# Principles of Snow Removal and Snow-Removal Machines

Karl Croce

This paper discusses the principles for snow removal and describes a snow-removal machine whose design is based on these principles. The machine can remove snow 3.5 m deep in one operation. For many years it has proved to be very useful on roads and airports.

## CASTING OPERATION

Snow-removing machines cast the snow away; therefore, the snow must be accelerated to a certain speed within the machine. The farther the snow is to be cast, the higher this speed must be. The cast is farthest when this speed moves the snow stream at an angle of 45 deg at the beginning of the cast. At this angle the casting distance is given by the ratio

$$W = \frac{u^2}{g} \tag{1}$$

where W is the casting distance in meters, u is the starting speed of the snow in m/sec, and g is the constant gravitation (9.81 $m/sec^2$). In this case, we have not taken account of the air resistance. Tests with machines, the impellers of which are equipped with radial shovels, have shown that at an angle of 45 deg at the beginning of the cast the ratio

$$W = \frac{u^2}{g} - 0.0023\ u^3 \tag{2}$$

is obtained for the reached casting distance W. Here $0.0023\ u^3$ is the influence of the air resistance, which is to be considered only in the case of long casting distances. Both ratios are shown in Figure 1.

Casting distances of approximately 8 to 15 m are necessary for removing snow on roads. In most cases, 8 m are sufficient, and distances longer than 15 m are seldom needed. The point is to build a machine that has the highest efficiency when casting 8 m, although some losses can be registered when casting 15 m. A casting distance of 8 m corresponds to a starting speed of the snow of 10 m/sec, and of 15 m, to approximately 15 m/sec. The machine must give this speed. Higher speeds are not necessary because then the snow is thrown farther than needed, and the energy used is lost.

In order to throw a weight of G kilos over a casting distance of W meters, a mechanical energy of A mkg is necessary, which is given by

$$W = 0.5\ G\ W \tag{3}$$

In this and in the following we have not taken account of any losses.

If G kilos of snow are to be thrown over a distance of W meters each second, then the needed energy N in hp is

$$N = \frac{G\ W}{150} \tag{4}$$

If a certain energy N is provided in a machine, then a snow weight equal to

$$G = \frac{150\ N}{W} \tag{5}$$

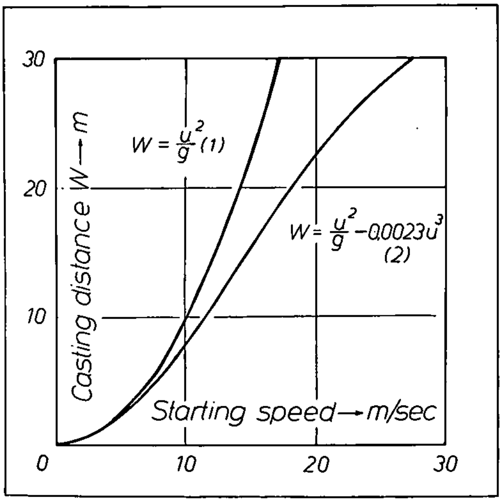

Figure 1. Casting distance of impellers with radial shovels at different speeds at the beginning of the cast.

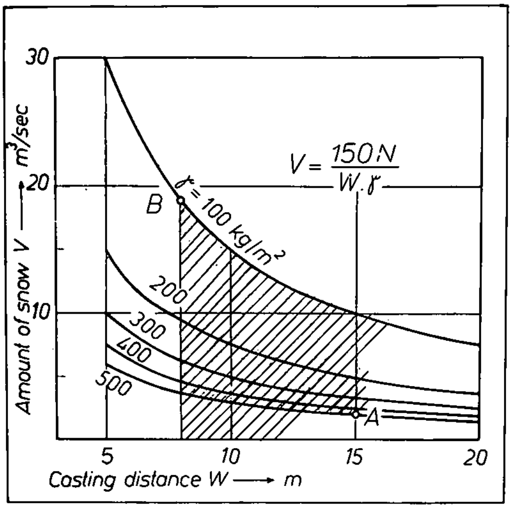

Figure 2. Amounts of snow removed by driving force of 100 hp at different casting distances.

can be discharged every second over W distance. In order to find out more, we have to know the possible amount of snow to be removed and the possible volume to be removed. These are obtained as follows:

$$V = \frac{150\ N}{W\,\gamma} \tag{6}$$

where $\gamma$ indicates the sepcific weight of snow in kg/m$^3$.

