typically from 0.1 to 1; in extreme cases they may reach 10. The achievement of much greater values requires great pressure drops to increase density and to force gas rapidly through the column, and high-speed injection, detection, and recording devices to assure the integrity of the rapidly eluting peaks.

Only recently have we constructed suitable equipment, which operates routinely in the pressure range from 1 to 170 atm (to tank pressures); our most recent instrumentation works with inlet pressures up to 2000 atm. The detection and readout systems are adequately fast, approaching 1 msec under optimum conditions. Our response time is apparently limited by the speed of injection—estimated at 0.05 second for the introduction of a full solute peak into the gas stream. Despite this speed, a correction was sometimes necessary because our turbulent peaks were frequently less than 0.1 second in duration.

Most details of our system have been described (*7*); modifications were mainly of injection and timing devices to increase speed and accuracy. Packed columns were constructed in the usual way. The high-efficiency gas-solid capillary column was prepared by R. D. Schwartz (*8*). Both helium and nitrogen were used as carrier gases; both afforded comparable separation speeds, but nitrogen, because of its greater density, enabled exploration over a greater range of turbulence.

Principal results for the capillary column (Fig. 1) show that for each solute-gas combination the reduced plate height, h (plate height over column diameter), increases steadily with Reynolds number until $\sim Re$ 2500 is reached; here there is a rather abrupt drop, followed by a downsloping shoulder.

The transition, appearing at $Re \sim 2500$ (the exact value is made uncertain by experimental variables), is in the vicinity of the point (usually around Re 2100) characterizing the onset of turbulence. The argument that this is a true turbulent effect is strengthened by the fact that each solute-gas system exhibits a transition at about the same Re, while the reduced velocity, the fundamental flow parameter in laminar peak-dispersion theory (*4*), differs more than fourfold between systems at their experimental transition points.

The experimental data in Fig. 1 can be compared with certain results from laminar plate-height theory, in the form applicable to high inlet pressures (*7*); such theory, modified for our purposes, predicts that h will increase with Re as the sum of terms

$$h = \psi_k (Re)^{\frac{1}{2}} + \psi_g Re$$

the first stemming from sorption kinetics; the second, from lateral diffusion in the carrier gas (the effect of a third term, for longitudinal diffusion, is indistinguishably compressed into the vertical axis by the high-velocity range). Only ψ_g is fixed absolutely by theory; thus $h = \psi_g Re$ has been plotted in Fig. 1 for the pentane in the N_2 system. This gives a minimum possible h, if one assumes laminar flow. In the laminar range, the corresponding experimental curve (pentane in N_2) exceeds this and is concave down, both results being expected.

We see that peak dispersion is reduced considerably by turbulence. By extending the laminar-theory line over the experimental range, we see that turbulence reduces plate height at least by factors of up to 40. The precise reduction is obscured by the continuing effect of ψ_k and by theoretical uncertainties as we approach supersonic outlet flow, gas nonidealities, and such.

At the upper limit of Fig. 1, Re = 16,000, pentane in N_2 is eluted from the 70-foot (21.4-m) column in 2.8 seconds with 7000 total plates, thus yielding a substantial 2500 plates per second. The inert solute methane in He is eluted in slightly less than 1 second and provides 8200 plates per second, which suggests the high potential of this method.

Ability of the column to achieve separation under turbulent conditions was verified by eluting a mixture of several light hydrocarbons in He at $Re \sim 7000$ (corresponding to an inlet pressure of 144 atm) and −74°C; the peaks were eluted rapidly with good resolution (Fig. 2). This separation was achieved in one of our first efforts; undoubtedly performance could be im-

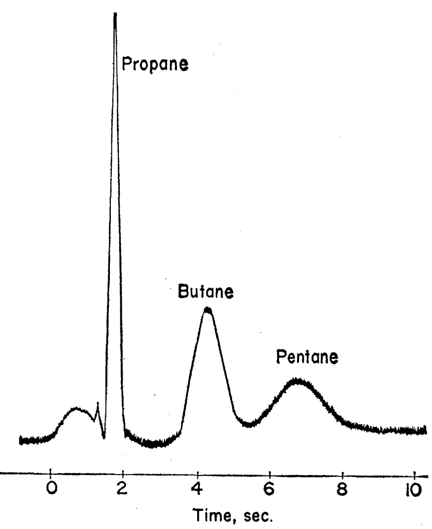

Fig. 2. Turbulent separation of light hydrocarbons at $Re \sim 7000$ in He; "Schwartz" capillary column at −74°C.

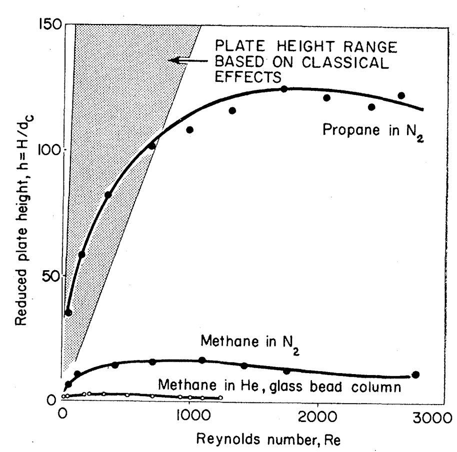

Fig. 3. Reduced plate height versus Reynolds number for gas-packed columns. Top two curves for NaI-coated alumina. Retention ratio for propane is 0.86. Turbulence fully developed for $Re > 100$.

proved by optimization of such factors as temperature and carrier gas.

