STATE ENGINEERING EXPERIMENT STATION

The Research Engineer

GEORGIA INSTITUTE OF TECHNOLOGY

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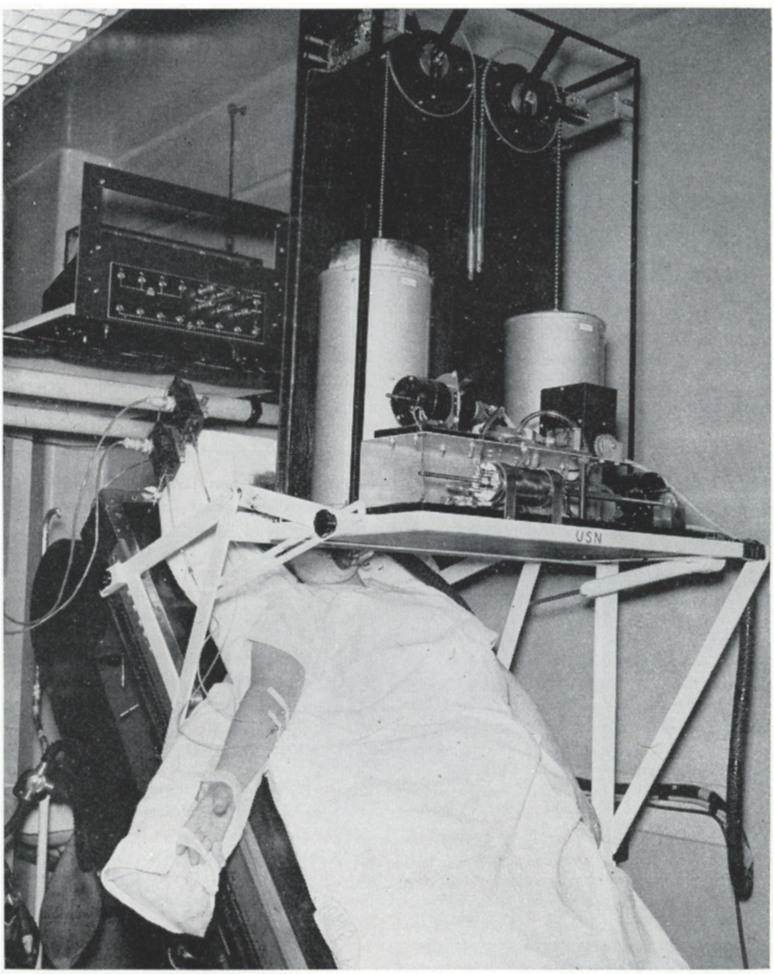

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RESEARCH PAYS OFF

By citing the example of one oil company for which research recently paid off handsomely, we would like to indicate not only how the petroleum industry and the motoring public stand to benefit from this company's research but also how *any* company, its industry and their public can expect to benefit from successful research.

The company in question has, through research, found a way to increase the recovery of crude oil from the Bradford (Pennsylvania) field and, at the same time, do so more economically than has hitherto been possible. In dollars and cents the pay-off to the company has already amounted to a sum that it says is "far in excess of

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Like the plants in our gardens, industries will only take root and grow where the "climate" is favorable and they receive the "nourishment" they require. However, industrial plants are free to seek their own environment, and they will only grace *our* garden when they know in advance that they will be well cared for. When different areas compete for the same industrial plant, one may satisfy some requirements and fall short in others. No area can offer industry raw materials that Nature did not give it, nor, over the short term, can it provide labor and markets unless its population and income are sufficient. Any area seeking to attract industry should examine carefully what it has to offer and then strive to make those assets as strong as possible.

Georgia's labor supply is one of our greatest advantages in attracting industry. We can maximize this advantage by training more of our young men in engineering and the sciences so that the availability of their specialized skills will reinforce the appeal of our abundant general manpower situation.

Adequate facilities for research and development, staffed by the best scientists obtainable, constitute another highly potent lure to industry. We have already seen how research has created *new* Southern industries—Herty's paper pulp from Southern pine and the Virginia-Carolina Company's synthetic textile fiber from peanut protein. I would like to point out that there are *numerous* types of industry that, because of their technical nature, actively seek location near research facilities. For example, a manufacturer of electronic instruments chose Palo Alto, California, as his plant site for one reason above all others—to be near Stanford Research Institute.

Above and beyond the raw materials and markets that renascent Georgia now offers industry, we can, if we will, offer "nourishment" to new plants by providing abundant scientifically trained manpower and a "climate" favorable to technological progress by utilizing and strengthening the research organizations of our state. Georgia Tech and its Engineering Experiment Station stand ready to serve in this undertaking.

BLAKE R. VAN LEER
President, Georgia Institute of Technology

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MEASUREMENT OF CARDIAC OUTPUT AN ILLUSTRATION OF MEDICAL INSTRUMENTATION

By R. A. LEE* AND FREDERICK DIXON**

This article describes a new piece of equipment for measuring blood flow in humans and discusses some of the problems peculiar to biological instrumentation that had to be solved during the development work. As such, it complements and extends Mr. Dixon's earlier article, "Philosophies Concerning Engineering Problems in Medical Research."

The degree and scope of modern scientific and technological successes sometimes lead us to overconfidence concerning the measurability of physical phenomena in general. We have become accustomed to the post-Aristotelian observation that knowledge is an almost certain consequence of measurement, and hence would be inclined to say that in the fields of biology and physiology much knowledge awaits merely the recording of much (more) data. The comment is probably accurate enough, but the word "merely" would be ill-advised. Many of the controlling mechanisms in living organisms prove to be difficult of access and isolation; the necessary instruments for measurement are often complex and unstable; and the reaction of an organism to the act of being measured can be both violent and unpredictable and is almost always variable. The instrumentation problem is, itself, difficult. In addition, in order to make use of and interpret the measured data, we must have theories about the operation and performance of living machines which are both sufficiently simple to be comprehensible and sufficiently general to be comprehensive. We are ultimately faced with the situation of a machine attempting to analyze itself.

In a previous article we discussed facts and ideas associated with the application of engineering skill to medical research.[6] To illustrate more concretely the role of the engineer in this field of endeavor, we will now describe some of the considerations entering into the design of a specific instrument to be used for human physiologic research. The device, which may be termed a "semicontinuous cardiac-output analyzer," was recently completed at the Emory University Cardiovascular Laboratory, Henry W. Grady Memorial Hospital, Atlanta, Georgia.*

Cardiac output is the volume of blood which the heart pumps, on the average, in a unit of time. The flow of blood from the heart is, of course, pulsatile in nature, so that at least one pulse repetition period must be taken to obtain the average volume output per unit time. Furthermore, since two successive pulses may differ from each other in amplitude (maximum instantaneous flow rate), shape and duration, it is desirable to include several heart beats in defining and measuring cardiac output.

Figure 1 shows a simplified schematic diagram of the cardiovascular system and its relationship to the respiratory system. Starting from the left auricle and ventricle of the heart, oxygenated blood is forced through check valves into the aorta and thence, through successive bifurcations of the vessels, into arteries, arterioles and capillaries which permeate all tissues of the body. The gaseous exchanges at the capillaries convert arterial blood into venous blood, which is returned through a similar but converging system of vessels to the right auricle and ventricle. The latter organ forces the venous blood into the lungs where it is once more oxygenated and delivered to the left heart for recirculation. The fact that the system is closed makes it possible to define cardiac output as the volume of blood pumped by either side of the heart per unit time. This is not strictly accurate, owing to the presence of leaks between the pulmonary circulation (blood pumped by the right heart to the lungs for cleansing) and the bronchial circulation (blood pumped by the left heart to the lungs for nourishing the lung tissues themselves); however, the errors concomitant with neglecting this complication are not large.

The determination of cardiac output is

**Instrumentation Engineer, Emory University.*
***Research Physicist.*

*The medical research project for which the instrument was built was sponsored by the U. S. Navy Bureau of Medicine under Contract No. N9onr92500.

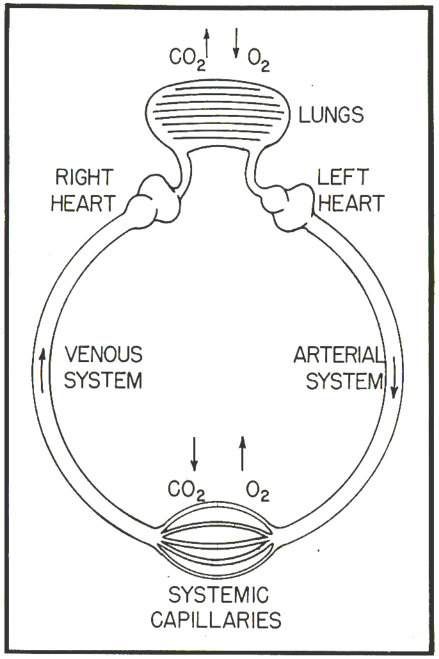

Figure 1. In the cardiovascular system, oxygen is taken in and carbon dioxide is given off by the body tissue, and the opposite transfer occurs at the lungs.

important because it permits calculation of the amount of work performed by the heart muscles and because it permits measurement of the metabolic activity of various organs of the body. For research purposes, it is necessary to determine cardiac output under a wide variety of conditions—including changes in body position (such as by tilting a subject from the horizontal to the vertical) and changes in body activity (such as by the administration of drugs or by exercise).

