CUTTING FLUIDS

By Eugene C. Bingham

ABSTRACT

Cutting fluids are used both to cool and lubricate. When lubrication is the more important, it is generally recognized that fatty oils are superior to mineral oils, although the reason has never been clearly explained. The evidence appears to be that the value of fatty oils is due to their residual valence or acidity which causes their adhesion to metal to be greater than is the case with mineral oils. If this should prove to be the case, it may yet be possible to synthesize an oil which has all of the virtues of lard oil without its obvious defects.

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PART 1. THEORY OF CUTTING FLUIDS

I. GENERAL

It is a curious fact that so many of the very common operations of our ordinary life are without adequate explanation. A case in point is the use of soap as a cleansing agent. It used to be said that the hydrolysis of the soap produced an alkali which saponified the grease, but this explanation is not in accord with the known fact that soaps act very well as detergents even when the grease is one not capable of being saponified, for example, a paraffin oil; to state that the soap emulsifies the grease is strictly in accord with the facts, but it in no wise explains the phenomenon—it merely describes it.

So again, the use of lard oil or other liquid in various cutting operations in the machine shop is universally recognized as beneficial; but there is general disagreement as to the cause of the improvement which is brought about.

(*a*) COOLING.—In various operations, such as sawing, milling, planing, turning, boring, reaming, tapping, and parting off, the tool becomes more or less heated in use, and to prevent the overheating of the tool a stream of liquid over the work is naturally beneficial;[1] it is stated by many that the main purpose of a cutting fluid is as a refrigerant or "coolant." Following up this explanation we should expect that water with its very high specific heat and latent heat of vaporization would be the best cutting fluid.

Water is actually used for this purpose, but only to a limited extent. For drilling ship plates and boiler plates, water is said to give just as good results as cutting solutions or soluble oils. It is used for rough turning and for grinding. But it is generally objected to because pure water rusts the machines, and the work as well, if the latter is of iron or steel. Naturally this difficulty has nothing to do with the theory which we are discussing and it can be overcome by adding to the water substances like soda or soap which tend to prevent the formation of rust. Such solutions are used satisfactorily in drilling and grinding; they are also used on brass, copper, and aluminum, although a cutting fluid is generally regarded as unnecessary for these metals. The fact gradually emerges that with difficult work, water and simple aqueous solutions do not give a smooth finish and they slow down production because the tools become quickly dulled.

(*b*) LUBRICATION.—It has been observed that the greatest wear of a tool in cutting operations is often not at the point of the tool, but on its face at some distance back from the point. This is a striking and very significant fact. It is illustrated by a single figure (Fig. 1) taken from Taylor's Art of Cutting Metals. This is proof of the very great friction between the chip and the face of the tool at some distance back from the point. The chip often adheres to the tool so firmly that a "bead" of metal appears

[1] F. W. Taylor, Art of Cutting Metals, p. 15. The effect of cooling the tool through pouring a heavy stream of water on it permits an increase of 40 per cent in the cutting speed.

FIG. 1.—*Showing tool with "Cutting edge still good but deep groove worn or guttered in the lip surface by the pressure of the chip," from Taylor's Art of cutting metals, Fig. 17e. In other cases, small particles of the chips scraped from the forging are pressed or welded into a compact pile on the lip surface of the tool*

to be "welded" to the face of the tool so that it is necessary to remove it forcibly.

It has therefore been suggested that the cutting fluid acts primarily as a lubricant. Since the lubricant reduces the friction, the heat which otherwise would have been developed is avoided. If the lubricant also removes heat by conduction, so much the better. According to this theory water is unsatisfactory because its viscosity is so low that it has very little lubricating value, and "cutting fluids" and "cutting lubricants" become synonymous terms.

This theory has the obvious merit of explaining why no lubricant is necessary in cutting certain brittle materials such as cast iron. Cast iron has very great compressive strength, but since it is also very brittle a chip does not form; hence lubrication is unnecessary.[2] It also explains why it is impossible to get a smooth surface in machining certain metals without oils, even when the speed and depth of cut are reduced as far as practicable, whereas a perfect surface is obtained as soon as an oil is employed. Under such conditions it appears probable that the cooling action of the lubricant is unimportant, and thus in the extreme case it becomes a question of lubrication pure and simple.

But lubrication is another of those common operations for which there is no adequate theory up to the present time. Thus the theory gives little to guide one in the selection of an appropriate cutting oil. In taking a heavy cut at high speed, the theory would seem to call for an oil of high viscosity at room temperature, so that at the elevated temperature the oil would still have sufficient viscosity to carry the necessarily heavy load. If the cooling effect of the oil is taken into consideration, one must also take into account the specific heat of the oil. It is a fact, however, that these two properties are practically never given any serious attention in the selection of a cutting oil. Whether these properties should be so generally neglected remains to be discovered.

There are properties of oils which have no relation to the theory of cutting fluids, but which nevertheless have importance in practice. (1) Cutting fluids should not separate out solids at ordinary working temperatures; (2) their components should not become immiscible with each other in use; (3) they should be stable and neither oxidize in the air, give rise to gummy de-

[2] Graphite, present in cast iron, can of course act as a lubricant.

posits, nor carbonize as they pass over the work; (4) they should not be liable to spontaneous combustion as, for example, when exposed on cotton waste (combustible fluids should not be easily volatile because this adds seriously to the fire hazard); (5) they should not give off unpleasant odors when heated, even after continued use; (6) they should not injure the skin of the workmen either directly or by means of disease germs; (7) they should not corrode the work or the machines; (8) they should not injure the machine even if the cutting oil becomes mixed with the lubricating oil of the machine itself; (9) for some operations the cutting oils should be fairly transparent; (10) they must be readily obtainable.

Were these the only things to be considered, it would be easy to provide a cutting oil which would meet all of the requirements. One would select a petroleum oil of low cold-test and fairly high viscosity, having regard for the temperature of the oil in use. Most machine shops would effect a great apparent saving were they to use a straight mineral oil in place of the oils now employed for many classes of work. Before, however, we conclude that the practice of modern machine shops is unduly bound by tradition, it is well to inquire into the theory of lubrication, and particularly into the theory of cutting lubricants, to see whether there are any other possible factors which can affect the lubricating value of an oil.

(*c*) Adhesion.—It is well-nigh universal experience that pure mineral oils, regardless of their viscosity, have a very limited usefulness as cutting lubricants. Lard oil, on the other hand, is the cutting oil *par excellence*. Nevertheless sperm oil is practically the equivalent of lard oil, and this is the more remarkable because sperm oil is much more fluid than lard oil; it does not resemble lard oil in its chemical composition, since it is not an oil at all in the strictly chemical sense but a liquid wax. According to general testimony, olive oil and neatsfoot oil are nearly equal to lard oil; and aside from their tendency to oxidize in the air, rapeseed, cottonseed, corn, peanut, and linseed oils would serve very well. Aside from their objectional odor fish oils would be useful. There is therefore a fairly sharp differentiation between the so-called fixed or fatty oils and the mineral oils.

This experience of the machine shop demonstrates that viscosity is not the only measure of the "lubricating value" of an oil. But this conclusion is directly contradictory to the results of Tower's investigations on very well lubricated bearings, which showed that the friction is dependent only upon the viscosity of the given oil. However, Tower's conclusions concerning ideal lubrication may be inapplicable to cutting oils, since these oils are used under conditions which are nearly the worst conceivable for effective lubrication.

The conclusion that viscosity is not the only measure of lubricating value is so highly important, not only in choosing a suitable cutting oil but in problems of lubrication in general, that it should not rest on hearsay evidence, no matter how widespread. We must inquire: What is the evidence upon which the machinist judges the fixed oils to be superior to others? Can this difference be measured quantitatively? Is there any similar preference for fixed oils in general lubricating practice or elsewhere? Is there any known property of fixed oils which can conceivably give them the supposed advantage?

In answer to the first of the above queries, it is very easy to demonstrate qualitative differences between the mineral and the fixed oils in a variety of ways. One finds differences in the smoothness of the finish of the work, in the speed of production, in the power consumption, in the life of the tool, and after a little experience one can judge the merits of the oils by the appearance of the shavings.

A skilled mechanic employed at this Bureau noted that in cutting off a rod of mild steel 1½ inches in diameter once, it was necessary to sharpen the tool 10 times when mineral oil was used; whereas with lard oil he could cut off the rod 8 times without resharpening. Moreover the cut surfaces of the latter were very smooth while the former were unspeakably rough.