Let us now go into the details of how these ratios are obtained according to the laws of casting or general mechanics. Figure 2 shows the possible amount of snow to be removed with a driving force of 100 hp at different throwing speeds between 5 and 20 m. The figure shows very clearly how much the amount of snow to be removed with a certain driving force depends on the casting distance and the weight of the snow. At a casting distance of 5 m and a specific snow weight of 100 kg/m$^3$, 30 m$^3$ can be removed each second; if the specific weight of snow is 500 kg/m$^3$ and the casting distance 20 m, 1.5 m$^3$ can be removed each second. Casting distances between 8 and 15 m are hatched in Figure 2.

## DIRECTION OF CAST

The job of snow-removing machines is to remove snow from trafficways and discharge it to the sides. This happens with the least possible expense of energy when the snow can be discharged at a right angle to the direction of traffic. If the throw is oblique to the direction of traffic, as it is with some machines, the casting distance, and therefore the energy, is more than needed. If the direction of the cast is inclined 45 deg forward, then the needed casting distance for attaining the same actual distance is increased approximately 1.5 times.

## HARDNESS OF SNOW

It is generally known that fresh snow is soft and loose. It is composed of ice particles that lie loosely on top of each other. The longer the snow lies after falling, the harder it gets. The snow particles are packed closer together and freeze, so that the snow gets harder. This depends largely on the temperature. In cold weather the snow

TABLE 1

SWISS HANDTEST FOR HARDNESS OF SNOW

| Hardness | | Object That Can Be Pressed Into Snow at 3 kg Pressure | Shear Firmness (kg/dm$^2$) |
|---|---|---|---|
| Grade | Description | | |
| 1 | Very soft | Fist | 0 to 1 |
| 2 | Soft | Stretched hand | 0.5 to 10 |
| 3 | Medium hard | Stretched finger | 5 to 15 |
| 4 | Hard | Pointed pencil | 10 to 30 |
| 5 | Very hard | Knife blade | 30 to 50 |

stays soft, but it gets hard quickly if the temperature changes rapidly from cold to warm to cold because the melt water covers the snow particles and acts as a kind of glue as soon as the temperature gets cold again.

Different measuring instruments are used to measure the hardness of snow. The "handtest," developed in Switzerland, is mostly used for snow-removing purposes (Table 1).

## CUTTING SNOW

When snow is removed, it must be picked up by the machines and conveyed. The top layer is cut, and picked up first. The mechanical energy needed for this depends on the hardness of the snow. How much energy is needed was determined by some tests with a snowcutter at different speeds in different hardnesses of snow. Figure 3 shows the necessary mechanical energy for cutting 1 kg of dry snow at a vehicle speed of 600 m/hr, cutting speeds of 3, 9, and 18 m/sec, and a cutting angle of the 4 cutting knives of 20 deg. At a cutting speed of 9 m/sec, soft snow requires a cutting energy of 2 mkg/kg; hard snow, 9.5 mkg/kg (almost 5 times as much); and very hard snow, 25 mkg/kg (12.5 times as much). This difference is more pronounced when one considers how far 1 kg of snow could be thrown with the energy needed to cut it. Soft snow could be thrown 4 m, hard snow 19 m, and very hard snow 50 m. The cutting energy for hard and very hard snow is much higher than that needed for casting. On the other hand, hardly any energy is needed for cutting very soft snow.

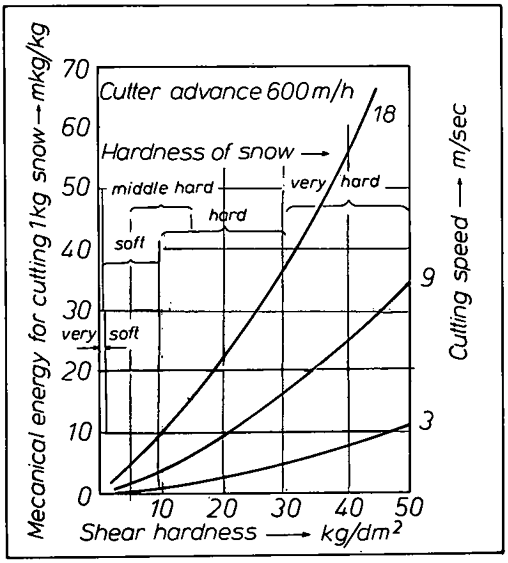

Figure 3. Cutting snow of different hardnesses with cutting speeds up to 18 m/sec and a vehicle speed of 600 m/hr (approximate values).