MEASURING CARDIAC OUTPUT

The obvious first choice of an instrument for measuring cardiac output would be a device capable of being placed in the aorta and responding to the fluid flow rate so as to give meter readings directly visible or recordable. Such a device would be analagous to an ammeter in an electrical circuit. Since the resistance to flow (ratio of pressure to flow rate) around the blood vascular system is quite high, the effect of the instrument's own resistance on the quantity being measured could probably be made negligible. However, the fact that the vessel in which the flow-rate meter would be placed has elastic walls (and hence a changeable diameter), together with the serious difficulties involved in entering the aorta, makes this approach generally unfeasible.

A second possible direct approach would be to tap a main artery and measure the amount of blood lost by the body in a given period of time. This method is supposed to have been tried on expendable prisoners in Germany during World War II; but, in addition to its objectionably severe and inhuman aspects, it has drawbacks due to associated alterations in the system being measured. If a very large vessel such as the aorta were cut, the total volume of blood available to the heart for pumping would rapidly diminish, so that only a short time average could be used. If a smaller vessel were used, to obtain a sort of aliquot, compensatory mechanisms could be expected to come into play which would alter the fraction of blood shunted into the open branch of the system.

The ballistocardiograph is a device for determining cardiac output from calculations based on Newton's third law of motion.[7,12] As blood is suddenly ejected out of the heart chambers during systole (contraction of heart) there is a recoil effect which can be measured by placing the subject on a critically-dampened spring-suspended table. Ballistocardiographs constructed to date respond to forces of reaction in one direction only; consequently, although the initial acceleration of blood is primarily along the longitudinal axis of the body, a complete picture of the effect is not obtained. Force components in three mutually-perpendicular directions should be measured, and the suspension table should allow tilting of the patient from horizontal to vertical positions. Major mechanical difficulties attend the inclusion of these features in ballistocardiographic instrumentation.

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BULK SAMPLING OF FARMERS' STOCK PEANUTS

By J. C. Moder*

Mispricing of farmers' stock peanuts because of inaccurate grading obviously results in a financial loss either to the buyer or the seller. This article discusses the problems of grading and suggests methods for arriving at a more accurate value.

The pricing of agricultural products, in particular farmers' stock peanuts, involves an extremely complex problem in bulk sampling. Establishing a reasonably accurate dollar value for an agricultural commodity requires taking a representative sample of sufficient size to give a grade that can be reproduced quite closely in repeated samplings. In studying this problem of bulk sampling and grading of farmers' stock peanuts, several interesting facts have been brought to light which may well have some application to the pricing of other commodities.

The present system of grading farmers' stock peanuts consists of obtaining a bucket sample of peanuts from the seller's truck by means of a sampling tube, followed by mechanical splitting to an eight-ounce sample for subsequent analysis. This sample is then cleaned by hand to determine the percentage of foreign material. From the cleaned peanuts, four ounces are hand shelled to determine the percentage of sound mature kernels, percentage of damaged kernels and percentage of moisture in the kernels.

An analytical study of this system of sampling and grading has conclusively shown that it is inadequate and may adversely affect either the buyer or seller.** It is inadequate for the following reasons:

(1) The sample for analysis is obtained in a biased manner as explained below and is not representative of the entire load of peanuts.

(2) The right of both parties to demand regrades, coupled with the seller's knowledge and the buyer's ignorance of the true contents of the truck load of peanuts in question, is, in effect, a bias in favor of the seller.

EFFECTS OF THE BIASED SAMPLE

The present sampling method is biased as stated in reason (1) above because of the inherent construction of the sampling tube and the manner in which the material enters the sampling tube openings. This tube which has a pointed bottom, will not sample material at the bottom of the truck for a distance of at least three inches. Also, peanuts having a high foreign material content will not flow freely into the tube. The effects can be summarized as follows:

(a) Rocks fall into the sampling tube in greater percentages than are present in the load of peanuts.

(b) Sticks and hay fall into the sampling tube in lesser percentages than are present in the load of peanuts.

(c) Foreign material, highly damaged peanuts, or high-moisture peanuts that may be at the bottom of the truck do not get into the sampling tube at all. These materials might be intentionally placed there or they might, in some cases, settle there in transit.

These effects have been verified by experimental tests and by observations made during the 1951 buying season. Thus, the sample selected for grading is biased in the case of rocky peanuts in favor of the buyer; in the case of high-stick-and-dirt peanuts, in favor of the seller; and in the case of peanuts subject to the effects of Factor (c) above, in favor of the seller.

Seemingly there is only one solution to this problem of biased samples. It consists of a method of automatically obtaining a representative sample of the entire load by unloading and reloading each truck. This sounds like a rather formidable undertaking. However, with suitable equipment it can be

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**The details of this study are given in a special report entitled, *Analytical Study of the Sampling and Grading of Farmers' Stock Peanuts*, Georgia Tech Engineering Experiment Station, Feb. 25, 1952.

accomplished at a reasonable cost. Furthermore, growing emphasis on marketing cleaner peanuts is increasing the need for plant precleaning facilities. The automatic sampling equipment can conveniently be combined with such precleaning equipment, thereby reducing the over-all costs of both units. Some of the advantages of precleaning all peanuts before marketing are as follows:

(1) More accurate and precise grades;

(2) Reduction in peanut damage and dirty-face 2's (split kernels which are dirty);

(3) More rapid subsequent shelling with fewer splits;

(4) Decrease in the storage volume required per ton of peanuts; and

(5) Improved housecleaning and reduced fire hazard in storage and plant.

A unit which can perform these functions of unloading, precleaning, automatic sampling and reloading is now being built. This equipment would have a capacity of about 300 tons of farmers' stock peanuts per day and would cost about $25,000. A similar unit having a capacity of about 100 tons per day could be built for about $12,000. If this equipment is amortized over a ten-year period, the total precleaning and sampling costs would be less than $1.00 per ton of farmers' stock peanuts. This seems to be a reasonable price to pay for the storage of clean peanuts, especially when out-grades must be guaranteed to equal in-grades.

EFFECTS OF REGRADES ON PEANUT PRICING

In addition to the error resulting from biased sampling, another factor, perhaps equally as important, is independently contributing to the mispricing of farmers' stock peanuts. This factor is "shopping around" by the seller. Even though both the seller and the buyer may call for a regrade, the seller is placed at a decided advantage due to his knowledge and the buyer's ignorance of the true quality of the load in question.

To establish this fact, a study has been made on the distribution of the values of peanuts as determined by the present grading system on repeated samples from the same load of peanuts. The random-chance variation in these values is considerable. For example, a load of peanuts whose true value is $184 per ton may have dollar estimates of its value which range from $157 to $211, as shown in Figure 1. Now it is reasonable to assume that the seller has a fair estimate of the value of his load of peanuts, whereas the buyer usually has no information other than that supplied by the grading system. Thus, if chance results in a grade estimate on the high side (above $184), the seller is satisfied, the buyer has no reason to be dissatisfied, and so the peanuts are sold. The other possibility does not follow the same course of events. If chance results in a grade estimate on the low side (below $184), the seller is dissatisfied and will demand a regrade or will merely market elsewhere. Now the chances are that the new grade estimate will be greater than the first; thus the loads will not be sold at the very low grade estimates. This has been verified by analyzing the results of a random sample of 200 regrades of runner peanuts made during the 1951 buying season. The second grades averaged $6.43 higher than the first. The net result of regrades is then shown in Figure 1 where the low grade estimates, indicated by the shaded area, are chopped off. This, in effect, raises the average price paid for all peanuts above their true value. It should be emphasized here that the seller who demands a regrade should not necessarily be criticized, since he is doing so merely to get a just price for his peanuts. The seller who chances to get a favorable price for his peanuts at the first sampling is the one who really profits.

This dilemma also has but one solution, and that is to decrease the variability in repeated grades to the point where regrades will no longer be demanded by the seller. This problem can best be solved by studying the individual analyses which go to make up the estimate of the dollar value of the peanut load.

A study of the damage analysis has been made by taking a number of samples from the same load of peanuts and having a number of inspectors grade each of these samples. A statistical analysis of these data indi-

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THIN METAL FILMS— NEW METHODS FOR THEIR PRODUCTION

By RICHARD B. BELSER*

Although thin metal films have been known from antiquity, the scope of their applications has been greatly increased by the use of different metals and, particularly, by the development of new film-forming methods. These new methods and a few modern applications of metal films are discussed in this article.

Thin metal films have been useful since the early history of civilization; they apparently originated among the eastern nations, or possibly Egypt. The first thin metal films were made of gold which, because of its ductility, malleability and noncorrosive nature, can be hammered or beaten to such extreme thinness that the sheets transmit light.** Other metals, copper, tin, zinc, palladium, lead, cadmium, silver and platinum, may be reduced to films in a similar manner, although it is likely that only silver and platinum were used almost as early as gold.

At first these films were primarily decorative in nature, used for such purposes as gilding and inlaying; they undoubtedly found other uses as talismans or as scientific curiosities among the first alchemists or philosophers. Their value as noncorrosive protection for the baser metals was undoubtedly discovered somewhat later.

Although glass mirrors coated with tinfoil appeared as early as the 13th Century, glass surfaces plated with a thin film of silver by chemical reduction were not created until 1835 by Liebig.[1] This discovery expanded the uses and production of thin films for manufacturing mirrors and instruments.