This conclusion was confirmed by the author, by cutting off a series of disks from a bar of mild steel 1⅜ inches in diameter, using an Armstrong cutting-off tool on a direct-drive lathe, giving constant speed and feed. A mineral oil was used whose viscosity at room temperature was identical with that of a given sample of lard oil. The oil was dropped into the groove just ahead of the tool by means of a pipette in such a way as to obtain a fairly uniform flow. After some preliminary experiments which proved the striking superiority of lard oil, the author cut off 20 disks with lard oil in the effort to find out how many disks could be obtained with a single sharpening. This attempt was abandoned after examination of the edge of the tool with a compound microscope showed that the dulling was still not perceptible. The surface of even the last disk was very smooth, as is shown in Fig. 2, *a*. After the tool was sharpened to remove any dulling that might have escaped detection and given as nearly as possible the same set as before, another disk shown in Fig. 2, *b* was cut off. All of the conditions were the same except that mineral oil was employed. The tool was badly dulled in cutting the first disk and broke in two on the fourth disk. The surface was very rough, as can be seen readily in the photograph. The chips were thrown out with violence and there was evidence of heating and heavy consumption of power. As to the nature of the individual chips, with lard oil the metal cut much like butter, the under side of the chip being perfectly smooth and the upper side finely corrugated. With mineral oil the corrugations were so deep that they extended completely through at the middle of the chip. This can easily be seen in the figure.

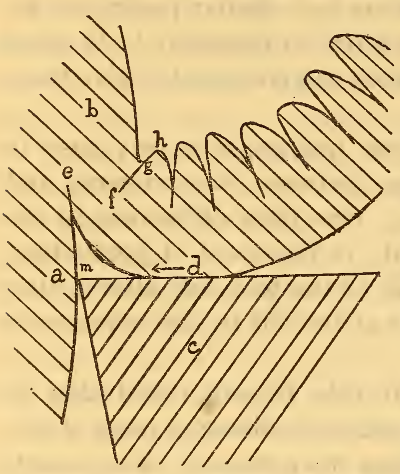

Fig. 3.—*Diagram to illustrate the relation of chip (d) to tool (c)*

To grasp the problems connected with this form of lubrication, it becomes necessary to consider in detail how the shaving is produced. Let *a* in Fig. 3 represent the body of metal from which the layer *b* is being removed by the tool *c*. The pressure of the tool at the point *d* wedges off the material and causes a fracture to extend into the work ahead of the tool at *e*. The point of the tool cleans up the rough surface, but the greater part of the pressure is exerted on the face of the tool at some distance back from the edge where, as has already been pointed out, the greatest wear occurs. The material in the region *f* is subjected to severe compression, and when the pressure reaches a certain critical value there takes place momentary plastic flow. The direction of flow *fg* is at an angle of approximately 45° with the pressure, which is taken to be normal to the surface *ad*.

As a result of the plastic flow the chip becomes about twice its normal thickness.[3] Since, however, the plastic flow can not begin

[3] The amount of thickening presumably depends on several factors, notably upon the friction of the chip on the tool as well as on the softness of the metal, cf. Taylor, Art of Cutting Metals, p. 119.

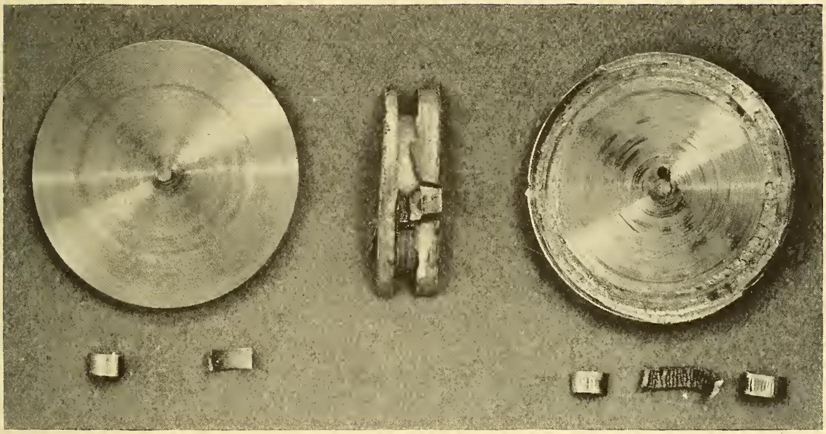

FIG. 2.—*Showing the difference in lubrication between lard oil* (*a*) *and mineral oil* (*b*) *in parting off mild steel rod*

The "bead" of metal which gouged into the surface of (*b*) may be actually seen at the middle of (*e*), where it formed on the tool. The chips with lard oil (*c*) are less deeply serrated than when using mineral oil (*d*)

surface of the glass was scratched perceptibly in the process." In other words there was *seizure*. Extending the work of Miss Pockels and Lord Rayleigh, Langmuir has devised a "talc test" by means of which the contamination of a surface may be determined, and he has studied the sliding friction with various kinds of contamination. Using a glass slider on a glass surface it was found that the latter could be tilted usually to an angle of 70° from the horizontal, often to 75° and in some cases 90° or even 92°, before the slider would begin to move.

The "sliding angle" of glass on glass was found to be 60°; that of glass on mica and of platinum on mica was 10°. Similarly the sliding angle of platinum on platinum was 35°, whereas for glass on platinum it was 30°. In each case the sliding angle was lower when the materials were different. Of course, the results are too few to admit of generalization. In every case the sliding angle was greatly lowered by adding a monomolecular layer of oleic acid.

In lubrication it is of paramount importance to keep the surfaces from coming into contact, for wherever the solid surfaces touch adhesion will occur. The problem of lubrication is theoretically one of great simplicity. The two metals are prevented from seizure by means of a third substance which may be a solid such as graphite or talc, a liquid such as lard oil, or even a gas such as air. If the third substance is a solid, it must be soft so that it will readily undergo plastic flow. If it is a liquid, it must adhere strongly and it must not be too fluid, lest it squeeze out.

The cutting of metals offers the most severe conditions for lubrication. The tool is continually taking off fresh metal, often at a high rate of speed and at high temperature. The pressure of the chip upon the tool is sometimes excessive. All of these causes tend to make adhesion between the chip and the tool very great and the need for a lubricant to prevent seizure may be imperative. That lubricant is best which has the greatest adhesion for the metal, since it is most strongly drawn into the space between the tool and the metal being removed.

Caution needs to be taken not to draw too broad inferences from the above statement. Thus in cutting brittle substances, such as glass or very hard steel, a shaving is not formed and lubrication is unimportant. In fact, seizure is apparently desired in order to get the tool to "bite." What is needed therefore is something which will clean the surface and cool the tool. Turpentine, either

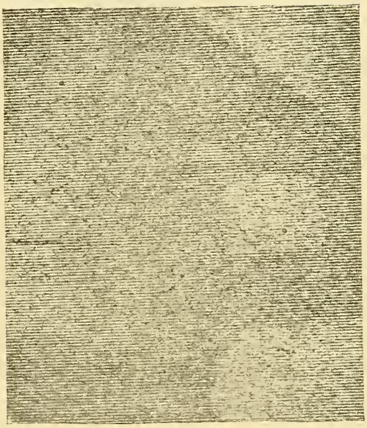

Fig. 4.—*Showing a piece of cast iron whose surface was smeared with lard oil (a), castor oil (b), oleic acid (c), and turpentine*

Where the oil was the work appears lighter colored, owing presumably to smoother finish. In the case of turpentine there was no observable effect

can not claim a direct proportionality between vapor pressure and adhesion. The fixed oils are characterized by a very small vapor pressure as compared with even the heavy mineral oils. Thus lard oil has a probable boiling point of 580° C, while a mineral engine oil was found to have a boiling point around 330° C. There must be a lowering of the vapor pressure of the absorbed film which is a function of the adhesion.

5. In grinding a given pigment in oil it has been noticed that the amounts of different oils required to give a paste of a given consistency vary very widely, and in a manner which can not be accounted for by the viscosity. It is quite possible that the effects are due to the different adhesion of the pigment for the various oils. It is suggested therefore that a given powder be ground in a similar volume percentage of oil and that the yield value [21] be measured.

6. In addition to the above there are practical methods. It appears that the so-called friction testing machine can sometimes be used to measure adhesion. It would appear probable that with a given bearing and two oils of the same viscosity, the oil having the lower adhesion would squeeze out first. It has often been stated that glycerol and molasses are absolutely devoid of lubricating value, although they have the requisite viscosity. If this is the case, then it ought to be readily possible to make a set of similar bearings and, having "run them in" on a friction-testing machine, to test different lubricants for the maximum load which each would carry before seizure took place. The author has devoted a large amount of labor in following up this lead. The only important result of his study is to prove that, with well-fitting bearings bathed in lubricant, glycerol, sugar solution, and gelatin solution will undoubtedly function as lubricants. We continued to dilute these materials with water until we obtained a viscosity of only 45 seconds, Saybolt, without obtaining seizure at a load of 800 lbs./in.^{2}. The machine used was of the "Cornell" type, with a journal 3¾ inches in diameter and 3½ inches long. The bearing block of lead-calcium alloy was 2 inches wide, thus providing a projected area of test bearing of about 7 square inches.

7. The flotation methods seem to offer at least a qualitative measure of adhesion.

8. It is possible to get comparative results from experiments in cutting a given metal under constant conditions of speed, feed,

[21] Cf. B. S. Bull., 13, p. 309; 1916.

rate of application of cutting liquid, etc. Power consumption, torque, finish on the work, and speed of production, and dulling of the tool all offer possibilities of measurement. Taylor[22] has worked out a "standard cutting speed" which should be given careful consideration by any one proposing to measure adhesion by this method. He used the cutting speed in feet per minute which would cause the tool to be completely ruined in 20 minutes under standard conditions.