The cutting energy increases with the hardness of snow. For this reason the snow should be removed as soon as possible after falling. Also one should work with the smallest possible cutting speed because few knives and a slow cutting speed result in thick pieces of snow and save cutting energy.

This all means that the organization of snow removing on roads that have to be kept clear permanently should be adjusted according to the techniques for removing soft snow, and the machines should be built accordingly. It is very suitable to possess some blade-type snowplows and a certain number of machines that remove soft snow especially well. Thus, it is possible to keep the road system clear of snow with the least possible expense in energy, because the snow does not remain long enough to get hard.

This is the way the road system in Bavaria is being kept clear of snow with success in spite of the heavy snowfalls, Bavaria has 932 km of expressways, 7,200 km of main roads, and 13,500 km of secondary roads at an elevation between 250 and 1,800 m. Each machine is correctly matched to the type of snow, whether hard or soft, that it removes.

## INTERNAL FRICTION OF SNOW

Snow becomes harder under mechanical stress. For this reason much energy is required to change its form. Under such stress the snow loses its original characteristics. Particles are pressed closer together, and the warmth caused by their rubbing and grinding welds them together. The needed energy to change the form cannot be recovered as with an elastic body; it is lost and only causes the snow to become harder and more compact.

For this reason heavy losses are caused by the deviation of the snowstream. Tests have shown that a snowstream that is deviated 90 deg loses half its energy because of the internal friction of the snow. The form of snow is plastically changed and exposed to centrifugal forces, which press it sideways. In addition, the stream is compacted in length because its speed decreases steadily. Snowstreams should not be deviated. The snow should be discharged in the direction it is being moved. Similar processes happen when the snow must be deviated within the machine. That is the case when the snow is picked up at a right angle from the advance of the vehicle and then discharged in another direction. The energy to pick up the snow is changed into internal friction, increasing the specific weight and the temperature of the snow, and is lost for the cast. Tests have shown how heavy the losses caused by such processes are. Samples of snow with specific weight $\gamma_o$ were pressed together to specific weight $\gamma_e$ in cylindrical containers. The mechanical energy in mkg necessary to bring 1 kg of snow up to the heavier specific weight was obtained.

Figure 4 shows the result. For the single $\gamma_o$ the curves for the increasing $\gamma_e$ are above each other. This means that the mechanical energy for compressing snow increases with increasing final weight. Each curve has a special highest value that, by $\gamma_o$ weight, lies between 80 and 100 kg/m$^3$. Naturally, loose new snow requires the most energy to be compressed. Most of the fine crystals of this snow must be broken up so that they can be compacted. Crystals of less fine snow do not require so much breaking up and slide more on each other when compressed.

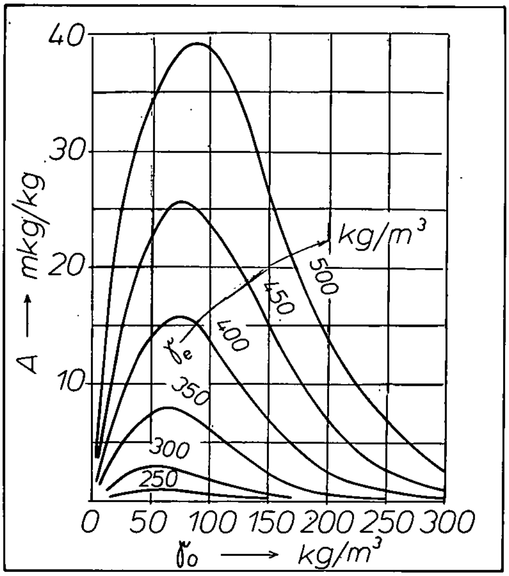

Figure 4. Mechanical energy for compressing dry snow from $\gamma_o$ to $\gamma_e$.

The curves shown in Figure 3 were made for dry snow at -5 C. When the temperature is higher, the figures decrease; and when the temperature is lower, they increase. The ice that composes the snow crystals is then softer or harder. Water in snow has the same effect as a lubrication fluid and causes less energy to be required for compression.