Along with the capillary column, many packed columns were tested under turbulent conditions; most were "inert" (nonretentive) glass-bead columns designed to help unravel the underlying phenomena. They included, however, three "active" gas-solid columns. Fig. 3 shows three relevant curves, all passing through a maximum; the top two apply to an "active" 50-foot (15.2-m) column packed with NaI-coated alumina particles of diameter $d_p = 0.38$ mm; the top curve, involving the retained peak propane, lies well above the middle plot for unretained methane.

This finding and the weakness of the maximum suggest that adsorption-desorption processes here limit efficiency of the column, thus masking the advantages of turbulence. The true potential of turbulent flow in packed columns is perhaps best illustrated by the bottom curve, applying to 0.51-mm glass beads in a 15.2-m column; h reaches a maximum of only 2.2 and then falls to 0.9; at 145 atm at the inlet, methane is eluted in 4.8 seconds with 18,000 plates, thus giving 3800 plates per second.

Theoretical interpretation of turbulence in packed columns is complicated by the fact that the coupling phenomenon (*4, 9*) (a consequence of flow-diffusion interactions) also reduces plate height at high velocities; both act gradually—not discontinuously as in capillaries. The two effects have not yet been unscrambled, but undoubtedly both are beneficial. The magnitude of their combined influence is shown in Fig. 3 by comparison with the shaded area representing the performance range of columns when one assumes classical theory—that is, without turbulence or coupling. The classical range pertains very roughly to all three systems shown. The reduction in plate height, caused by turbulent and coupling effects, is clearly significant.

J. Calvin Giddings
William A. Manwaring
Marcus N. Myers
Department of Chemistry, University of Utah, Salt Lake City 84112

References and Notes

1. A corresponding maximum in a nonsorbing liquid column was reported by J. H. Knox, *Anal. Chem.* **38**, 253 (1966).
2. J. C. Giddings and R. A. Robison, *ibid.* **34**, 885 (1962).
3. J. C. Sternberg and R. E. Poulson, *ibid.* **36**, 1492 (1964).
4. J. C. Giddings, *Dynamics of Chromatography*, pt. 1, *Principles and Theory* (Dekker, New York, 1965).
5. J. H. Knox, *Anal. Chem.* **38**, 253 (1966); D. S. Horne, J. H. Knox, L. McLaren, *Separation Sci.*, in press.
6. V. Pretorius and T. W. Smuts, *Anal. Chem.* **38**, 274 (1966).
7. M. N. Myers and J. C. Giddings, *ibid.* **37**, 1453 (1965).
8. R. D. Schwartz, D. J. Brasseaux, R. G. Mathews, *ibid.* **38**, 303 (1966); column prepared and loaned by R. D. Schwartz, Shell Development Co.
9. J. C. Giddings, *Nature* **184**, 357 (1959).
10. Supported by NIH grant GM 10851-09.

8 August 1966

Silicone Rubber: A New Diffusion Property Useful for General Anesthesia

Abstract. *Ether, nitrous oxide, halothane, and cyclopropane diffuse through silicone rubber. General anesthesia can be produced in dogs by passing the vapors of any of these anesthetic agents through a coil of silicone rubber tubing, each end of which is placed in an artery and vein. Potential applications include a new method for general anesthesia and a simple accurate vaporizer for halothane.*

We have found that the four most commonly used anesthetic agents, ether, nitrous oxide, halothane and cyclopropane, diffuse through silicone rubber. This observation was made after several kinds of tubing used for perfusion of organs were flushed with ether. Only the silicone rubber tubing continued to smell of ether 1 hour after it was dry. This indicated that ether had diffused across the wall of the tube. One milliliter of ether was then placed in a silicone rubber tube and sealed at each end with a paper clip. When the tube was placed on a Mettler balance, weight was lost from the tube at a constant rate because of vaporization of ether from the surface. When the supply of ether was depleted the tube collapsed, an indication that the diffusion of air into the tube was much slower than the diffusion of ether out of it. The tube did not re-expand until over an hour later.

When tubes of varying thickness and length were filled with ether and occluded at both ends, the rate of transfer of ether through silicone rubber was directly proportional to surface area, and inversely proportional to thickness. Moreover, increasing the wall thickness introduced a latent period of diffusion (Fig. 1). Weight loss did not occur until ether had reached the outside surface. Thus, for a tube with a 0.5 mm wall, weight loss began almost immediately, and peak diffusion rate reached 4.1 mg/cm^2 per minute. For a tube 1.5 mm thick, the weight loss did not begin for approximately 5 minutes and then the diffusion rate reached a peak of only 0.85 mg of ether/cm^2 per minute.

Silicone rubber tubing is inert when implanted in the body. Such tubes have been permanently inserted from the radial artery to a suitable vein in the same arm in patients with renal failure (*1*). This bypass is then opened whenever the patient requires hemodialysis from an artificial kidney to enable his blood to flow through a dialysis coil. We placed such a shunt from the femoral artery to the femoral vein in heparinized dogs (30 kg). To allow catheterization of the femoral vessels, the dogs were anesthetized briefly with pentothal and then allowed to wake up gradually so that the ether anesthesia could be tested. The silicone rubber tubing used was 12 cm long. When the tubing was dipped into ether, ether vapor was expired in the alveolar air after 6 minutes; this caused hemolysis. Therefore, ether vapor alone was passed over the tube, and ether appeared in the expired air in 6 minutes; there was no hemolysis. This short length of tubing did not admit enough ether to produce general anesthesia. However, by increasing the length of the tubing through which the blood flowed, deeper levels of anesthesia were reached. When tubing of 5.0 mm outside diameter (OD) and 1.0 mm wall thickness was exposed to ether vapor, a small coil (Fig. 2) made from 450 cm of tubing produced deep surgical anesthesia in these large dogs. (Shorter lengths of tubing could be substituted when thinner tubing was used.) Any level of anesthesia could be obtained simply by exposing more or less of the coil to 100 percent ether or by exposing