9. A number of variations of the above methods will readily suggest themselves. It has been shown that when solutions of various electrolytes are filtered through clay, a portion of the electrolyte is adsorbed. So, if a metal powder were shaken up in a solution of oil in some solvent like ether and then centrifuged, it might be found that the amount of oil retained was a function of the adhesion between the metal and the oil. The author has shown elsewhere[23] that if a mixture of two liquids is forced through long, fine, capillary tubes or pores, such as are found in a column of clay, the rate of flow will be affected by the relative adhesion of the two liquids for the solid material. There will, therefore, result a partial separation of the components of the mixture. Such a separation has been demonstrated by Gilpin and his coworkers in connection with petroleum. This method might be applied to lubrication by forcing the two oils to be compared through powdered metal until an equilibrium is established, when the adhering oil could be extracted and analyzed.

10. In connection with the measurement of adhesion we may refer to the change of surface energy when 1 cm^2 of interface is formed between two liquids, as measured by Harkins. He has obtained the following values, which are of great interest:[24]

	Ergs
Water *vs.* water	145. 6
Ricinoleic acid *vs.* water	94. 9
Caprylic acid *vs.* water	93. 7
Octyl alcohol *vs.* water	91. 8
Oleic acid *vs.* water	89. 0
Castor oil *vs.* water	87. 7
Ethyl ether *vs.* water	79. 2
Benzene *vs.* water	66. 2
Paraffin oil *vs.* water	47. 8
Hexane *vs.* water	41. 2

The adhesion of liquids to water seems remote from their adhesion to steel and other metals. But according to the views of

[22] Art of Cutting Metals, p. 41.

[23] B. S. Bull., 13, p. 324; 1916.

[24] J. Amer. Chem. Soc., 39, pp. 354, 541; 1917. See also Southcombe, Engineering, 109, p. 184; 1920.

Langmuir and also of Harkins, adhesion is dependent upon the presence of active groups in the molecules, the hydroxyl group, carboxyl group, double bond, etc. When a layer of oil only 1 molecule deep is placed on water or a solid surface there is a distinct change of properties, as shown by Miss Pockels and Lord Rayleigh. Results privately communicated by Dr. Langmuir show that a layer of paraffin oil can be readily washed off from a surface of glass, mica, calcite, platinum, sphalerite, galena, pyrites, or magnetite by simply passing the contaminated surfaces through a gentle stream of running water. But in every case it was found to be impossible to remove the greasiness due to oleic acid by repeatedly passing through a stream of water. He says:

We may assume that the attractive force between hydrocarbon molecules and the solid surface is greater than that between hydrocarbon molecules, but active groups like those contained in water or oleic acid are attracted to the solid surface very much more than are hydrocarbon molecules. The paraffin oil thus readily wets the solid, if brought into contact with it, but the hydrocarbon molecules are readily displaced from a surface layer when water or oleic acid is present.

This is exactly in accord with our own ideas arrived at from a different point of view.

11. Langmuir has noted that fairly constant results were obtained in the use of the slider referred to above by starting it in motion down the inclined plane of glass and noting the angle at which motion just stops. For example, if oleic acid or other oily substance is put on and then thoroughly wiped off, the sliding angle is reduced from 50 down to 6 to 10°. Paraffin oil lowers the sliding angle nearly as effectively as oleic acid, presumably owing to the fact that the active group of oleic acid is in contact with the glass, so that the free ends of the molecules are the same in both cases. Whatever the explanation, this is evidently not a possible method for the measurement of adhesion.

Langmuir has also measured the contact angle of a drop of water with various surfaces contaminated with oleic acid.

Thus he gets:

	Degrees
Mica	24
Quartz	31
Glass	42
Platinum	72
Calcite	82
Sphalerite	92
Galena	106

These results are specific, but it is too soon to say exactly what is their significance.

II. CONCLUSION

Cutting oils are used partly on account of their cooling value, partly on account of their value as lubricants. But the value of an oil as a cutting lubricant is not measured by any known test. Apparently a high adhesion of the oil for the metal is necessary. A number of methods are suggested for the measurement of this quantity, but its maximum development seems to be dependent upon residual chemical activity, such as is present in oleic acid. According to this view the prevalent practice of excluding as far as possible free oleic acid from a cutting oil is shortsighted. We can even go further and predict that for many, if not all purposes, it may yet be possible to synthesize an oil which has all of the virtues of lard oil without its obvious defects. Thus sulphur in the free condition or as sulphide possesses a great amount of residual affinity. Many oils when heated with sulphur dissolve it to a greater or less extent. Pine oil, which is largely used in flotation, has residual affinity which causes it to absorb sulphur readily. The product we have found to possess great virtue as a cutting oil either by itself or diluted with large amounts of mineral oil. For it is to be noticed that, if our argument is correct, small quantities of a substance of high adhesive qualities will entirely alter the properties of an inferior oil. Others have noted the fact that the properties of an oil are greatly altered by small amounts of impurities. Miss Pockels showed that the behavior of purified oil is quite different from that of the common oil. Richter states that the tendency of oil to spread on water is due only to the free oleic acid contained in it. Lord Rayleigh showed that when sufficiently purified "the drop remains upon the water as a lens, and flattens itself out, if at all, only very slowly."

To test this further the author made a series of experiments. In correspondence and conference with a large number of practical users of cutting oils in quantity, it was found that some users were convinced that regardless of cost, or convenience, certain oils sold under trade names were indeed superior to even the best lard oil. Some of the best oils according to general consensus of opinion contain sulphur in large quantity. On analysis one showed 5.5 per cent sulphur, and not only blackened copper but evolved large quantities of hydrogen sulphide when boiled. Apparently it contained a considerable amount of pine oil. There was an odor of phenol which was probably used in very small quantity merely for the sake of its odor. Even without phenol it would probably be germicidal, and testimony is that in working with such an oil the men have been unusually free of the customary infections. With a knowledge of the proper composition of cutting oils, users should be able to write specifications more intelligently, thereby securing better oils, and with the possibility of supplying their own needs they may be able to secure better terms.

PART 2. TESTS

I. DETERMINATION OF SPECIFIC HEAT, DENSITY, SURFACE TENSION, VISCOSITY, AND LUBRICATING VALUE OF TYPICAL OILS

(By A. W. C. Menzies, W. G. Kleinspehn, G. Q. Lewis, and Eugene C. Bingham)

In the study of cutting oils in particular and the question of lubrication in general, it seems necessary to determine the different properties of fixed and mineral oils which may possibly produce the effects upon their value as lubricants, which we have been discussing. A. W. C. Menzies has determined the specific heat, surface tensions, and densities of certain oils. He used cottonseed oil, castor oil, and a commercial brand of naphthene-base oil "U." The samples were furnished by this Bureau. In the case of the first two, the oils themselves were used as calorimeter fluid, and the rise in temperature was observed when a perforated brass cylinder of known heat capacity and at known temperature was dropped into the calorimeter. In the case of castor oil, the viscosity was so great that the above method was not satisfactory. The oil was therefore placed in a 25 cc cylindrical glass bulb furnished with a calibrated capillary so as to form a very sensitive thermometer, whose readings were compared with those of the calorimetric thermometers. The castor-oil thermometer, taken from a chamber at 0° C was immersed in a water calorimeter and readings made at simultaneous temperatures of calorimeter and castor-oil thermometer. Due correction was made for the heat capacity of the glass of the bulb. The calorimetric thermometers were supplied with Reichsanstalt certificates of corrections rounded to fiftieths.

TABLE 1.—Specific Heats of Oils

Kind of oil	Temperature rise in degrees centigrade	Specific heat
Cottonseed oil	(1) 20.6–28.6	0.4537
	(2) 21.3–29.3	.4502
Average specific heat at 25.0 ° C		.452
"U" oil	(1) 19.1–27.9	.4141
	(2) 21.4–29.9	.4122
Average specific heat at 24.6 ° C		.413
Castor oil	(1) 0.0–20.5	.487
	(2) .0–20.5	.478
Average specific heat at 10.2 ° C		.483

Each of the specimens of oil was previously freed from water and dissolved gases by heating at 180° or higher in a vacuum. The densities were determined in a quartz glass dilatometer. Temperatures were measured with a set of Allihn type thermometers, of satisfactorily constant zero points, furnished with Reichsanstalt certificates to 0.1° up to 200° and to 0.2° above 200°. The threads were completely immersed. Surface tensions were measured in a glass capillary tube of radius 0.3254 mm, and the data assume a zero angle of contact with the glass. The lower meniscus had a diameter of over 34.2 mm. Due regard was given to the remarks of Richards[25] in reference to the measurement of surface tension. Violently stirred baths of a lard substitute and of fused nitrates were used to maintain uniform temperatures.

TABLE 2.—Density and Surface Tension of the Furnished Specimen of Cottonseed Oil

Temperature in degrees centigrade	Density g/cm³	Surface tension dynes/cm²	Temperature in degrees centigrade	Density g/cm³	Surface tension dynes/cm²
20	0.920	32.7	130	0.847	24.4
30	.913	31.0	140	.840	23.7
40	.907	31.1	150	.834	23.1
50	.900	30.2	160	.827	22.5
60	.893	29.4	170	.821	21.9
70	.886	28.6	180	.814	21.3
80	.880	27.9	190	.808	20.7
90	.873	27.1	200	.801	20.1
100	.867	26.4	210	.795	19.5
110	.860	25.7	220	.788	18.9
120	.854	25.0	230	.782	18.4

NOTE.—The oil was freed from dissolved gases and water by heating at 200° C in a vacuum.