Experience shows that new snow in a snow-removing machine increases from an original specific weight of 100 kg/m$^3$ to approximately 350 kg/m$^3$ while being conveyed. Snow that weighs 200 kg/m$^3$ at the beginning increases to a weight of approximately 450 kg/m$^3$. If this compression were caused only by pure pressure, then each kg of snow would need a compression energy of 5 or 6 mkg/kg. With the same energy, the same kg could be cast 10 or 12 m. Similar losses occur whenever the direction of the snow is changed within the machines. The real compression energy needed is often more. It has become clear that the energy lost in compression is just as much as that needed for casting snow.

## IMPELLERS

Most snow-removing machines have impellers with radial shovels for accelerating and discharging the snow. These impellers turn in a casing that covers the range of impellers and that has an opening through which the snow will be discharged. The snow is conveyed in the direction of the impeller shaft and then picked up by the shovels. The centrifugal force causes it to slip toward the tips of the shovels all the way against the casing. Then the tips of the shovels force it to slide on the inside surface of the casing all the way to the opening, where it can leave the casing.

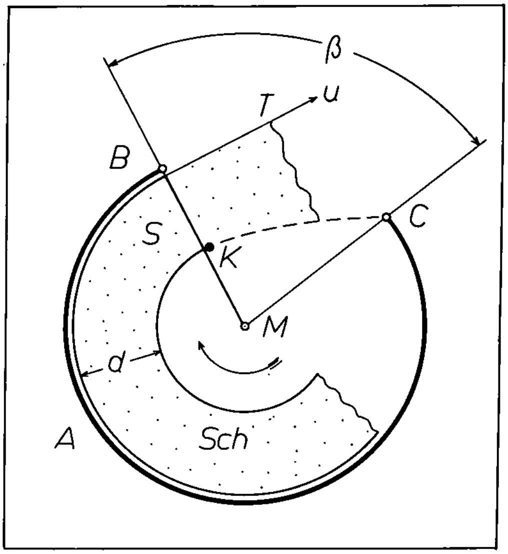

Figure 5. Movement of snow in impellers.

Figure 5 shows a cut at right angle to the impeller shaft. The opening B-C in casing A stretches over the centri-angle $\beta$. The shovels S, of which only one is shown here, are leveled, radial surfaces and revolve around the middle point M of the impeller in the direction of the arrow. In this figure, the shovel is shown so that its outer edge has reached the beginning of the opening B. The dotted circle Sch represents the snow that the other shovels, which are not shown here, force into a circular movement.

In the areas where the casing is shut, the snow can follow the centrifugal force only if it compresses under its action. When it reaches the opening B-C, it can leave the impeller toward the outside.

The outside layer of the ring has the circumferential speed u of the impeller. At B it starts leaving the impeller along the tangent T. While the shovel moves farther in the direction of C, other layers that are farther inside also reach the outside edge and attain this speed. They fly tangentially. In the meantime the shovel has moved on farther; these tangents form a flat angle with the course of the outer layer. The courses of the single layers tend to fly apart from each other in a fan pattern. The speeds that these layers attain are not exactly the same as the circumferential speed that each of the single layers attain at the outer edge of the shovel. This component is not large. It presses the fan formed by the cast back together.

There is a relation between the centri-angle $\beta$ of the opening and the radial thickness d of the snow layer. The thickness d should be only so much that the point K of the inside range of the snow layer Sch along the dotted line K-C attains the outer edge of the shovel when this reaches the casing again at C. Research has proved that this relation is purely geometrical and does not depend on the speed of the impeller. The thickness d of the throwable snow layer, which is formed in the impeller, depends only on the opening in the casing and not on the revolution number of the impeller. When calculating d, which cannot be done in detail here, we obtain

$$d = R - r_0 \tag{7}$$

whereby

$$r_0 = c\,R \text{ and } d = R(1 - c) \tag{8}$$

can be set. The figure value of (1 - c) in relation to the centri-angle $\beta$ of the opening is shown in Figure 6. For $\beta$ = 70 deg, as is often the case, we obtain (1 - c) = 0.46 and

