the fact that it contains so many variable elements. And, in fact, the great length of time consumed in making each single experiment was caused by the difficulty of holding 11 variables constant and uniform throughout the experiment, while the effect of the twelfth variable was being investigated. Holding the 11 variables constant was far more difficult than the investigation of the twelfth element.

As, one after another, the effect upon the cutting speed of each of these variables was investigated, in order that practical use could be made of this knowledge, it was necessary to find a mathematical formula which expressed in concise form the laws which had been obtained. As examples of the 12 formulae which were developed, the 3 following are given.

$$P = 45{,}000\ D^{\frac{14}{15}}\ F^{\frac{3}{4}}$$

$$V = \frac{90}{T^{\frac{1}{8}}}$$

$$V = \frac{11.9}{F^{0.65}\left(\frac{48D}{3}\right)^{0.2373 + \frac{2.4}{18+24D}}}$$

After these laws had been investigated and the various formulae which mathematically expressed them had been determined there still remained the difficult task of how to solve one of these complicated mathematical problems quickly enough to make this knowledge available for everyday use. If a good mathematician who had these formulae before him were to attempt to get the proper answer (i. e. to get the correct cutting speed and feed by working in the ordinary way), it would take him from two to six hours, say, to solve a single problem; far longer to solve the mathematical problem than would be taken in most cases by the workman in doing the whole job in his machine.

Thus a task of considerable magnitude which faced us was that of finding a quick solution of this problem, and as we made progress in its solution the whole problem was from time to time presented by me to one after another of the noted mathematicians in this country. They were offered any reasonable fee for a rapid, practical method to be used in its solution. Some of these men merely glanced at it; others, for the sake of being courteous, kept it before them for some two or three weeks. They all gave us practically the same answer, that in many cases it was possible to solve mathematical problems which contained 4 variables and in some cases problems with 5 or 6 variables, but that it was manifestly impossible to solve a problem containing 12 variables in any other way than by the slow process of "trial and error."

A quick solution was, however, so much of a necessity in our everyday work of running machine shops that in spite of the small encouragement received from the mathematicians we continued at irregular periods, through a term of 15 years, to give a large amount of time searching for a simple solution. Four or five men at various periods gave practically their whole time to this work (among these men were Mr. Sinclair, Mr. Gault, and Mr. Barth) and finally, while we were at the Bethlehem Steel Co. the slide rule was developed, which is illustrated on folder No. 11 of the paper "On the art of cutting metals," which is in the hands of your committee and is described in detail in the paper presented by Mr. Carl G. Barth to the American Society of Mechanical Engineers, entitled "Slide rules for the machine shop, as a part of the Taylor system of management" (Vol. XXV of The Transactions of the American Society of Mechanical Engineers). By means of this slide rule one of these intricate problems can be solved in less than half a minute by any good mechanic, whether he understands anything about mathematics or not, thus making available for everyday practical use the years of experimenting on the art of cutting metals.

This is a good illustration of the fact that some way can always be found of making practical, everyday use of complicated scientific data which appears to be beyond the experience and the range of the technical training of ordinary practical men. These slide rules have been for years in constant daily use by machinists having no knowledge of mathematics.

A glance at the intricate mathematical formulae which represent the laws of cutting metals should clearly show the reason why it is impos-

sible for any machinist, without the aid of these laws and who depends upon his personal experience, correctly to guess at the answer to the two questions:

What speed shall I use?

What feed shall I use?

even though he may repeat the same piece of work many times.

To return to the case of the machinist who had been working for 10 to 12 years in machining the same pieces over and over again, there was but a remote chance in any of the various kinds of work which this man did that he should hit upon the one best method of doing each piece of work out of the hundreds of possible methods which lay before him. In considering this typical case it must also be remembered that the metal-cutting machines throughout our machine shops have practically all been speeded by their makers by guesswork and without the knowledge obtained through a study of the art of cutting metals. As I have said before, in the machine shops systemized by us we have found that there is not one machine in twenty which is speeded by its makers at anywhere near the correct cutting speed. So that, in order to compete with the science of cutting metals the machinist, before he could use proper speeds, would first have to put new pulleys on the countershaft of his machine and also make in most cases changes in the shapes and treatment of his tools, etc. Many of these changes are matters entirely beyond his control, even if he knows what ought to be done.

If the reason is clear to you why the rule-of-thumb knowledge obtained by the machinist who is engaged on repeat work cannot possibly compete with the true science of cutting metals, it should be even more apparent why the high-class mechanic, who is called upon to do a great variety of work from day to day, is even less able to compete with this science. The high-class mechanic who does a different kind of work each day, in order to do each job in the quickest time, would need, in addition to a thorough knowledge of the art of cutting metals, a vast knowledge and experience in the quickest way of doing each kind of handwork. And by calling to mind the gain which was made by Mr. Gilbreth through his motion and time study in laying bricks, you will appreciate the great possibilities for quicker methods of doing all kinds of handwork which lie before every tradesman after he has the help which comes from a scientific motion and time study of his work.

For nearly 30 years past time-study men connected with the management of machine shops have been devoting their whole time to a scientific motion study, followed by accurate time study with a stop watch of all elements connected with the machinist's work. When, therefore, the teachers, who form one section of the management, and who are cooperating with the workingmen, are in possession both of the science of cutting metals and of equally elaborate motion-study and time-study science connected with this work, it is not difficult to appreciate why even the highest-class mechanic is unable to do his best work without constant daily assistance from his teachers.

Now, gentlemen, what I have been trying to illustrate is the effect which the development of a great science has upon the workman's daily life. The sciences of shoveling and of bricklaying are comparatively small, and yet their effect upon the workman is great. The science of cutting metals required 26 years of constant effort to develop, and what I have been trying to show you is that when a large science, such as this, is applied to the work of a first-class mechanic, even though he be a man having a good high-school education, that the effect of science upon the work of this man is quite as great as the effect of the smaller science, such as that of bricklaying, upon a less intellectual and less well-educated man.

You will remember that Mr. Barth, with the knowledge obtained from the science of cutting metals, was able to show the high-class mechanic how to do work from two and one-half to nine times as fast as he had formerly done it, and this with no greater effort to himself than he had exerted before.

Now, gentlemen, the development of the science of cutting metals is merely typical of what is going to take place in all of the great industries of this country during the next twenty to thirty years. Already bleaching has been taken out of the old rule-of-thumb methods and developed into a science, and the dyeing