[25] J. Am. Ch. Soc., 37, p. 1674; 1915.

TABLE 3.—Density and Surface Tension of the Furnished Specimen of Naphthene-Base Oil, "U"

Temperature in degrees centigrade	Density g/cm ^{3}	Surface tension dynes/cm^2	Temperature in degrees centigrade	Density g/cm ^{3}	Surface tension dynes/cm^2
0	0.942	32.5	140	0.849	21.1
10	.940	31.5	150	.842	20.5
20	.929	30.6	160	.835	19.8
30	.922	29.6	170	.829	19.2
40	.915	28.7	180	.823	18.6
50	.908	27.8	190	.817	18.0
60	.901	27.0	200	.811	17.4
70	.895	26.2	210	.805	16.8
80	.888	25.4	220	.799	....
90	.881	24.6	230	.792	....
100	.874	23.9	240	.786	....
110	.868	23.2	250	.780	....
120	.861	22.5	260	.774	....
130	.855	21.8			

NOTE.—The oil was freed from dissolved gases and water by heating at 180° C in a vacuum.

TABLE 4.—Density and Surface Tension of the Furnished Specimen of Castor Oil

Temperature in degrees centigrade	Density g/cm ^{3}	Surface tension dynes/cm^2	Temperature in degrees centigrade	Density g/cm ^{3}	Surface tension dynes/cm^2
20	0.957	34.0	130	0.879	24.9
30	.950	33.0	140	.872	24.2
40	.943	32.1	150	.865	23.5
50	.936	31.2	160	.858	22.9
60	.929	30.3	170	.851	22.3
70	.922	29.5	180	.844	21.7
80	.915	28.7	190	.837	21.1
90	.908	27.9	200	.829	20.5
100	.901	27.1	210	.822	19.9
110	.894	26.3	220	.815	19.3
120	.886	25.6	230	.808	18.8

NOTE.—The oil was freed from dissolved gases and water by heating at 200° C in a vacuum.

The surface tension curves for these three oils are nearly identical.

W. G. Kleinspehn has measured the fluidities of cottonseed oil, linseed oil, and other oils. The method is that already described by Bingham.[26] The measurements were in duplicate. The data are given in Table 5.

[26] B. S. Bull., 14, p. 59; 1917.

TABLE 5.—Fluidities of Several Oils

COTTONSEED OIL

Temperature in degrees centigrade	Limb of viscometer	Time in seconds	Specific volume	Density	P_o	P	Viscosity	Fluidity
			cm³/g	g/cm³	g/cm²	g/cm²		
0.7	L	807.0	1.073	0.8070	289.77	289.77	184.29	0.5425
	R	807.8	....	....	289.59	289.59	184.36	....
10	L	482.2	1.080	.9260	289.73	289.72	110.11	.9079
	R	482.7	....	....	289.57	289.56	110.16	....
20	L	615.9	1.088	.9190	139.39	139.39	67.66	1.478
	R	616.4	....	....	139.26	139.39	67.65	....
30	L	316.1	1.096	.9123	178.07	178.05	44.36	2.255
	R	316.3	....	....	177.86	177.84	44.34	....
40	L	352.0	1.104	.9055	110.69	110.68	30.70	3.257
	R	352.5	....	....	110.55	110.54	30.71	....
50	L	386.6	1.113	.8988	72.82	72.81	22.18	4.508
	R	388.0	....	....	72.60	72.59	22.20	....
60	L	596.2	1.121	.8924	35.74	35.74	16.79	5.957
	R	597.0	....	....	35.68	35.68	16.79	....
70	L	469.4	1.129	.8860	35.10	35.09	12.98	7.709
	R	464.0	....	....	35.45	35.44	12.96	....
80	L	363.8	1.123	.8904	30.83	30.80	8.84	11.32
	R	366.3	....	....	30.68	30.62	8.85	....
90	L	300.9	1.132	.8835	30.71	30.67	7.28	13.70
	R	303.0	....	....	30.62	30.60	7.32	....
100	L	253.2	1.141	.8765	30.82	30.78	6.15	16.26
	R	255.0	....	....	30.71	30.67	6.17	....

"U" OIL

Temperature in degrees centigrade	Limb of viscometer	Time in seconds	Specific volume	Density	P_o	P	Viscosity	Fluidity
10	L	6054.4	1.069	0.9353	411.70	411.30	1,964.50	0.051
	R	6067.3	....	....	411.30	410.25	1,965.70	....
20	L	2086.6	1.077	.9286	410.56	409.02	675.15	.148
	R	2086.8	....	....	410.26	409.85	674.75	....
30	L	856.4	1.084	.9225	409.85	409.43	276.62	.362
	R	856.2	....	....	409.73	409.34	276.48	....
40	L	404.0	1.091	.9163	409.77	409.36	130.47	.749
	R	403.9	....	....	409.65	409.25	130.40	....
50	L	348.6	1.099	.9102	251.68	251.41	69.14	1.446
	R	348.8	....	....	251.60	251.33	69.16	....
60	L	332.8	1.106	.9040	154.14	153.95	40.42	2.474
	R	333.0	....	....	154.04	153.86	40.42	....
70	L	442.2	1.114	.8978	72.85	72.78	25.40	3.934
	R	442.5	....	....	72.79	72.71	25.38	....
80	L	446.6	1.122	.8913	48.13	48.08	16.94	5.901
	R	448.4	....	....	47.99	47.95	16.96	....
90	L	487.6	1.130	.8848	31.03	30.99	11.92	8.384
	R	490.7	....	....	30.86	30.82	11.93	....
100	L	360.4	1.139	.8783	31.08	31.05	8.83	11.297
	R	365.9	....	....	30.79	30.74	8.87	....

NOTE.—P_o is the true average pressure producing the flow and, of this pressure, the part P is used up solely in overcoming the viscous resistance. Cf. B. S. Bull., 14, p. 70; 1917.

TABLE 5.—Fluidities of Several Oils—Continued

LARD OIL

[Stearin crystallizes out at low temperatures. The effect of heating the oil is shown by the marked change in fluidity after cooling to 50 and 20° C.]

Temperature in degrees centigrade	Limb of viscometer	Time in seconds	Specific volume	Density	P_o	P	Viscosity	Fluidity
			cm³/g	g/cm³	g/cm²	g/cm²		
20	L	391.5	1.096	0.9126	266.99	266.98	82.38	1.214
	R	391.6	....	....	266.89	266.88	82.37	....
30	L	405.0	1.104	.9058	165.89	165.88	52.96	1.890
	R	405.0	....	....	165 76	165.75	52.91	....
40	L	509.3	1.112	.8933	89.00	88.99	35.72	2.780
	R	510.1	....	....	88.89	88.88	35.73	....
50	L	457.7	1.120	.8926	70.13	70.12	25.29	3.955
	R	458.4	....	....	69.99	69.98	25.28	....
60	L	495.6	1.129	.8861	47.79	47.78	18.66	5.354
	R	497.6	....	....	47.67	47.66	18.69	....
70	L	377.8	1.137	.8794	47.78	47.77	14.22	7.028
	R	379.0	....	....	47.66	47.65	14.23	....
80	L	426.0	1.146	.8726	33.24	33.23	11.16	8.953
	R	428.6	....	....	33.12	33.11	11.18	....
90	L	409.0	1.155	.8657	27.79	27.78	8.98	11.17
	R	410.7	....	....	27.66	27.65	8.95	....
100	L	335.0	1.165	.8586	27.79	27.78	7.33	13.62
	R	337.2	....	....	27.67	27.66	7.35	....
50	L	506.2	....	....	64.99	64.98	25.92	3.855
	R	508.0	....	....	64.86	64.85	25.96	....
20	L	520.7	....	....	210.40	210.39	86.34	1.157
	R	521.7	....	....	210.31	210.30	86.46	....

Each of the fixed oils here tested has a considerably higher specific heat than does the single mineral oil, which may probably be taken as typical. Even at that the highest specific heat is a little less than one-half that of water.

The fluidities of the two fixed oils are generally greater (Fig. 5) than the fluidities of the mineral oil at the same temperature. The characteristic feature, however, is that the increase of the fluidity with the temperature is so much greater with the mineral oil. The contrast between the two classes of oils is brought out much more clearly when we plot the fluidities against the specific volumes, Fig. 6. The viscosities in centipoises are plotted in Fig. 7. Only a small portion of the curve for the mineral oil can be shown on the plot.

Although the specific heat and the slower change of fluidity with the temperature are both in favor of the fixed oils, we have tried to show that the adhesion is probably the main reason for the superiority of the fixed oils as *lubricants*.