$$d = 0.46\ R$$

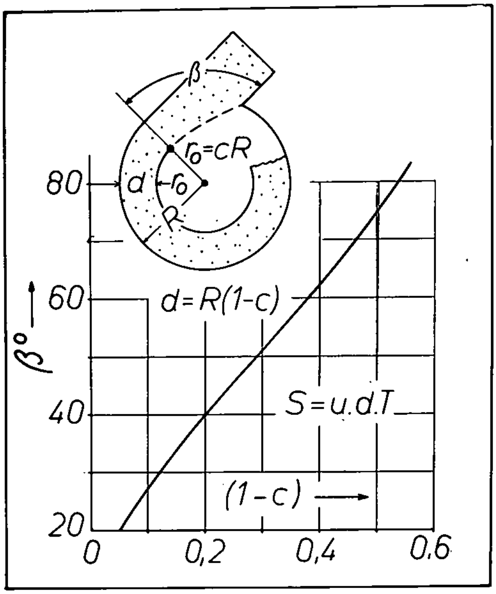

Figure 6. Auxiliary values for calculating the swallowing capacity S of the impellers.

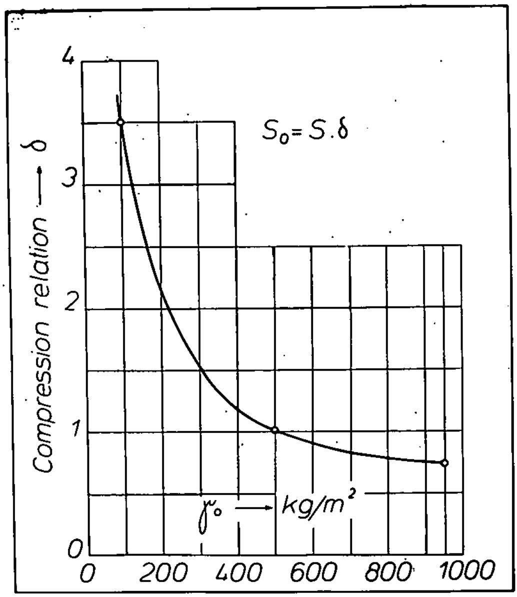

Figure 7. Amount of snow $S_0$ that has been removed from trafficway with specific weight $\gamma_0$ in relation to swallowing capacity S of machine.

## CAPACITY

The thickness d is an important factor for the largest amount of snow, S, that such an impeller can convey. This amount of snow is called "swallowing capacity." If more snow is fed into the impeller than it can swallow, the thickness of the circular ring exceeds the limit determined by the opening in the casing. The inner layers cannot be discharged while the shovel passes by the opening. They remain in the impeller and jam and clog it. The whole impeller then contains one mass of compressed snow, and it is a big job to empty it. The swallowing capacity of an impeller with a certain right angle opening of the cast is a result of the permissible thickness d of the snow layer to be discharged, of the height of the impeller shaft, and of the speed with which the snow leaves the impeller. Because it does not differ much from the circumferential speed u of the impeller, the swallowing capacity can be calculated accurately enough with the circumferential speed.

$$S = u\,d\,T \tag{10}$$

It increases linearly with u. Because the casting distance also increases linearly with the circumferential speed of the impeller, the same linear relation must exist between the swallowing capacity and the casting distance. The farther the snow is cast, the more the impeller can swallow.

Many snow-removing machines use this in order to transform their driving power into casting distance. Because the impellers swallow too little with the required low number of revolutions, they cast farther than needed while working with a higher number of revolutions. They have a slightly higher capacity but use more energy in vain because they transform their power into a long cast, which is not needed. It is better to build machines that swallow enough to take advantage of the driving power and that operate with a low number of revolutions.

An impeller that has to cast the snow to a certain distance must have a certain circumferential speed and can convey only a certain volume of snow in each time unit. It depends on the centri-angle of the opening for the cast and on the height of the impeller shaft.

The calculated swallowing capacity results from the snow that leaves the machine in the snowstream. This means it is a result of compressed snow. To find out the quantity of snow that the impeller can pick up requires that the compression, which comes about in the machine, be taken into account. There have been no tests made on the compression relationship in such machines. One must relay on estimations. These are more easily made by observations. New snow with a specific weight of 100 kg/m$^3$ is brought up to 350 kg/m$^3$ in a snow-moving machine. Compression is less with heavy snow; snow with a specific weight of 500 kg/m$^3$ will not be much more compressed. Besides, it is known that ice removed with 950 kg/m$^3$ is loosened up to approximately 700 kg/m$^3$. This makes it possible to show the relation between the compression, $\delta$, and the specific weight, $\gamma_0$, of snow in Figure 7. If the amount of snow, $S_0$, to be removed by such impellers is calculated with the swallowing capacity S, it is a result of

$$S_0 = S\,\delta \tag{11}$$

## REMOVING SNOW

Casting distances of 8 to 15 m require adjustable circumferential speeds of 10 and 15 m/sec. Of course these circumferential speeds should be obtained with the driving engine for the impellers always turning at full speed so that the machine removes as much snow as possible. Combustion engines, usually used in such machines, give full efficiency only when running at a certain speed. A change gear is necessary between the engine and the impellers.