With the discovery of electrolysis and electroplating shortly after 1800, thin films really came of age. In a few years their uses extended to include those common today. Decorative and noncorrosive films are still the most common. Thin films find other applications as coatings to withstand frictional wear or to build up undersized or worn parts and as aids in manufacturing elements of electrical and electronic products. The electroplating industry, a complete field within itself, is too extensive for further discussion here.

Three methods of producing thin metal films for decoration or surface protection are "hot tinning" with molten metal, dipping and rolling. A more recent introduction into industry is metal spraying. Wire is fed into a spray gun, melted by a flame and blown out onto the surface to be plated.

In addition to the methods already mentioned, evaporation and sputtering are also gaining some industrial importance in the production of thin metal films. Although these latter methods have been known to

Figure 1. Wires of the metal to be plated by evaporation are hung on the glowing coils above the substrate.

**Research Physicist.*

**The thickness at which this first occurs is given 1/150,000 inch, which is about 1/3 the wave length of blue light. Actually green light is transmitted by such films. This measurement agrees with measurements made here on evaporated gold films about 1650 angstroms (0.0000063 in.) thick. It is stated in the *Encyclopedia Britannica* that one ounce of gold has been beaten into 300 square feet of gold leaf.

scientists for a long time, only within recent years has their application to industry become significant. Since they are probably less well known to most readers than the previously named techniques, evaporation and sputtering have been made the primary subjects of this discussion.

Evaporated Films

Of the two methods, evaporation is the more important. Its name is descriptive of the principle involved—that a metal heated to a sufficient temperature in a vacuum will melt and vaporize. The atoms thus released will condense in quantity on the first cool surface they contact. The vacuums employed are rather extreme, about one-millionth atmospheric pressure and, preferably, about one ten-millionth or less. In some processes, approximately one hundred-millionth atmospheric pressure is necessary.

Because of the extremely low pressures required with the vacuum chamber, two special pumps are employed in series. The first resembles a refrigerator compressor, being a rotary pump with spring-actuated valves sliding against an elliptical rotor. Called the forepump, it exhausts through an oil-sealing system to the atmosphere. The second pump is either an oil diffusion or a mercury vapor pump, usually the former. Both of these pumps work on the principle of the aspirator in that a stream of oil or mercury vapor follows a closed path from the boiler up a chimney. There it is diverted downward by baffles in jets of vapor to be condensed and returned to the boiler below. Air molecules from the vacuum chamber expand into the returning vapor and are forced downward to the inlet of the mechanical pump through which they are pumped to the atmosphere outside the system. Although diffusion pumps will not exhaust against atmospheric pressures, their pumping rate is tremendous when they are properly backed by a mechanical pump. Their size appears to be almost unlimited, and, since they have no mechanical moving parts, they are durable and efficient. The large-scale development of these pumps has promoted many new uses of high-vacuum processing in industry; vacuum evaporation is one technique so benefited.

Normally, metals are evaporated by heating in contact with an electric filament. Short wires of the metal are suspended on a filament of tungsten or molybdenum, depending on the metal to be evaporated. A typical arrangement is shown in Figure 1. As the filament temperature is increased, each suspended wire melts and, because of surface tension forces, draws up to the filament where it appears as a small globule. Raising the temperature further causes the globules to vaporize. A transparent vacuum chamber, i.e., a glass bell jar, will be darkened by the condensing metallic film. In a similar manner, every intercepting surface is coated. Hence, an object placed where it will intercept the metallic vapor will be coated with the evaporating metal.

Almost all metals can be evaporated. The exceptions are primarily the heavy metals of the platinum group, whose melting temperatures approach that of tungsten. In general, these are extremely rare and little used metals. Evaporation is impractical for metals with melting points above 2,000 C. On the other hand, films of gold, silver, aluminum, copper, nickel, palladium, titanium, zirconium, chromium, cadmium, indium, tin, zinc and other metals can be readily deposited by the evaporation technique. All of these metals except palladium have been deposited on glass substrates at the State Engineering Experiment Station. Such films can be deposited on many different substrates provided that the material does not outgas or vaporize at a rate faster than the vacuum pumps can handle. Thus films can be deposited on glass, plastics, cloth, paper and many other substances, as well as on metal. In contrast to electrodeposited finishes, evaporated films acquire the finish of the substrate and, when deposited on polished surfaces, need no further polishing. A film's adherence to various substances varies, depending on the metal and the substrate used, how the substrate was cleaned, the pressure in the vacuum chamber and possibly other factors. Good adherence can generally be obtained by properly adjusting the relationships between these factors. In general, films adhere fairly well to glass or metals when these are properly

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THE AUTOMOBILE ENGINE

By R. L. ALLEN*

Most American motorists want their cars to be able to get off to a fast start and to still have a reserve of acceleration for passing other cars at high speeds. How automobile manufacturers build in "high performance" at both ends of the speed range is described in this article.

We Americans are not an easy people to satisfy in our automotive demands, and we won't be while fuel stays relatively cheap in this country. A major goal of almost every American automobile manufacturer is to put a little more horsepower in his car than there is in any other make. This is not a new goal, but recently it has been given more attention than in former years. The desire seems to stem from the premise that each driver wants to be able to beat all other drivers away from every stoplight. It isn't that we who buy and drive automobiles always intend to be the first from the stoplight, but we like the smug feeling that we could if we wanted to. There is nothing we hate worse than running out of acceleration before we get to a speed that frightens us.

We have made many other demands on the automobile manufacturer without realizing what we were asking, and the manufacturers have responded amazingly well to our demands. The only engine controls we now consider desirable are ignition switch, starter button and accelerator pedal. The engine must be able to idle indefinitely at 300 rpm or operate at several thousand rpm and high load for hours at a time; and the demand on the engine may change from one end of the scale to the other in a matter of seconds. It must respond immediately to its controls in any weather from coldest winter to hottest summer. There must be no noise or vibration under any of these conditions. The only service we expect to give the engine for thousands of miles is oil and gas, with possibly a few minor adjustments. Finally, the operator must not be required to know any more about the engine than the proper order in which the controls are to be operated. There is probably no other type of engine in operation from which so much is demanded or which meets the demands so well.

Every year a new model comes on the market. The advertisements proclaim that the horsepower and the compression ratio have been increased and the mileage per gallon of gas improved. When we look at the engine, if we look at all, it appears just like the engine that was in last year's automobile. However, when we drive it, we find that it will do almost everything the advertisements claim—except for the gas mileage. In many cars the engine horsepower has been stepped up year after year without changing the basic size or outward appearance at all. This has been accomplished by such things as larger and better carburetors, better manifold design, increased compression ratio and better fuels.

The main reason that horsepower is so important is that the power required to

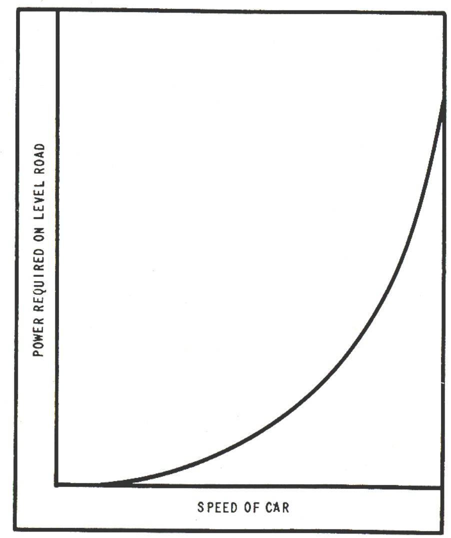

Figure 1.

*Professor of Mechanical Engineering and Faculty Research Associate.

move the car along a level road at constant speed increases approximately as the cube of the speed. This means that if it requires eighty horsepower to move a car at eighty miles per hour, then it will take almost twice that to make it travel one hundred miles per hour. (See Figure 1.) Most of this power is used in just pushing the car through the air. Since most standard-size cars have about the same frontal area, the power needed to keep them moving at a given speed is about the same. It also means that adding another ten or twenty horsepower isn't going to make the old car go much faster, *but you will be able to get to the faster speed more quickly*. You will also have some acceleration left when the other fellow's runs out.

At low speeds, the power that an automobile engine will produce is almost directly proportional to the revolutions per minute. This is indicated by Figure 2 in which the solid curve represents the relationship between engine speed and available power for an unmodified engine and the dotted curve the same relationship for the engine after its rated horsepower has been increased. As the speed increases the curve begins to level off and, in the high-speed range begins to drop.

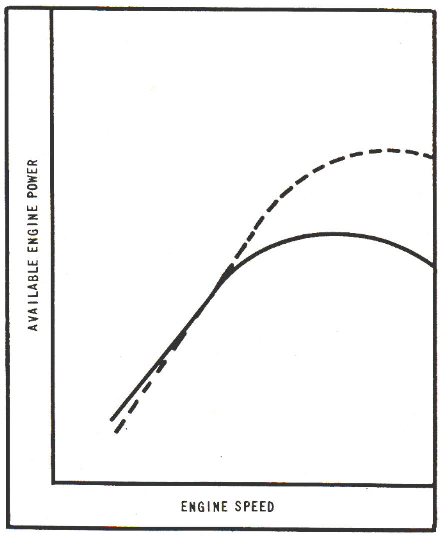

Figure 2.