G. Q. Lewis of the U. S. Navy Yard at Washington has made an elaborate study of the cutting properties of fixed oils, compounded oils, and trade preparations. He employed for the tests the actual machines and materials which are to be used in practice. He has found several trade preparations to be superior to even lard oil in boring chrome nickel steel propeller shafts with an elastic limit of 100 000 lbs./in.^{2}. He has secured an increase of production of 50 to 100 per cent over the earlier practice, where a mixture of 10 per cent rapeseed oil and 90 per cent paraffin oil was used. A saving of 13 per cent in the cost of the oil was also obtained. One

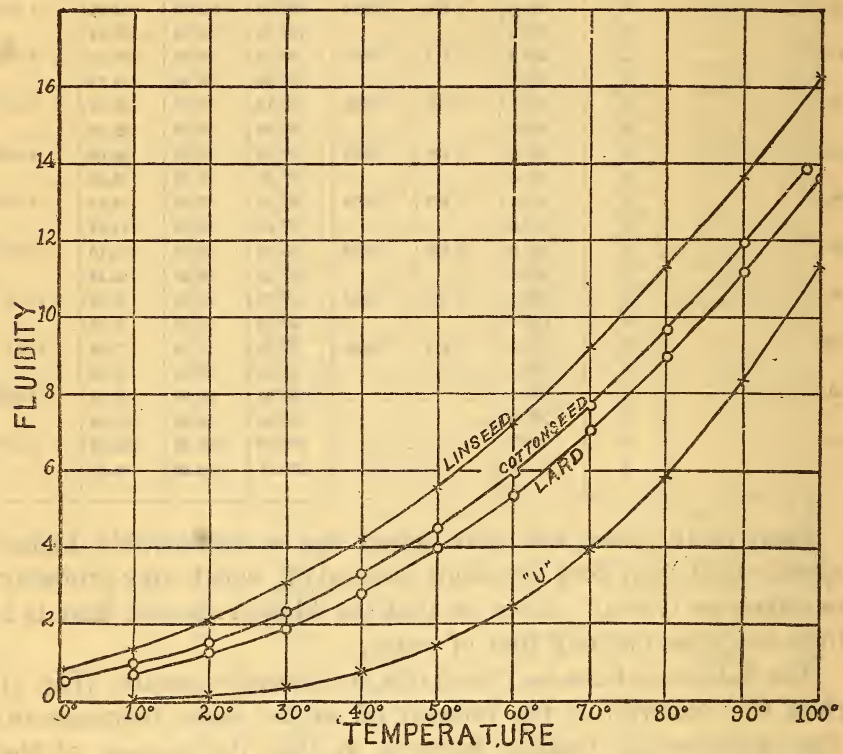

FIG. 5.—*The mineral oils increase in fluidity more rapidly with the temperature than do the fixed oils. A single asphalt-base oil "U" is here compared with lard, linseed, and cottonseed oils*

particular mixture increased production on a turret lathe 100 per cent; on small brass work it greatly increased the life of the tool and the cutting speeds; on a small lathe cutting gimble centers for torpedo gyroscopes from "Ketos" tool steel it doubled production and increased the life of the tool about 300 per cent. In an automatic screw machine, cutting alloy steel screws for securing air flask heads, a 1 to 6 mixture, costing 35.6 cents per gallon, gave results slightly better than those obtained with lard oil at $1.52

per gallon. When both oils were used under the same conditions, pieces cut from the same bar were smoother and therefore more desirable when the new preparation was employed. In the tool shop a 1 to 6 mixture at 35.6 cents per gallon, and later a 1 to 10 mixture at 29.2 cents per gallon, replaced sperm oil at $1.79 per gallon.

The results of numerous other tests are also given in the report. We merely add Fig. 8, which is an example of a graphical com-

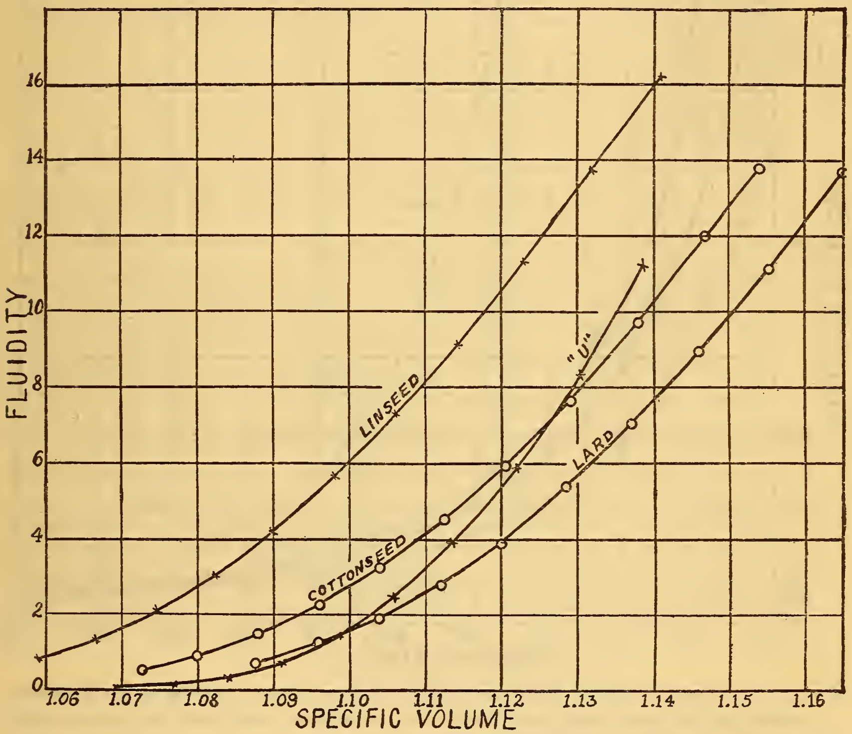

FIG. 6.—*The contrast between the mineral and fixed oils is most clearly brought out when the fluidity in absolute units is plotted against the specific volume in cubic centimeters per gram*

parison of different oils so diluted with paraffin oil that each of the mixtures would cost 35 cents per gallon. The machine was run by its own motor which was connected with an ammeter and voltmeter. The machine was run at a rate of 120 r. p. m. with a feed cut of 8 inches per hour on chrome nickel steel. The watts and the temperature of the oil were measured and were plotted against the elapsed time. With lard oil or pure mineral oil the tool would break down at once. With two of the mixtures tested, Nos. 13

and 18, the tool worked steadily without any balk whatever. With the other mixtures the machine balked and had to be started over again, as can be seen by the sharp maxima appearing in the curves. Mixture 13 is the one which had been found in the earlier tests to give such superior results. The temperature curves do

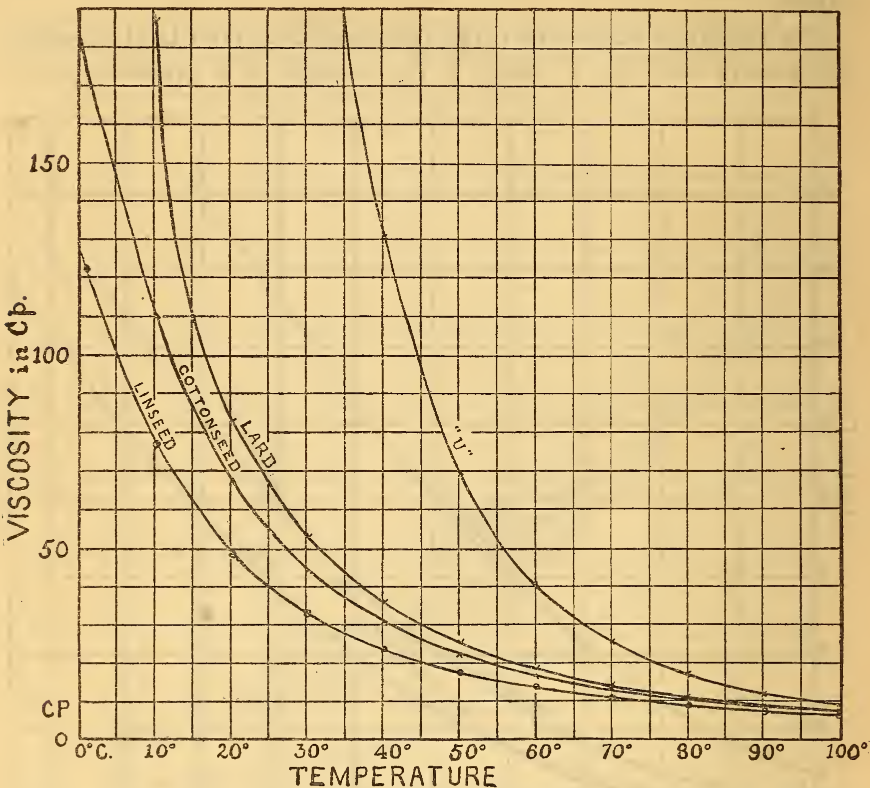

FIG. 7.—*It is more usual to plot vicosity against temperature, but due to the hyperbolic character of the curves, the figure would need to be more than tenfold its present height to show the complete curve for the mineral oil*

not seem to show any relation to the value of the oils, so they are not reproduced.