During snow-removal operations, the cast should always have the required length. The impellers must revolve at a constant speed. The amount of snow that can be removed with the available energy changes with the specific weight of the snow to be removed. The speed of the vehicle must adjust itself to the snow. Also the changeable snow uses all the available power in the removing system. The driving power for the speed of the vehicle must permit repeated adjustments to the number of revolutions.

It has proved best to equip the machines with 2 engines. One engine keeps a regulated and constant speed with the highest output that permits a cast of the required distance and that is adjustable because of a transmission. The other engine is used to regulate the vehicle speed so that the snow-removing system always picks up and conveys to its highest capacity.

## CLEARING CAPACITY

The snow-removing machines should be judged according to how well they can do their jobs. For the mechanical parts, a quality measure should determine the effect of the energy. It should tell how quickly a machine can remove the snow from a trafficway.

The more snow a machine can remove in each time unit, the quicker the road is clear. This could mean ever bigger machines are needed. This, of course, is not our intention. We need a way to measure that does not depend on the size of the machine. Such a way is obtained when the amount of snow removed in a time unit is divided by the output of the machine. This measure is called "clearing capacity." The higher the figure is, the better the job done by the machine in the time allowed.

The amount of snow G in tons that has been removed by a machine can be calculated in m$^3$/hr as a result of research of snow depth, clearing width, and advance. It should be recalculated into tons/hr with the specific weight of the snow, because then the specific weight of snow does not play an important role anymore. If that is done, then the specific weight of the snow should be given in order to calculate the volume that has been removed.

The driving power also determines the clearing capacity. It depends on the engines that are used. The clearing capacity R is a result of

$$R = \frac{G}{N} \tag{12}$$

This gives the number of tons of snow removed by the mechanical energy in the drive of the machine. In addition, the hardness of the snow has to be given. The harder the snow is, the more mechanical energy needed for loosening the snow. This energy is lost and cannot be used for conveying the snow. Therefore, the measure is not complete if the hardness of the snow is not given.

The clearing capacity we have expressed here is an absolute measure for the efficacy of the machine in different snow conditions. If snow-removing machines are always judged according to this clearing capacity, it will be advantageous for the further development of the machines. The engineers must try to build a machine that will clear as much snow as possible with the least possible driving power. This is attained by keeping the casting distance as short as possible. Then the driving power is transformed into a short cast for much snow and not into a long cast for little snow. The casting distance should be just enough to keep the trafficways clear. Eight meters are usually sufficient; often fewer meters may suffice.

The complete nominal power of the engine should be used for the calculation of the clearing capacity. This will force the proper design of the clearing system. This system should be able to transform the full power into conveying movement even with a very short cast. The clearing system must have a sufficient swallowing capacity even with a very short cast, that is, with a small circumferential speed. This means that all parts of the machine must be able to handle the amount of snow being removed; that is, they must be able to pick up, convey, and discharge the snow without jamming and clogging. Otherwise, the amount of snow picked up by the impellers cannot be discharged unless the opening and other passages through which the snow is conveyed are large enough.

## MACHINE HS 291

Figure 8 shows a large snow-removing machine that meets these requirements. The machine is equipped with a diesel engine with 275 hp or more for the snow-removing and casting systems and a diesel engine with 200 hp for the vehicle. The latter is equipped with a transmission and regulates the speed of the machine by acting on all 4 wheels. The speed can be regulated between 118 and 64, 000 m/hr. The vehicle is steered with the rear axle, so that the sideway directed steering power with long lever arms influences the front part. This and the short distance between the axles (3.6 m) permit the machine to drive around sharp curves even in deep snow. The clearing system is equipped with two impellers with diameters of 1.17 m (wheels with shovels) located side by side and opened toward the front. The impeller shafts are in the direction of travel. The 2 circular-shaped working profiles are completed by a casing that forms a rectangular profile with a clearing width of 2.9 m. The height of the casing is 1.39 m. Each impeller is equipped with 4 strong shovels. The inside edges of these form a hollow that becomes narrower toward the back. The shovels are formed like spirals, so that they act as a screw in the snow under the advance of the vehicle, without accelerating the speed of the shafts. The losses caused by acceleration of the shafts are very light. The impellers, with a depth T of 0.62 m, run in cylindrical casings with tangentially arranged casting chutes. The rectangular opening where the chute is fitted

Figure 8. Snow-removing machine with clearing height up to 3.5 m and clearing width of 2.9 m.