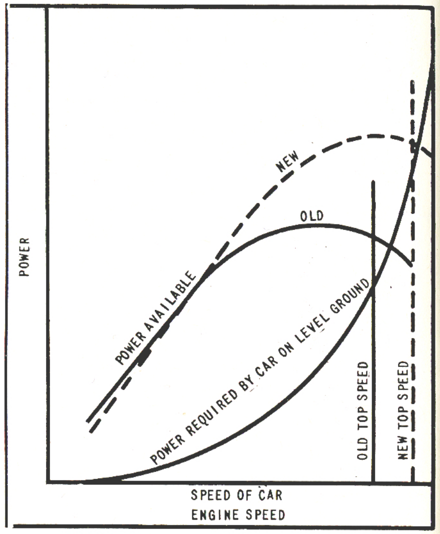

Figure 3.

If we combine the curves in Figures 1 and 2, we obtain Figure 3. At any speed of the car less than the point where the curves cross, there is much more power than is needed. We have to keep the throttle partly closed to keep the car from running away; but the more reserve we have, the more acceleration is available or the steeper hill we can pull without shifting gears. The point at which the curves cross is the point where we run completely out of acceleration, that is, where we have reached top speed of the car. The acceleration available at a given speed is proportional to the vertical distance between the curves. As will be seen in Figure 3, this acceleration stays with us much better with the newer engines, but their top speed is not much greater.

The curves in Figure 3 can be changed individually or changed in relation to each other. The only convenient way to change the horsepower required to drive the car is to make the car smaller. It is heresy to mention smaller cars, however. Since Mr. Jones has a big car, the rest of us want big cars. So, what may be done to the other curve and its relation to the power required? Fortunately, the engine manufacturer has concentrated on this curve and on fitting it to

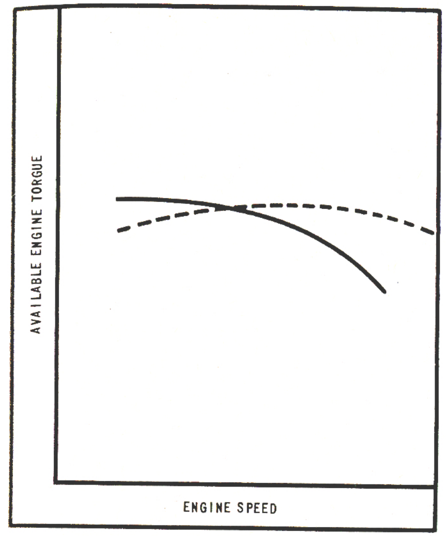

Figure 4.

the power required in any manner demanded by the driving public.

Engine horsepower is directly proportional to the product of engine torque and speed. The torque curve for the same-size engine before and after increasing the horsepower is shown in Figure 4. The horsepower is also a function of the amount of air the engine can consume. A curve showing the rate at which air is drawn into the engine would look very similar to Figure 2. A curve showing the maximum amount of air drawn into the engine per revolution would look much like the torque curve in Figure 4. In order to get more horsepower, more air must pass through the engine. The ideal curve would be one in which the engine took in the maximum amount of air per revolution, with this amount staying constant at all engine speeds. A typical curve is shown in Figure 5, for both the old and the new engine. There are many factors which affect this curve, the following being some important ones.

(1) Displacement of the engine (area of the pistons multiplied by the length of stroke)
(2) Number of cylinders
(3) Timing of the intake and exhaust valves
(4) Size of valves
(5) Lift of valves
(6) Intake manifold and carburetor
(7) Shape of combustion chamber
(8) Ratio of the diameter of cylinder to length of stroke
(9) Exhaust manifold, including the exhaust pipe and muffler

The displacement of the engine fixes the maximum point on the air-consumption curve for an engine which is not supercharged. Since we want more horsepower for the same size of engine, however, the displacement is fixed. An engine with a given displacement can have a large number of small cylinders or a small number of large cylinders. Other things being equal, the greater the number of cylinders for a given displacement, the closer the curve approaches the ideal. Unfortunately, there are disadvantages to engines having a large number of small cylinders. They are complicated to build and maintain. Also, as the cylinder dimensions decrease, the ratio of surface to volume increases and heat transfer increases. Most manufacturers have settled on six or eight cylinders as a good compromise.

The series of events as they occur in a cylinder of the typical automobile engine operating on the four-stroke cycle is shown in Figure 6. The complete cycle requires two revolutions of the engine. The exhaust valve opens several degrees before the end of the power stroke and closes a few degrees after the top center position, during the be-

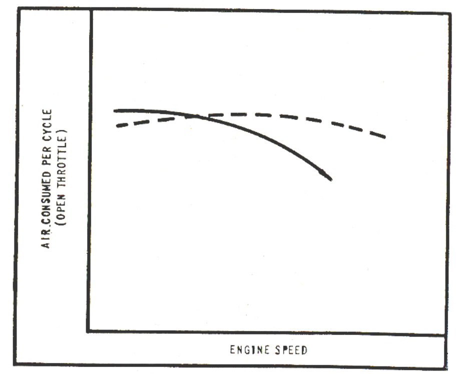

Figure 5.

ginning of the intake stroke. The intake valve opens a few degrees before the end of the exhaust stroke and closes several degrees after the beginning of the compression stroke.

The valve timing has a very great effect on the shape of the curve in Figure 5. If the valves are timed to open and close nearer to the top and bottom center positions, the low-speed end of the curve will be raised (solid line in Figure 5). This is good, because it gives the old jalopy lots of pep at low speeds. Unfortunately, it also causes the high-speed end of the curve to droop. This is bad, because the maximum horsepower is lowered, and, even though we start fast from the stoplight, the other fellow can pass us before we have gone very far. If the valves are timed to open and close farther from the top and bottom center positions, the low-speed end of the curve will droop (dashed line in Figure 5). This isn't as bad as it seems at first, because the intake valve closes so late that some of the air is pushed back out of the cylinder at the beginning of the compression stroke during the low speeds. This allows us to increase the compression ratio without an annoying detonation or "ping." Although this drooping of the curve may give us just a little sluggishness at low engine speeds, it won't be too noticeable. Anyway, we have an ace in the hole for the problem of low-speed performance. One nice thing about timing the valves this way is that we keep the high-speed end of the curve up, and this is pay dirt so far as horse-power is concerned. There is even acceleration left when we reach speeds that ought to scare us to death.

There are other things that can be done to keep the high-speed end of this curve high, such as making bigger valves, making them open wider or using larger carburetors. But let's see the ace in the hole we had for the low-speed end of the curve. In recent years there have been new developments in transmissions, which take care of this end also. These include the overdrive, the fluid clutch, the torque converter and the automatic gear shift. Most of the new transmissions combine two or more of these. In general, the less the engine torque is multiplied

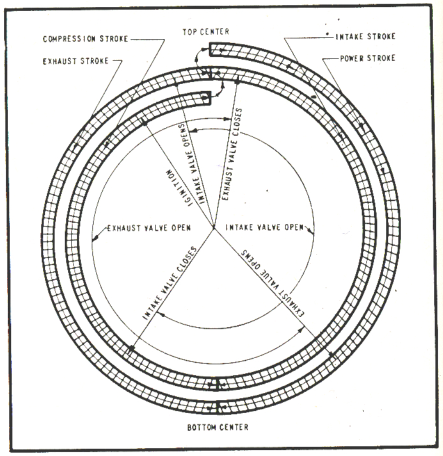

Figure 6.

before it gets to the rear wheels, the better gas mileage will be obtained. However, the more it is multiplied, the greater is the acceleration that will be obtained. These new transmissions automatically multiply the engine torque when the driver calls for acceleration and then stop multiplying it as soon as he lets up on the accelerator. With these new transmissions the low-speed engine torque is no longer so important, and this leaves the manufacturer free to concentrate on the high-speed end. The old driver could do most of the things with a conventional gear shift that the automatic transmission does for the modern driver, but it took practice.

With the new transmissions today's driver doesn't have to learn as much as formerly. The clutch pedal and gear shift have been eliminated, and there is plenty of acceleration at low car speeds and at high speeds. These improvements may cost the driver a little more gasoline, but headlights in the rear view mirror look so much better to him than taillights through the windshield that he feels it is worth the price.

CARDIAC OUTPUT

Continued from Page 4

Some investigators have calculated blood flow rates from measurements of arterial blood pressure as a function of time.[2] The method requires certain assumptions to be made about the resistance of blood vessels to flow. In actuality, the diameter of an arterial vessel changes not only because of its elasticity but also because of activation of muscle fibers in its walls. Thus, the resistance of a flow path at any instant is a highly uncertain quantity. It is expected that advances in mechanical theories of flow in nonrigid tubes will greatly improve the value of this technique for determining cardiac output.

Radioactive or dye-pigment tracers may be injected into the blood stream at one point and the concentration of the tracer measured at a distant point of the system as a function of time. From a graphical plot so obtained it is possible to calculate mean circulation time, dilution and finally the mean blood-flow rate, or cardiac output. One present technique employs a blue dye injected in a pulmonary artery by means of a catheter (the flexible tube is introduced into an opening in one of the right-arm veins and is passed through the vessels leading to the heart, into and through the right auricle and ventricle).[4] Semicontinuous blood sampling for dye concentration is made at the bracchial artery of the left arm. Errors may be introduced in this procedure by shunting of blood across the main flow circuits and by early recirculation of labeled blood. However, the method is potentially good, and measurements agreeing within 10 to 20 per cent can consistently be obtained with careful analysis of the blood samples and control of the injection rate. Recent work with radioactive tracers has been especially encouraging.