The author desired to test this oil on other operations. For this purpose a number of samples of oil were made up. A few of these were:

1. The preparation which had given best results at Navy Yard.
2. Lard oil.
3. A mixture of 90 per cent of paraffin oil and 10 per cent of oleic acid.

The oleic acid had been heated with sulphur.

4. Pine oil, sulphur, and turpentine.

These samples were placed in plain bottles with numbers only, sufficient dye and pyridine being added to the lard oil to disguise it. They were then given to a skilled mechanician to be used in threading wrought iron. The resulting threads were examined with a microscope by several independent observers. There was

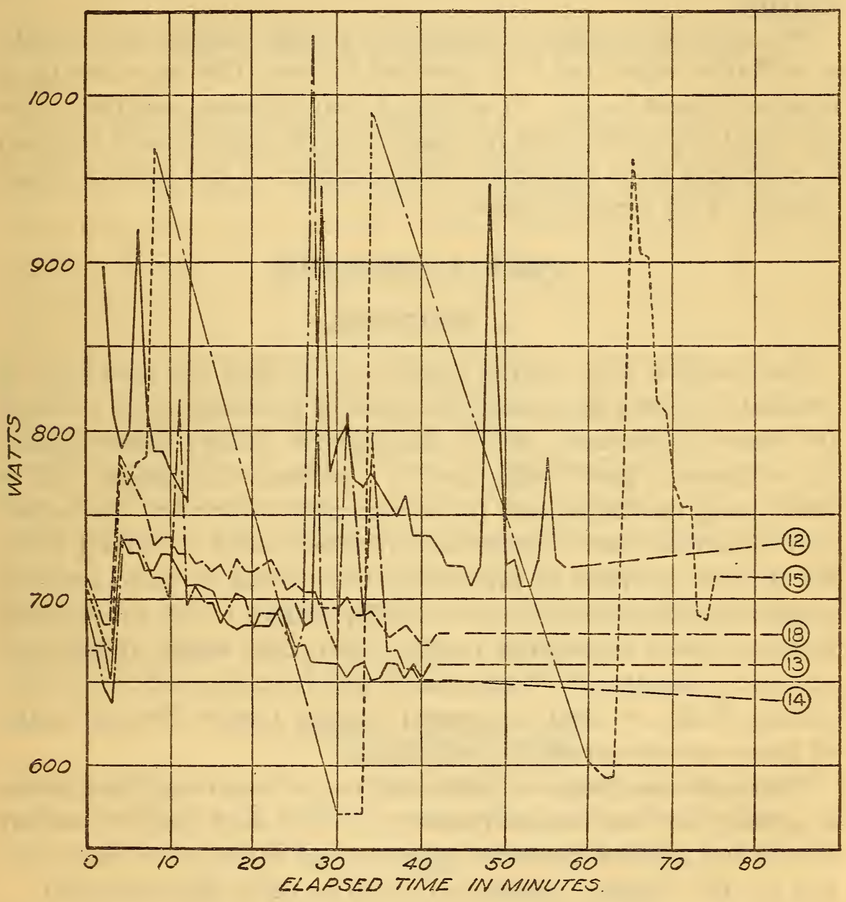

Fig. 8.—*Navy Yard tests showing fluctuations in power consumption when using various oils for lubrication.*

general agreement that the lard oil gave the best results and the new preparation, No. 1, the worst results. The results fell in the order, Nos. 2, 4, 3, 1. They were very decisive for this particular operation. Pure mineral oil was, of course, inferior to all of these.

It appears likely that lard oil is better than anything which has been devised for certain operations. It may be, however, that for certain other operations, when a good lubricant is necessary, a substitute may do as well as or better than lard oil, and at a fraction of the cost. The prediction seems to be amply justified that oils with high residual affinity, such as those containing oleic acid, or pine oil with sulphur, will be found best. But it is noted that the trade preparation No. 1 also contained several per cent of sulphur.

So many persons have contributed to this bulletin in a variety of different ways that it is pleasant to have this opportunity to express thanks to all. It is hoped that bringing together these results of experience may not only be of practical benefit but that it may lead to a systematic investigation of the subject which shall be of far-reaching value.

PART 3.—PRACTICE

I. PURPOSES

The purpose of a cutting fluid is (*a*) to cool the work; (*b*) to lubricate, thereby increasing the speed of production; (*c*) to lessen the wear of the tool; (*d*) to diminish the energy consumption; (*e*) to insure a good finish; and (*f*) accurate dimensions; (*g*) to wash away the chips; and (*h*) occasionally to prevent the formation of metallic dust. Materials are often added to cutting fluids for the sole purpose of preventing the rusting or corrosion that would otherwise occur, but it is hardly correct to say that cutting fluids are used to prevent rusting, since that result, though important, is incidental. In the same way it is incorrect to say that cutting fluids are used to prevent disease merely because many of them contain germicidal substances.

There are two ways in which the use of a cutting fluid assists in getting accurate measurements: (1) The work may be unduly heated and thereby expanded unless a good cutting oil is employed, and (2) the "finish" obtained by such an oil is often essential.

Cooling is said to increase the cutting speed on wrought iron and steel from 30 to 40 per cent and on cast iron from 16 to 20 per cent. It is to be noted that the most effective cooling is obtained by directing the cooling fluid on the shaving at the point where it is being formed, because thereby, through cooling, the plastic flow of the material is lessened as well as the tendency of the shaving to seize on the tool. At the same time the fluid can be drawn in readily between the shaving and the tool, as the pressure fluctuates, and act as a lubricant.

Washing away the chips is quite important in such operations as deep drilling; for example, in the manufacture of rifle barrels. Securing a strong, continuous shaving is an advantage in such work and it is necessary to have a lubricant with sufficient adhesion. The stronger the force of the stream of cutting liquid the better it will carry away the chips, as well as cool and lubricate the parts. It sometimes happens that metallic particles are not carried away by the emulsions and they cause the dulling of the tool. This condition is avoided by using a stronger emulsion.

If the material is tough, a lubricant is necessary, but if brittle, it may be dispensed with. With cast iron, for example, no lubricant is necessary, but water in the form of an alkaline solution or emulsion may be used to cool the work, wash away the chips, and prevent the dust from getting into the air. The lubricant used in a given case will naturally depend upon the finish desired and the tolerances allowed. For roughing operations on a given material a cheap lubricant may suffice, whereas for fine operations on the same material, such as in the manufacture of micrometer screws, the best grade of lubricant is demanded regardless of price. There is the further fact that with some machines such as turret lathes and automatics, the cutting fluid and the oil used to lubricate the machine are liable to intermingle. In such cases an emulsion which would be serviceable as a cutting fluid would be worthless as a lubricant in the machine. It is perhaps needless to add that a cutting liquid must be used which will also serve to lubricate the machine.

II. SUBSTANCES USED

The substances used as cutting fluids may be classified under the heads (*a*) oils, (*b*) air, (*c*) aqueous solutions, and (*d*) emulsions.

1. OILS

We may subdivide the oils used into fixed oils, mineral oils, and compounded oils.

(*a*) Fixed Oils.—The fixed oils may again be subdivided into animal oils, fish oils, and vegetable oils.

Animal Oils.—Under animal oils we have the several varieties of lard oil, No. 2, No. 1, extra No. 1, and winter strained prime, tallow oil, neat's-foot oil, sperm oil, wool fat, horse oil, and whale oil. Lard oil is the cutting oil *par excellence.* It is used on the most difficult work such as cutting delicate threads, tapping and cutting gears, deep hole drilling in steel and forming work such as the making of handles and balls on the turret lathe. It is not suitable for cutting very hard steel and glass, or where the heat production is excessive. Although lard oil does not vaporize, it carbonizes and gives rise to offensive odors. Small amounts of free acid present in the oil are probably beneficial and they do not cause corrosion of brass parts. There should, however, be not more than 15 per cent of free acid, as an excess of acidity will cause gumming and the formation of verdigris. In the great majority of cases substitutes for lard oil can be used to advantage.

The very high cost of the fixed oils as a class makes it desirable that the purchaser make suitable tests to determine that the material is both unadulterated and sanitary. Horse oil, in particular, seems to have been severely criticized from a sanitary point of view, but this is perhaps unwarranted.

Not only should the free acid be not too high, but the stearin should be kept as low as possible. During the winter months the lubricant stands in relatively cold shops overnight or over week ends, and if stearin separates out to any material extent, the oil is practically inoperative and means must be provided for heating it considerably above ordinary room temperature until the stearin goes back into solution.

Sperm oil is practically interchangeable with lard oil as a cutting oil, in spite of the fact that it does not resemble it in chemical composition and that it has a much higher fluidity.

Fish Oils.—Several users have experimented with fish oils. The report is that the results were satisfactory but the odor was so objectionable that their use was abandoned. Fish oils, however, can be deodorized, and it is understood that these deodorized oils are already available. Whale oil has been abandoned on account of its odor, but otherwise it would be satisfactory.

Vegetable Oils.—Under vegetable oils, olive oil, rapeseed oil, mustard-seed oil, castor oil, peanut oil, soya-bean oil, cocoanut oil, cottonseed oil, corn oil, and linseed oil have been more or less extensively used. Under the heading of vegetable oils we may also include creosote oil, turpentine oil, turpentine, pine oil, and rosin oil, although they are distillates and therefore are not "fixed oils."