Figure 9. Snow-removing machine in operation.

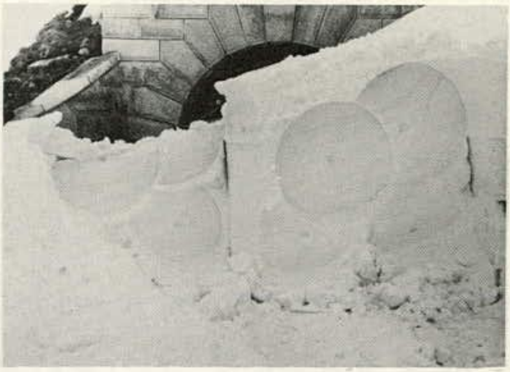

Figure 10. Cleared road with clearing profiles in hard snow (snow depth 3.5 m).

to the casing stretches over the centriangle $\beta$ at 71 deg. The casing of each impeller and the chutes pivot around the axle of the impeller, so that the snow can be discharged to the right as well as to the left. A changing gear is installed in the drive of the impellers so that adjustments can be made for different casting distances.

The picked up snow is moved sideways without having to be deviated. There are no losses caused by deviation. The streams are directed at a right angle to the advance. The obtained casting distance is used fully.

To loosen harder snow, a strong propeller 1.30 m in diameter is installed on the shaft extensions of the impellers. The snow is loosened in front of the impellers. The precutting propeller cuts thick pieces of snow so that no energy is lost in cutting small pieces. These precutters, together with a third precutter in the center down toward the point of the casing, permit the machine to be used also for cutting and removing very hard snow. This sort of snow can also be removed quite continuously at a slow speed.

Above the casing the clearing head carries additional precutting propellers with 1.50-m diameters. These are mounted on articulated arms that permit adjustments to the height and the distance between the propellers. These precutters are driven much slower than those on the impeller shafts, so that they cut bigger pieces of ice. Thus, little energy is needed for loosening the snow. The cut snow falls down in front of the impellers where it is picked up and discharged (Figs. 9 and 10). When these additional propellers are adjusted to full height, the clearing height is 3.5 m. It is then possible to clear snow with this depth continuously without the machine having to climb on top of the snow. The author knows of no other machine that can remove snow at such depths in one operation. All adjustments of the clearing system are operated hydraulically without having to interrupt the job.

These machines have been working for quite some years in areas where heavy snowfalls are common. They keep roads and railways free of snow during the winter and are also used in the spring to clear pass roads that have been closed all winter. These machines are also made with very long casting distances for use at airports. There are also very small machines that can be pushed by hand. They are being used in many countries all around the world.

## Informal Discussion

A. G. Clary

What are the relative merits of this type of machine compared with those of the Snowblast type of machine?

L. David Minsk

This is one of the few plows that has been developed based on scientific principles. Dr. Croce began his study of snow in 1936 and continued it during the war at the Bauhof fur den Winterdienst at Inzell, Bavaria. I have seen this machine operate very effectively in low-density snow. The precutters or "vorschneider" are designed to handle a dense snow situation. More often than not, in my experience, it requires extremely precise control by the operator to avoid crowding the machine too rapidly into the snow. When this happens the shear pins in the precutters break, and then they become a liability. The effectiveness of this machine in low-density snow is unquestioned in tests that have been run in Germany, Switzerland, and in this country. Its effectiveness in higher density snow is so much dependent on operator skill that its value is reduced. The horizontal auger type, as represented by the familiar Snogo, is effective to some extent, but again it densifies the snow as it moves it across the entire front face to reach the impeller.

The Rolba principle, as represented by the Snowblast (its called the Rolba system in Europe) is effective in high-density snow because of the milling principle under which it operates, as is the Peter plow which is also a Swiss development. The Schmidt plow is similar to the Peter plow. The relative effectiveness of these plows has been shown in various tests. However, each manufacturer can point to some tests that will substantiate his claims. You have to evaluate them yourself.