THE FICK PRINCIPLE AND APPARATUS

The universal law of conservation of mass forms the basis of one of the most fundamental and widely used principles of physiologic experimentation. The mathematical formulation actually employed is known in physics as the "equation of continuity" and in medicine as the "Fick Principle"—in honor of the man who first applied it there. The principle is almost axiomatic and will be stated as follows: the difference between the amount of a substance conveyed to an organ and the amount conveyed from that organ in a given interval of time is equal to the amount of the substance absorbed or produced by the organ in that time interval.

From reference to Figure 1 it is evident that the substance (oxygen) and the organ (lung blood) constitute a possible system for analysis by this principle. The amount of oxygen carried to the lungs in the blood stream in a given period of time can be expressed as the product of the average concentration of oxygen in the blood stream by the volume of blood which enters the lungs in the given period. If F denotes the average rate of inflow of blood during a time t, and if C_v denotes the average concentration of oxygen in the venous blood entering the lungs, then $C_v Ft$ is the amount of oxygen conveyed to the lungs by the blood stream in the time t. Similarly, if C_a denotes the average concentration of oxygen in the arterial blood leaving the lungs, then $C_a Ft$ will be the amount of oxygen carried away from the lungs by the blood stream in the time t—because the average flow of blood into and out of the lungs is the same and, in fact, is by definition "cardiac output." Thus, by the Fick principle, the blood must during its passage through the lungs absorb an amount of oxygen equal to $(C_a - C_v)Ft$, the transfer occurring, of course, in respiratory processes. Denoting by $Q(t)$ this quantity of oxygen "consumed" in the period of time t, we can now write the Fick equation for cardiac output F:

$$F = \frac{Q(t)}{(C_a - C_v)t}.$$

We could obviously have written a similar equation for the substance carbon dioxide, and the use of this alternative metabolite has some advantages.[11]

To express the oxygen consumption Q in a more useful form, we again use the law of conservation of mass, or the equation of continuity considering the gas stream into and out of the lungs as the "conveyor:"

$$Q(t) = C_i V_i(t) - C \; V_e(t);$$

where C_i and C_e are respectively, the average concentrations of oxygen in inspired and expired air, and where $V_i(t)$ and $V_e(t)$ denote the volumes of air inspired and expired in the period of time t. All of these quantities are either known or can readily be measured, with the exception of the inspired air volume V_i. In this case, since the only significant constituents of respired air are oxygen, carbon dioxide, and nitrogen (the concentrations of which are all known or measurable for inspired atmospheric air), and since nitrogen transfer in the lungs is essentially nil, V_i can be calculated by measuring one quantity, namely, the average concentration of carbon dioxide in expired air, say C'_e.*

Thus, if we assume that inspired air is of known and unchanging composition, the determination of cardiac output by the Fick principle, considering oxygen as the conserved substance, involves measurement of five variables: two requiring fluid analysis—namely, the average concentrations of oxygen in arterial blood, C_a, and in venous blood, C_v; and three requiring gaseous analysis—namely, the average concentrations of oxygen, C_e, and carbon dioxide, C'_e, in expired air and the volume, V_e, of air expired in the time t during which the concentration averages were taken. A schematic diagram of the apparatus which was constructed for the Emory University Cardiovascular Laboratory to obtain these measurements is shown in Figure 2.

*Actually, expired air is essentially saturated with water vapor at body temperature. However, as it is possible to correct for this vapor rather easily, no further mention of it will be made in this paper.

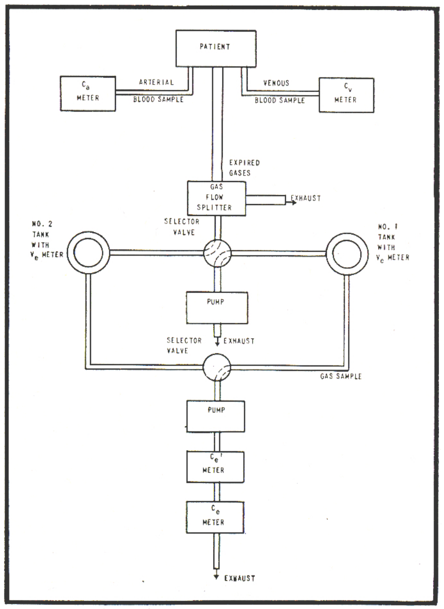

Figure 2. Schematic diagram of apparatus for determining cardiac output by the Frick Principle.

The fluid analysis part of the system is mechanically quite simple, involving pumps to remove arterial and venous blood samples from the patient and deliver them to suitable oxygen concentration meters.

The gaseous analysis part of the system includes a mouthpiece, or mask, having flutter valves (not shown in Figure 2) by means of which inspired and expired air flows are kept separate. The expired air stream is reduced in amount by a splitter which vents some known fraction (80 per cent) of the flow to the outside, while passing the remainder into one of two collecting tanks through an electrically controlled selector valve. The purpose of the splitter is to permit use of a smaller and more convenient tank than would be needed to collect all of the gas expired by a heavily breathing patient in the time t over which measurements have to be averaged. Successive breaths of air forced into one of the collecting tanks are mixed together by diffusion and air currents, so that the total volume collected over the interval of time t becomes a homogenous "aliquot" of average composition. At the end of the averaging period, the expiratory air stream is diverted to the second tank by a change in position of the selector valve. While the second tank is filling breath-by-breath, the following sequence of operations is performed with the first aliquot: (1) the volume of gas collected is measured, from which the total volume of gas expired in the averaging period t can be calculated by taking into account the known splitting ratio; (2) a sampling pump draws some of the mixed gas out of the tank and passes it through meters which measure the concen-

trations of carbon dioxide and oxygen; and (3) just before the second tank reaches the end of its averaging period, an exhaust fan empties the first tank completely so that it will be ready for a new cycle of gas collection and analysis.

The whole process is performed automatically, through electrical controls, and could be maintained for an indefinite length of time. Thus, determinations of cardiac output are provided "semicontinuously"—in successive averaging periods of duration t—by the reciprocal functioning of the twin collecting tanks.

Thus far the discussion has been concerned primarily with the selection of a method and a type of apparatus for solving the cardiac-output measurement problem. We want now to consider specific design details of the instrumentation and to point out some of the compromises which had to be accepted in developing a practical operational system. It must be admitted that engineering refinements, and what the physicist would term "elegance," had all too frequently to be sacrificed in order to make use of equipment components already at hand or having "good delivery dates" from manufacturing sources. Concessions to economy and expediency are, however, sometimes unavoidable in engineering. The "austere" approach to "first models" may even result in a more compact, less costly finished product than would have resulted from unlimited incorporation of components originally considered desirable.

THE GASEOUS ANALYSIS SYSTEM

Figure 3 depicts typical characteristics of the expiratory gas stream in resting man. The graph of instantaneous flow rate (known as a pneumotachogram) shows that the velocity of effluent air throughout a breathing cycle varies widely, and, even under supposedly stable and unchanging conditions of the subject, some variation in the pulse contour occurs from one breath to the next. The graphs of oxygen (O_2) and carbon dioxide (CO_2) concentrations reveal that the ratio of these two functions of time is by no means constant throughout the breathing cycle, and, again, variations may be observed

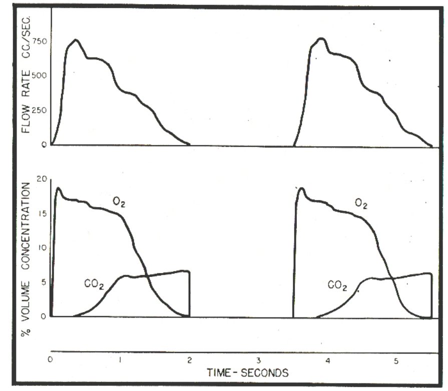

Figure 3. A typical pneumotachogram for two consecutive exhalations (by resting man) is shown in the upper line while the corresponding oxygen and carbon dioxide concentrations are shown below.

from one breath to the next.*

It was pointed out earlier that cardiac output is best defined by taking a time average over several heart beats. It is now evident that determinations of cardiac output by the Fick method require an averaging time of at least one breath period. However, there is another and much more important factor to be considered: the Fick equation implies that the air and blood involved in the interchange of oxygen can be isolated from all other air and blood naturally present. Actually, because of the inaccessibility of the system constituents and because of their somewhat random interaction, a considerable phase difference may exist between what is measured in the fluid analysis and what is measured in the gaseous analysis. The only apparent way to circumvent this fundamental difficulty is to choose an averaging time so large that all lags in the respiratory and circulatory processes be-

*The following comments may clarify oxygen-carbon dioxide relationship in expired air. Inspired atmospheric air is high in oxygen and low in carbon dioxide. The gas which is first expelled from the mouth or nose in expiration is that which has filled the trachea and bronchial passages—where little interaction between air and blood can occur; it is, therefore, essentially atmospheric air. The terminal gas of expiration is that which has filled the alveoli, deep within the lungs, where blood and air are in intimate contact and can reach gaseous equilibrium through the physical process of diffusion.

come negligible. A cycling period of 60 seconds was finally chosen for the Emory University apparatus, in order to acquire other advantages of a long averaging time. However, provisions were made to change later to a 30-second cycling period, which it was felt would be the minimum time interval needed to satisfy the validity requirement for the Fick method.