From the iodine numbers of these oils it can be seen that the tendency to oxidize and, therefore, to gum is very great in linseed oil, and it is moderate in some of the other oils such as cotton seed. The tendency of the oil to give trouble by gumming, and the fire hazard as well, can be reduced by diluting it with mineral oil.

In continuous use it is obvious that all cutting oils will become contaminated. They should be sterilized frequently by heating, all solid particles should be given an opportunity to settle out, and after a certain time the whole system should be cleaned out and the oil purified or replaced.

The objection to the fixed oil on account of expense does not apply to the distilled oils of vegetable origin. The tendency of pine oil to produce a foam is objectionable, but when this oil is compounded with sulphur and a mineral oil this tendency is reduced. These oils appear not to be very widely used except in emulsions, where rosin oil and soluble creosote are apt to cause foaming. They come to the top, adhere to the chips, and frequently choke up the system.

Cottonseed oil is much used in the South, but many have rejected it, owing to its gumming. It is suggested that there are many operations, such as threading and tapping by hand, where cottonseed oil could be used either alone or in mixtures. But it will not do in place of lard oil for very fine work. Corn oil has been suggested for use on account of its low cold test.

The use of white lead and linseed oil in tapping and threading by hand seems to be very common. A number of other solids are used to a greater or less extent. Graphite, sulphur, and ground mica are examples.

In drawing fine lead wires cold it is creditably reported that palm oil, which contains free palmitic acid, works perfectly, whereas vaseline of almost identical consistency is no good. If the metal is drawn warm enough, beef tallow, which contains stearic acid, works well, but paraffin is not good. This is evidence of the effect of adhesion.

Turpentine is very useful for certain classes of work, as in cutting aluminum, very hard steel, and glass. But the fire hazard is great with its use. It is often compounded with lard oil. By itself it is too fluid to act as a lubricant. It is recommended where lard oil causes a "glaze."

(*b*) MINERAL OILS.—The mineral oils are naturally cheaper than the fixed oils. In fluidity they range from kerosene, which is used in cutting brass and aluminum, to heavy engine oils. They prevent rusting and are very stable, so that corrosion, carbonization, and gumming are small factors. They are not cheap enough to compete with emulsions on the one hand; and on the other hand, because they do not have sufficient adhesion to those steels which are difficult to work with emulsions, their use is not very satisfactory. On aluminum, kerosene is preferable from every point of view to a fixed oil. On brass, a paraffin oil of 25 to 28° Baumé mixed with 5 per cent of 300° fire-test kerosene is described as ideal. On these metals many use no cutting fluid whatever. On account of the fire hazard emulsions might better be used.

(*c*) COMPOUNDED OILS.—Compounded oils are the natural result of the desire to secure the adhesion of the fixed oils combined with the stability and cheapness of the mineral oil. Thus compounded oils are being supplied under a great variety of trade names, many of which suggest the presence of lard oil. Some of the compounded oils actually do contain considerable amounts of lard oil, while others contain none at all. A typical formula may be given as follows:

	Per cent
Lard oil	25
Corn oil	15
Natural West Virginia petroleum	60

Many users state that fixed oil must be present to the extent of from 10 to 50 per cent, and that thereby the valuable advantages of lard oil are gained in full measure. On the other hand, for some classes of work there is abundant testimony that even 50 per cent of lard oil is not sufficient. One large user testifies that 10 per cent of rapeseed oil added to a paraffin oil caused a positive loss in cutting value.

It should be observed that "cutting compounds," which are very satisfactory to many large users, apparently contain no fixed oil whatever. Thus there is possible a great saving in fats by a knowledge of the best usage in regard to cutting oils. It appears probable that the necessary adhesion can be gained by thoroughly incorporating sulphur in oils, such as red oil (oleic acid) and pine oil, which themselves have considerable adhesion. It will not do, however, to have the sulphur merely in coarse suspension, as it will settle out. It should be chemically united.

2. AIR

Air can not be considered as a lubricant for the purposes which we are here discussing, and it has very little cooling effect. However, with a brittle metal like cast iron it is used successfully to take away the chips, and thus it prevents the loading and choking of the tools. The flying of the chips makes guards necessary, and the dust is also an inconvenience.

3. AQUEOUS SOLUTIONS

Water alone has been found satisfactory in some cases, as in the drilling of ship plates and boiler plates. Water does not generally give a smooth finish, nevertheless it is sometimes used to give a bright, smooth surface to steel, which is called a "water-cut" surface. It may also be used on brass and aluminum, but water is in disfavor, owing to the fact, noted by every machinist, that it rusts the machines and the work as well if this is either iron or steel.

To prevent rusting, an alkali may be added to water. Thus for some operations, such as grinding and drilling, a 1 to 2 per cent solution of sodium carbonate has been found satisfactory. Caustic soda, borax, sodium silicate, and sodium resinate are all used.

A soluble soap is added with the same end in view. Thus a solution of 50 pounds of sodium carbonate and 25 pounds of soft soap in 200 gallons of water is said to have given satisfactory results in boring deep holes, as in gun tubes. Soap, moreover, has the advantage that if oil is added it will readily form an emulsion which will possess the cooling properties of water and will lubricate better than water, either alone or containing soda or soap. Soap solutions have the disadvantage that as the water evaporates they become sticky and may clog the feed pipes, etc.

4. EMULSIONS

There are three types of material used for making emulsions:

1. One class of "soluble oil" is made from mineral oil compounded with a neutralized sulphonated oil. The fixed oils when treated with sulphuric acid unite with the acid to form so-called sulphonic acids, which after neutralization with alkali are readily soluble in water. Rosin oil, though a less valuable product, is sometimes used. The mixture with mineral oil is, of course, not soluble in the strict sense, but it does emulsify in the heated solution.

2. The second type of soluble oil is made from a mineral oil compounded with an alcoholic solution of soap. Potassium or "soft" soap is preferred. Both of these are marketed as clear oils. In use the oil is stirred into water, usually 1 part of oil to 4 parts of water.

3. The third variant is marketed as paste made of a thick soap solution and mineral oil. These are known as cutting pastes or compounds.

Of the three forms the last is the least desirable, and the second is perhaps the most so, as it may be made without expensive apparatus and requires much less technical skill to fabricate. The chances of its being made properly are therefore greater. One very large user has developed the following formula, which is reported to give very satisfactory results and may be taken as typical:

	Gallons	Per cent
Water	2.00	6.0
Alcohol	1.50	4.5
Caustic solution (30° B)	.75	2.0
Kerosene	6.00	17.5
Oleic acid	3.00	9.0
Machine oil	21.00	61.0
Total	34.25	100.0

This amount of soluble oil is then diluted to make 860 gallons for average work. Another typical formula is made up as follows:

	Per cent
Caustic soda	0.65
Alcohol and water	5.8
Resin acid	1.64
Fatty acids	11.76
Mineral oil (22.5° B)	80.15

Such an oil is diluted with water according to the kind of metal to be machined or the character of the operation. In a dilution of one to three parts of water, it is said to do the same work under any and all conditions that is required of pure lard oil. It should be observed that neither of these formulas contains either a fixed oil or a disinfectant. Soluble oils will take care of the most difficult as well as the lightest work at a far less cost for the same treatment than any other cutting lubricant. They are particularly recommended where the heating is excessive. The emulsion must be exceedingly fine grained, so that it will penetrate readily and not tend to settle out. Emulsions give trouble on automatics or machines with turret heads because the emulsion gets under the turret and displaces the lubricant. In this case the turret will stick and the machine has to be taken apart and cleaned. If the operator will frequently squirt lubricating oil through the turret, it will tend to obviate the difficulty.

In filtering through a column of chips, as in a deep bore hole, it has been repeatedly noticed that the character of the emulsion becomes changed. Presumably the oil is held back and the lubricating property of the emulsion is lost. The very virtue of an emulsion, that its composition can be readily changed to suit conditions, is thus a disadvantage, since it is also continually changing during use. Thus, the system must be watched and occasionally it should be thoroughly cleaned out and a new emulsion put in. This should be done anyway, from sanitary reasons. The oil can be recovered by the use of a rotary separator.

Some waters are sufficiently hard or salty in character to render an emulsion unstable. Strong acids are, of course, destructive to emulsions in even exceedingly small amounts. If the water of the locality is suspected of causing instability of the emulsion, rain water may be tried, and if this removes the difficulty, it may be found possible to soften the water. In making an emulsion it is well to follow the exact procedure which has been found to be successful. Too much mineral oil in the emulsion is a cause of instability. Ammonia is often present in soluble oils but it is not to be recommended, since it will tend to make an unstable emulsion and to promote corrosion.

Gum arabic and starch are sometimes added to cutting oils, presumably in order to increase the stability of the emulsion. Phenol and cresol are frequently used because they give the mixture a distinctive odor and render it less habitable by disease-producing bacteria. The use of phenol, even in the form of its salts, is objected to, and it would appear that recently developed disinfectants are far less likely to be injurious to the workmen and are at the same time better germicides.

III. OPERATIONS AND MACHINES

The character of the operations performed, the shape and adjustment of the tool, the speed, feed, and depth of cut have more to do with the choice of a cutting fluid than the character of the steel. It is therefore feasible for the management to predict beforehand the most suitable lubricant and save time and materials. For the great majority of operations aqueous solutions and emulsions made up of suitable strengths over quite a wide range should undoubtedly be used.

For drilling, an emulsion (say, 1:20) is most commonly used, but for light, slow work a compounded oil, or even lard oil, is resorted to. For rough drilling, water containing a little soda, soap, or borax is employed. Much soda will give rise to foaming.

For reaming, an emulsion (1:3) is generally used, although the work is often done dry. For a high polish and for extremely heavy work, compounded oil or lard oil is resorted to.

For milling, emulsions (1:20) are almost universally used, with alkaline solutions, compounded oils, and lard oil as variants. Planing is often done dry. Sometimes a lubricant is applied with a brush. In many cases, however, an alkaline solution or a dilute emulsion (1:20) is used, especially if a high polish is desired.

In tapping and threading, emulsions are not so often successful as in the above cases, but they are used nevertheless in a large minority of instances. Lard oil and compounded oils are resorted to generally, with or without the addition of white lead to prevent the binding of the taps and dies and to secure a smooth, steam-tight finish.

Turning practice in different shops and for different operations shows the widest variance. Some workmen turn dry, others with alkaline solutions, emulsions, compounded oils, corn oil and—where a high finish is desired—lard oil and turpentine.

On automatic screw-cutting machines and machines with a turret head it is best to use a compounded oil with as small a proportion of fixed oil as will serve the desired ends.

IV. MATERIALS

The nature of the material should be taken into account in determining the most suitable oil. There is a consensus of opinion that soft steel and wrought iron are difficult metals on which to get a good surface without the use of lard or sperm oils. Some of this difficulty can be overcome by the shape of the tool, one with more rake being required for the soft metals. A change of speed or feed also helps at times. Without suggesting a cause, we may be permitted to merely report the fact that speeding up the operation has often decreased the number of failures from "bugging" and also the excessive wear on the tools. In threading wrought iron in dies it is almost impossible to get a good thread without the use of lard oil or sperm oil. In drilling deep holes in tough steels at high speed of production, as in making rifle barrels, lard oil or its equivalent is positively necessary. Of course, it is possible that pine oil united with sulphur and compounded with a suitable mineral oil will in time replace lard oil, which is needed for other things.

Lard oil or some oil with good adhesion will be used where a long chip is obtained, and it will not be needed where the chips are short, which indicates a brittle material. In the latter case, cooling is the more important function of the cutting oil.

With a very hard, brittle steel, turpentine is called for, to cause the tool to "bite," since lard oil would merely produce a glaze.

Forming tools sometimes have a tendency to "hog" the metal, which is an indication that a better lubricant is required. It must be remembered that a very thin film of good oil is often sufficient to give the smooth surface that is desired, whereas it can not be obtained by the use of a flood of water or other substitute.

V. FORMULAS

It is advisable for the engineer of tests in each large organization to give careful study to the subject of cutting oils rather than accept too readily the customary substitutes supplied by the trade. Of the several hundred materials on the market some are good while others are positively harmful. Small concerns buy up odd lots of oil where they can be obtained cheaply, but they are not always able to keep their products uniform. The freight rates to and from their plants have to be added to their costs. It is, after all, not difficult to manufacture a cutting oil, but it is difficult to analyze a compounded oil so as to be able to state with certainty whether it is constant in composition and whether the components are healthful and pure. Moreover, the user can, by studying his own needs, change his formulas until he finds that his needs are being met in the most economical manner.

The number of formulas required by a large works need not be very great. The practice of a single concern, taken as typical, may be given in detail:

1. *Pure Oils*.—(*a*) Pure lard oil, off prime, free fatty acids, determined as oleic acid not over 5 per cent. Restricted to cutting nickel steel and other steel of high cutting hardness. Its delivery is controlled under rather rigid restrictions.

(*b*) Pure mineral spindle oil, viscosity 100 seconds, Saybolt Universal at 40° C, flash point in open cup, 185° C. Used in many classes of work, both in automatic machines and on turret lathes and on other machines where a light-bodied oil is adapted. It is used in turning, shaping, and cutting both steel and copper and in all operations on brads in automatic machines.

2. *Compound Oils.*—(*a*) Equal parts of lard oil and mineral spindle oil. Used generally on automatic machines and on other lathes in heavier classes of work for processes which include tapping and threading. It is also used on machines which are changed frequently from operations for which the pure mineral spindle oil would be used to operations involving tapping and threading for which the lard-oil mixture is required.

(*b*) Equal parts of mineral spindle oil and heavy mineral oil, viscosity of the latter 730 seconds, Saybolt Universal at 40° C, flash point, 205–210° C. This mixture is substituted for the spindle-lard-oil mixture wherever practical experience shows that it is economically possible.

3. *Water Compounds.*—(*a*) Solution of water and soda. Used in turning of large shaft forgings.

(*b*) Solution of soap and water. Used on simple milling and drilling operations where a water lubricant of light body is satisfactory.

(*c*) Emulsion of water, soap base, soda, and lard oil. Used where a water lubricant of good body is required. It is generally in use on boring mills, Gisholt lathes, cold cutting-off saws, milling machines, etc., and in the cutting of metals in general.

(*d*) Emulsion of water, soap base, soda, lard oil, and mineral spindle oil. Used solely for the grinding and finishing of small steel shafts.

The above table gives a clear idea of the number of cutting fluids which are deemed necessary to meet all the needs of a large plant, but obviously the amounts of the different fluids which are required will be very different. It is interesting to note the experience of a large manufacturer on this point. He finds that a pure paraffin oil (25° Be) can be used for 98 per cent of the work requiring a cutting oil. For the large portion of the remainder he uses 40 per cent of off-prime lard oil or sperm oil compounded with 60 per cent of paraffin oil (25° Be). For only a very small portion of the work he uses off-prime lard oil or sperm oil.

VI. APPLICATION OF THE FLUID

Taylor[27] seems to have been the first to recognize the very great gain in cutting speed which can be made by having the cutting fluid applied in a heavy stream with as much force as practicable directly upon the chip. From what has already been said it is obvious why this should be so. It has been noticed that many of the machines work better in winter than in summer, which can be explained by the more effective action of the cooling fluids. With the better lubricants, such as lard oil, it is probable that no corresponding gain would be obtained by the use of a heavy stream even if it were practicable.

The use of white lead combined with the oil used in threading and tapping is readily justifiable. By itself the oil would quickly

[27] Art of Cutting Metals, p. 11.

run off, but by adding a finely divided solid the fluidity of the mixture is lowered and it "stays put." If white lead were objected to on account of the danger of poisoning, it could probably be replaced by zinc oxide or deflocculated graphite. Unfortunately, workmen find graphite objectionable on account of the color.

VII. KIND OF CUTS

Where the heating is necessarily very great, an emulsion is always to be preferred. If for some reason a better lubricant seems required, one would naturally suppose that the lighter the cut the less viscous the oil need be, and, conversely, with a deep cut one might expect to have to use an oil with high viscosity. This, however, is not the case, for if the viscosity of the oil is high it will be slow in reaching the surfaces to be lubricated and the cooling effect of the oil will also be reduced. Hence, an oil of low viscosity is preferred for all high-speed work. To emphasize the importance of cooling, it may be said that in milling the teeth of steel gears, the thinnest soap solution that can be used without rusting the machine will do better work than pure lard oil. In using pure lard oil for this purpose, the friction of the tool is so great as to burn the oil and fill the room with smoke. The life of the cutters is no longer with pure lard oil than when a water compound is used.

VIII. HYGIENIC ASPECTS

The used oil contains sharp metallic particles which are sufficiently small to enter the hair follicles of the skin. If not washed out, they may block up the openings to the sebaceous glands, produce irritation and abrasions, and therefore a favorable environment for pus-forming bacteria. The oil itself should not produce any irritation to the skin, but it is suited to catch germs which are floating about and retain them. The clothing has this same tendency where it becomes moistened with the cutting fluid. The main precautions to be taken are (1) the removal of the fine particles of metal from the used oil, particularly those which are less than 0.04 mm in diameter; (2) cleanliness on the part of the workmen, with abundant facilities therefor, also preventing the cutting fluid from coming into contact with the clothes and person more than is necessary; and (3) the avoidance of the use of strong acids in sulphonated oils or from the pickling liquor and too great an excess of fatty acids or of alkali, or the use of irritating antiseptics, etc., in the composition of the oils.

The metallic particles can best be removed by settling in a large tank. This is easier to accomplish if the oil is not too viscous and therefore if the oil is hot. It may be cleared by filtration or by means of a centrifugal separator.

It is an excellent practice to have available in the wash room a soap emulsion of a light petroleum oil to rub on the hands and arms before using the soap and brush. This makes the greasy layer more fluid and thereby facilitates its removal by means of soap and water.

The United States Public Health Service is making a study of the hygienic aspect of cutting fluids, hence a more detailed discussion of the subject would be out of place here.

WASHINGTON, April 20, 1921.