Normal resting man breathes some 6 liters of air per minute. Thus, to cover one extreme of experimental conditions, it was essential that volumes of gas in this order of magnitude be accurately measurable. The conditions of physiologic activity of interest in the Cardiovascular Laboratory's research program prescribed an upper extreme of 30 liters of air per minute. Investigation of the market in gas collection devices resulted in a narrowing of immediate choices to either 6-liter or 30-liter capacity spirometers. These are similar to the familiar basal metabolism apparatus, consisting of a cylindrical metal bell which is suspended from a pulley with a counterbalancing weight so as to move in and out of a concentric cylindrical tank of water in accordance with the influx or efflux of gas through a pipe entering the closed chamber at the water surface. The 6-liter tank would give more accurate readings for small volumes. However, used with a 4:1 gas-flow splitter, it would multiply errors in measuring larger expiratory volumes. Partly because of space considerations and partly for another, phenomenological reason (to be brought out below), it was decided to utilize standard 6-liter spirometers for gas collection.

Perhaps the most troublesome problem in the development of the mechanical apparatus was to obtain a satisfactory compromise between the "dead space" and "back resistance" properties of the system. It had been shown by exploratory studies with the pneumotachograph that a human subject can detect resistances to breathing which exceed a back pressure equivalent to 6 millimeters of water. This meant that, unless the proposed apparatus could be sufficiently "loosely coupled" to the human system, the process of measuring cardiac output might alter the very quantity sought through the action of neurohormonal anxiety mechanisms or even (by pure physics) through the mechanical loading itself. The resistance of the piping, flow splitter and selector valve had to be kept low, and any friction in the movement of the spirometer bells had to be minimized. At the same time, however, the volumes of the piping, etc.—in which air from one 1-minute cycle would be trapped and form part of the sample obtained for the next 1-minute cycle—had to be kept "negligible." If small-diameter tubing from the patient to the apparatus proper were employed as a means of reducing this dead space, the resistance to flow would be increased. To minimize both dead space and back resistance, the tubing could be made short; but then the apparatus proper would have to be almost on top of the patient. This was undesirable not only for psychological reasons (another form of overly tight "coupling"), but also because it would severely restrict movement of the patient to obtain the desired conditions of tilt, etc.

As frequently happens in engineering research and development, the apparent problem resolved itself into a new problem raised by the apparently logical solution of a previous problem. After selection of the 6-liter size for the gas collection tanks, two standard spirometers were purchased and immediately modified to provide sampling outlets and other features called for by the over-all system arrangement. At the same time, empirical design of a gas-flow splitter was undertaken to shunt 80 per cent of an airstream one way and pass 20 per cent into either one of the modified spirometers. Because of the highly variable flow rates encountered in expiratory pulses and the necessity for obtaining accurate volumes in the collected aliquot, attention was directed toward matching the mechanical impedance characteristics of the 80 per cent "dumping" circuit with those of the tank circuit (in, of course, a 1:4 ratio) so that a constant split would be obtained over a wide range of air velocities. No simple way could be found to simulate simultaneously the inertia of the tank and counterweight (providing impedance to acceleration), the friction of the pulley and of the bell in contact with water

(offering resistance to velocity) and the compliance of the volume of air already residing in the tank (tending to buffer out sudden changes in volume). It was particularly distressing to discover that the frictional effect was not constant and could not be made constant even by installing the best ball bearings in the pulley wheel and adding detergents to the water to reduce "clinging" on the sides of the bell. The only practical answer at this point was to make the resistance of the piping leading to the tanks large, so large in fact that the variable impedance properties of each tank would be satisfactorily masked.

Thus, by choosing the "best" gas collectors, the adverse coupling between instrument and patient (the avoidance of which was the original objective) had ultimately to be accepted in part; but this compromise permitted greater physical isolation of the instrument and patient and thereby (without introducing too much dead-space error) reduced another form of adverse coupling as well as a mechanical obstacle to necessary movement of the patient. This circle of interacting factors is fairly typical of biological instrumentation problems.

Design of the remaining components of the gas analysis system proved to be comparatively straightforward, and the end products will be discussed only briefly. In order to obtain automatic recordings of the volumes of expired gas collected in the tanks per minute, a photocell arrangement is used in conjunction with a plastic pulley wheel on which has been painted an opaque spiral figure. As the wheel rotates with the rising spirometer bell, it changes the amount of light transmitted through the plastic from a fixed source located in line with the photocell on the opposite side of the pulley. The photocell output had, of course, to be calibrated against tank volume.

The pump for forcing samples of the tank gas aliquots into the oxygen and carbon dioxide analyzers consists of a reversing piston arrangement. The piston moves in a cylinder so constructed that, as the sample from one tank is drawn into the chamber on one side of the cylinder, the sample obtained from the other tank during the preceding half-cycle is pushed out into the metering circuit.

The quantitative measurement of components in a gaseous mixture is most accurately accomplished by methods of chemical analysis. However, these methods do not lend themselves readily to continuous processes. Methods of analysis based on physical properties of the gas molecules are more feasible; and, depending on the particular mixture of interest, a wide assortment of choices may be utilized for selective gas determinations.[9] For an oxygen-nitrogen-carbon dioxide combination, the strong paramagnetic susceptibility of oxygen may be used to distinguish it from the other two gases. Inasmuch as a commercial instrument utilizing this principle was already in hand and was claimed to be suitable for the job,[1] no other possibility was seriously entertained. For carbon dioxide determinations there were commercially available cheap, reliable and reasonably accurate instruments based on the thermal conductivity properties of the gas.[5,8]

The response time of both paramagnetic oxygen meters and thermal-conductivity carbon-dioxide meters is quite long—about 40 seconds. It was partly to accommodate these lags that the 60-second cycling time was chosen for the cardiac-output apparatus. In addition, both instruments require that the flow rate of the sampled gas through the detecting cells be slow (50-200 cc/min) and constant. This characteristic was achieved by driving the gas sampling pump with a constant-speed motor through a rack-and-gear transmission. The fact that the tank gas aliquots from which the samples were drawn are essentially homogeneous ensures that each gas meter approaches an asymptotic reading during each averaging period.

One more feature of the gas analysis portion of the system should be mentioned. It is obvious that an arbitrary one-minue interval may not include an integral number of breaths. The question arose as to whether it would be more desirable to keep successive cycling periods of constant duration or to terminate each cycle at the end of a breath. It was decided that the latter would be physiologically more valid in the Fick method of determining cardiac output. This meant that the master timing controls would have to be synchronized not only with a standard clock but also with the respiratory activity of the patient. A suitable system for sensing the completion of a breath was not very difficult to devise, but the need for a physiologically valid as well as mechanically satisfactory solution is typical of biological engineering problems.

BLOOD ANALYSIS SYSTEM

The accepted physical method for continuous determination of the oxygen content of blood makes use of differences in the light-absorptive properties of oxygenated and deoxygenated blood which exist in the red and infrared spectral regions. The technique, developed by Wood and Millikan, led to the design of a practical instrument, the *oximeter,* for clinical purposes.[10,12] In the oximeter, blood samples are drawn into accurately constructed chambers (called cuvettes) which are irradiated by light in the desired spectral range. The transmitted light is broken into sharp bands centered about wavelengths of 6500 Angstrom units (infrared) and 8000 Angstrom units (red) by means of suitable selective filters. Pairs of photocells on the opposite side of the cuvettes respond to the relative transmissions of the blood at these two wavelengths. Calculations based on knowledge of the characteristic curves and on the measured outputs of the photocells permit determination of the oxygen concentrations in the blood samples.

Because of problems attendant to the collection and oximetry of blood aliquots over successive 1-minute periods, the blood analysis system was designed for continuous sampling. The arterial and venous blood-sampling pumps indicated in Figure 2 consist of a pair of large syringes connected to the patient by narrow-bore tubing, in which the oximeter cuvettes are interposed. The syringes are pulled out at a very slow rate (4 cc/min) by a motor-driven screw. Instantaneous readings of blood-oxygen concentration which are obtained from the oximeter by this means must be converted to 1-minute time averages by mathematical operations on continuously recorded curves before the fluid analysis data can be combined with gas analysis data to obtain cardiac output determinations.

RECORDING SYSTEM

The choice of methods for recording the various pieces of information obtained with output apparatus was largely determined by the availability to the project of an 18-inch strip-paper camera. To obtain the photographic traces, a bank of optical galvanometers was set up in a light-tight tunnel connecting with the camera lens. The use of a long optical lever arm provides very high instrument sensitivity. Although, from a mechanical standpoint, the recording apparatus is less elegant than might be desired, any system other than a photographic-optical galvanometer arrangement would have required expensive electronic amplifiers.

In practice eight instrument channels are used: one for the volumes of expired air measured at each of the collecting tanks on alternate 1-minute cycles; one each for the concentrations of oxygen and carbon dioxide in the expired gas samples; four for the infrared and red oximeter readings of venous and arterial blood oxygen; and one for introducing coding or other auxiliary information on the records. The photographic paper is run through the camera at a speed of 1.25 millimeters per second, and approximately eight feet of recording is obtained in a typical experimental procedure.

The analysis of all this information is necessarily complex and time-consuming. Several unique adjustable scales have been devised to aid in making quantitative measurements from the records and in computing cardiac output from these intermediate data.

The instrumentation techniques employed in the semicontinuous cardiac-output analyzer described here admittedly do not constitute the best solution to the problem of measuring the flow rate of blood. Several much less complicated approaches seem feasible, but, at the moment, they must await further development. As has been indicated, the innate characteristics of the human cardiovascular system preclude as simple an

approach as might be made in nonliving rigid and accessible flow systems. The same sequence followed by other engineers—study, design, build, test and improve—must be followed by the biological instrumentation engineer. As he gains experience in what is a relatively new field, his work may be expected to contribute importantly to human welfare.

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SAMPLING PEANUTS

Continued from Page 6

cated that the results obtained by each inspector were not significantly different from those obtained by the other inspectors. More specifically, there was no significant difference in either the experimental technique or the judgment of the various inspectors. Similarly, there was no significant difference from one sample to another. This is what would be expected, since damaged peanuts are normally distributed at random throughout the load of peanuts. Thus, the variation of repeated damage analyses can be attributed entirely to chance variation in the damage content of the four-ounce sample analyzed. This conclusion was verified by comparison of the experimental variation with the theoretical variation predicted by the mathematical laws of chance. If the following assumptions are made,

(1) the four-ounce sample of peanuts, which for the runner type contains approximately 200 kernels, is a random sample from an infinite source of peanuts,
(2) the good and damaged kernels are all approximately the same weight,
(3) the presence of a damaged kernel in one-half the peanut does not affect the probability of obtaining a damaged kernel in the other half of the peanut,

then the Binomial Expansion can be used to calculate the expected chance variation in percentage of damaged kernels in repeated samples. This theoretical variation, expressed as the average range between duplicate analyses, has been calculated for a number of sample sizes and is shown by the solid lines in Figure 2. The experimental values plotted on this graph show excellent agreement with the theoretical curves. This verifies the previous conclusion that the variation in repeated estimates of the damage content is due to the chance variation in the damage content of the samples graded. Thus, the sample size necessary to keep this variation within any prescribed limits can be calculated.

Of the other variables involved in pricing peanuts, only the percentage of sound mature kernels and the percentage of foreign material are important. A similar study has shown that their variation decreases with sample size in about the same manner as the damage analysis.

To solve the problem which has resulted from "shopping around" by the peanut-seller, a sample size must be chosen which will have an inherent variability of such a magnitude that this practice will be unnecessary and will gradually disappear. It is felt, after studying Figure 2 and the other factors involved, that this can be accomplished in the

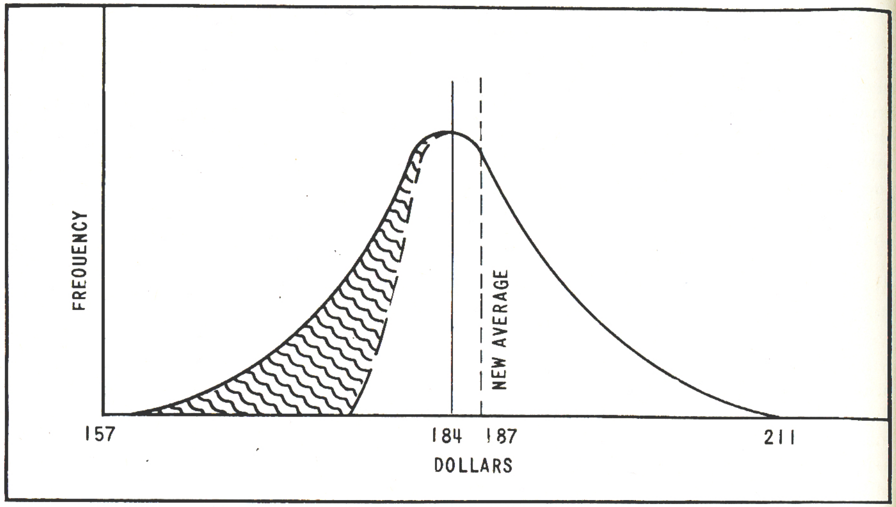

Figure 1. Although repeated samplings of the same load would give a distribution of estimated values as shown by the solid curve, the seller, knowing quite closely the load's true value, will reject all bids falling in the shaded area and will accept any new bid falling above the true value.

peanut industry by using a sample of about two pounds. Grading a sample of this size will undoubtedly call for the use of some automatic equipment to speed up the operation. However, it is seemingly the only satisfactory solution to the problem. It is felt that a sound grading system will improve buyer-seller relations, as well as aid the buyer in properly segregating the peanuts according to damage content, a point which is extremely important in selecting peanuts to be shelled for the edible trade.

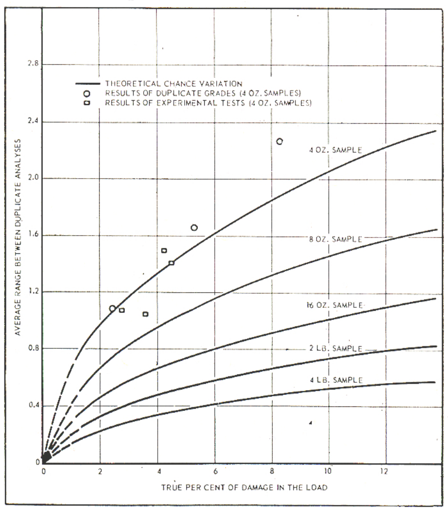

Figure 2. Theoretical variation in the indicated proportion of damaged kernels as shown by duplicate samples.

SUMMARY

In conclusion, the following recommendations on sampling and grading farmers' stock peanuts are made.

(1) Preclean all peanuts before sampling.
(2) Automatically sample the entire load of peanuts as it is being reloaded.
(3) Use about a two-pound sample for grading.

Points of general interest brought out in this study are the importance of the precision as well as the accuracy of any system for grading an agricultural commodity and the need for sound statistical analyses of sampling problems to determine the type and size of sample required as well as the mechanical developments necessary to facilitate collecting and handling these samples.

THIN METAL FILMS

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cleaned, but their adherence to organic substrate is less predictable.

The thicknesses of deposited films may be estimated, in a rough fashion, by evaporating a known weight of metal and by assuming that it is deposited as a spherical shell with a radius equal to the filament-substrate distance. Thus $4\Pi R^2$ multiplied by the thickness of the film multiplied by the density of the metal is equal to the weight of the metal evaporated; and the thickness is equal to the weight of evaporated metal divided by $4\Pi R^2$ times the density. A correction would normally be made for the difference between the planarity of the spherical shell and the substrate. However, a number of other factors of greater magnitude influence the actual thickness, making the correction of little importance. These elements are the type of filament, the type of metal, the type of chamber and the scattering occurring both in the chamber and from the substrate. These scattering effects appear to be primarily functions of the filament-substrate distance. In work at the State Engineering Experiment Station, films deposited at distances of 5-7 cm checked well in actual thickness with film thicknesses predicted by the formula. In general, thicknesses for a specific setup should be checked by weighing sample films.

Accurately measuring the thicknesses of such films is no mean feat, since they normally are only a few millionths of an inch thick. Such measurements are generally obtained by weighing the metal deposited on previously tared substrates with a sensitive analytical or micro-analytical balance and, from the weight obtained, calculating the thickness. For dense metals such as gold this technique is relatively accurate; for aluminum it is not very applicable. A second method considered extremely accurate utilizes the multiple-beam interferometer described by Tolansky[3] and Scott[2]. Except for special scientific uses or in research investigations, exact thicknesses are not of great importance. The fact that these films normally are considerably thinner than electroplated films may somewhat limit their usefulness.

Present uses of evaporated metal films are primarily decorative, and such novelties as metal-coated plastic, cloth and paper may be familiar to the reader. The early uses for these films included optical equipment such as mirrors. Aluminum mirrors deposited by this method are superior to those of silver from the standpoints of permanence, noncorrosiveness and abrasion resistance, although they are slightly inferior in reflectivity when compared to newly coated silver mirrors. However, silver becomes tarnished with age, while aluminum retains its original reflectivity. Evaporated films have gained considerable prominence in the electronic industries through use in capacitors, circuit elements and crystal plating. Other uses which are purely theoretical or scientific will be discussed later.

Sputtered Films

Sputtered films are also deposited in a vacuum, but, instead of being evaporated from a filament, atoms are knocked from a metal cathode by means of high-speed particles accelerated by a high potential impressed between electrodes in the vacuum chamber. The vacuum requirements for sputtering are considerably less difficult to obtain, since a good mechanical vacuum pump will readily reach the necessary vacuum of one ten-thousandth to one hundred-thousandth atmospheric pressure.

The general setup for sputtering may be seen in Figure 2. A high voltage is impressed between the cathode, C, and the anode, A. The cathode is made of the metal to be sputtered (such as silver). The substrate is positioned at S, a distance generally about 3-5 cm from C. An inner cylinder of glass, D, is sometimes used to confine the discharge. The anode is usually made of aluminum which sputters at an extremely low rate. All other metal should be eliminated. Greases and gaskets must also be shielded.

The operation of the unit, although not completely understood, is thought to be as follows: when a high voltage is impressed across the electrodes at a vacuum of one-tenth to one-hundredth mm of mercury, the air (or other gas) molecules are ionized. Positively charged particles bombard the cathode, where their energy is expended. The collisions appear to energize certain metallic atoms of the cathode sufficiently for them to escape and, in essence, evaporation from microscopic areas occurs. These atoms upon contact with a suitable substrate are captured and a metallic film is built up. The rate at which this occurs is normally considerably lower than in evaporation. The latter may take place in seconds, whereas sputtering may take from a few minutes to a few hours. However, sputtered films exhibit excellent adherence as a result of the cleaning action of ionic bombardment of the substrate during or before the sputtering. This effect may be somewhat enhanced by reversing the polarity in the chamber for a short period prior to the actual sputtering operation.

The advantages of sputtering over evaporation are simpler equipment, better adherence and, possibly, better control of film thickness once the equipment is calibrated. Its disadvantages are lower production rate, limited number of metals which may be employed practically,* and limitations imposed by the ability of substrate to withstand the heat generated in the operation. There is

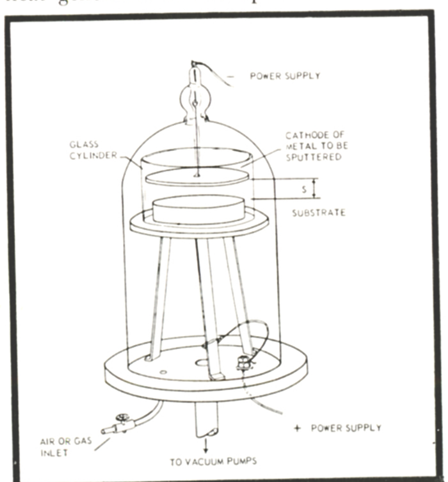
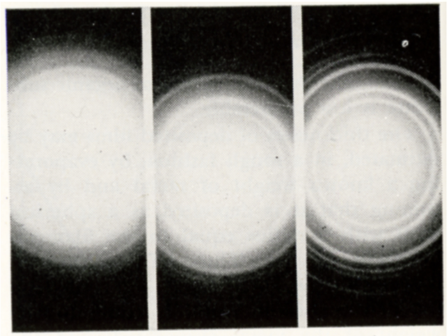


Figure 2. Although many modifications have been developed, these elements are typical of sputtering apparatus.



A. 15Å *B. 30Å* *C. 70Å*

Figure 3. Silver films only four atomic layers thick (A.) begin to give the electron diffraction pattern of bulk gold. As the film thickness increases, the pattern becomes more distinct.

a further disadvantage that the whole operation appears to be a little tricky on occasion, although good results seem uniformly obtainable once the process is stabilized.

Sputtering has its greatest application in coating mirrors and in coating quartz crystals in the electronic industry. Silver and gold are the metals most commonly sputtered.

The commercial uses of evaporated or sputtered films have been discussed in some detail. They also have applications in the field of the theory of metals and of matter, and these are of special interest to metallurgists, physicists and chemists.

The vast technological development of our present civilization has been made possible to a considerable degree by the great progress attained in the production and refinement of metallic substances. The history of man has been measured and titled by each step forward in this direction, e.g., the stone age, the bronze age, the iron age. In more recent times has come the mass production of steel, aluminum and magnesium; and the future looks bright for other metals such as titanium, zirconium, vanadium and beryllium.

Because of the many valuable properties

*A list of metals and sputtering rates is given in *Techniques in Experimental Electronics* by Bachman, John Wiley and Sons (1948), page 118.

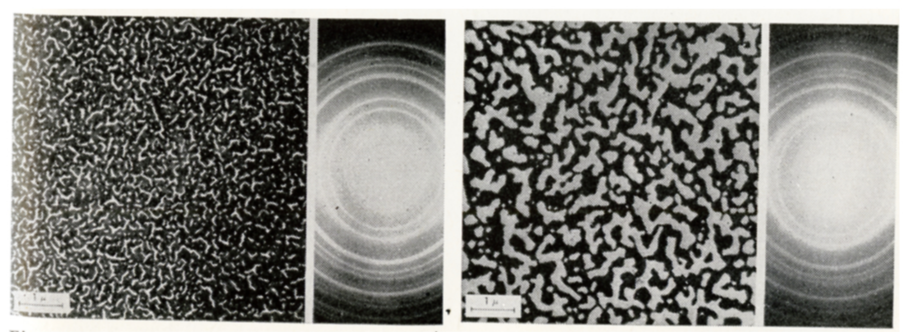
of metals, the exact nature of their structure has been of interest to scientists of all periods in history. Their properties of strength, elasticity, reflectivity, conduction of heat, conduction of electricity, density, hardness, ductility, malleability, etc., have been the subject of many investigations aimed at determining why they are what they are in the various metals. The considerable change in these properties which results when a small percentage of one metal is added to another is also of extreme interest; and this whole field of alloys remains a most fertile one for future investigation, for the number of combinations that may be studied is almost without limit.

If one builds up metallic structures atom by atom, as may be done in evaporation and sputtering, it would appear that he may obtain interesting information concerning their structures and properties. Similarly he can build up mixtures of metals by depositing two or more simultaneously and can observe the reactions of the resulting films to various measurements and treatments.

Many astute inferences can be drawn from electron micrographs, electron and x-ray diffraction patterns of the films and study of their electrical resistivities and optical properties. These may provide information concerning the type and size of the metal crystals, the growth of such crystals, the corrosion resistance of the metal, rates of metallic diffusion, etc.

The thickness of thin films may have a marked effect on their properties, as the following discussion of gold films evaporated onto glass or silicon monoxide substrates indicates. Such films of three or four atomic layers in thickness are hardly visible to the eye. However, films ten atomic layers thick are definitely visible, and those of about twenty-five atomic layers exhibit fairly high reflectivity, although they are semitransparent and they transmit green light. At an average thickness of four atomic layers (about 15×10^{-8} cm), such films appear to have a structure corresponding to the normal crystalline form of gold, that is, face-centered cubic. However, electron diffraction patterns show a fuzziness indicative of smaller size crystallites. At film thicknesses of 15-20 atomic layers, definite sharpening of the diffraction-pattern lines is observed, implying a normal gold structure (see Figure 3). Studies show a very large reduction in the electrical resistivity of these films with increases in thickness through the range of 4-20 atomic layers. For films 25 atomic layers thick, the resistivity is about five times that normal for bulk metal. A gold film 50 atomic layers thick has a resistivity approximately twice that of the bulk metal.

If gold (or other metal), when evaporated, leaves the filament atom by atom and arrives at the substrate in similar fashion, the atoms might not be expected initially to bond with each other as completely as they are bonded in bulk metal, especially considering the effects of surface forces, the possible irregularities on the surface of the substrate and the possible introduction of impurities by the gas in the chamber. However, with increasing time, temperature,



Figures 4 and 4a. The aggregation and sharpening of diffraction pattern lines which occur upon heating very thin gold films are shown in these before and after pictures.

pressure and other factors, one might expect better bonding between adjacent atoms. This can actually be noted by measurement. However, if the temperature is increased considerably, the excited atoms appear to overcome the original bond to each microscopic unit area of the substrate and combine, because of cohesive forces, into more or less spherical globules randomly scattered over the surface of the substrate. Such aggregation causes drastic changes in the observed properties of the films.

Heating extremely thin gold films (less than 100 angstroms thick) in air to relatively low temperatures (under about 300° C) causes changes in all of the observed characteristics, as indicated in Figures 4 and 4a. Depending upon the degree of heating, partial or complete aggregation apparently occurs, making the film become almost invisible, its resistivity becomes very large or infinite and the color of the light it transmits may change from green to red. Also, the lines of its electron diffraction pattern usually sharpen appreciably. In the case of somewhat thicker films, the reactions to heating are different: the resistivity may decrease, and aggregation does not occur to the same degree. Obviously, information on considerable value may be derived from observation of these changes.

The observations reported here were made on the basis of a series of tests on a simple metal, gold. The fact that gold continues to show its noble nature, particularly as regards corrosion resistance, even in very thin films seems quite impressive. However, each metal has many interesting features, and, of the 70-odd metals now recognized, only a few have been studied in any detail by the methods just described. It is toward the countless experiments yet to be performed that one should look for new frontiers in thin metal films.

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RESEARCH PAYS OFF

Continued from Page 2

all its production-research expenditures during the past ten years." By discovering how it can reduce the amount of water necessary to inject into the field in order to "flood out" the oil, the company has saved $2,000,000 in operating costs and an additional $195,000 in pumping costs. It has also been able to bring to the surface 310,000 more barrels of oil with a sales price of $1,312,000.

The company's payoff is obvious from the above figures. The impact on the petroleum industry and American motorists of any improvement in the recovery of Bradford crude oil can be understood in the light of two facts: because of its particular composition, it is the preferred raw material for lubricating oils; and it is in far greater demand than the waning Pennsylvania field can supply. The Bradford field still contains an estimated 750,000,000 barrels of oil, only part of which is economically recoverable by known methods. In speaking of research results to date, the company's president recently said, "The record of progress encourages the belief that even further advances may be anticipated as a result of continued research devoted both to studies on methods for reducing production costs and for the improvement of recovery efficiency. For every one per cent increase in the present recovery method, 7,500,000 barrels would be added to the recoverable crude-oil reserves of the field."

Consideration of how the competitive, free-enterprise system works is all that is necessary to predict what the success of this research really means—additional profits for the company, more abundant easily processed raw material for the refiners and top quality lubricants at lower cost for the consuming public. Working backward in this chain of causation, it seems safe to say that if research can make it possible to give the public the product it needs at a price it can afford, then research will have a payoff in *your* business.