DESIGN OF A THREE-SPINDLE MULCHING LAWN MOWER

by

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1.1 Project Summary

This thesis presents the design of a three-spindle mulching lawn mower. The design actually consists of a number of modifications to an existing mower, but the operation of the final product is significantly different than that of the original machine. The new design was primarily intended to process grass at a higher rate without sacrificing performance or requiring a larger engine. To achieve this goal of better efficiency, a mower housing was developed which allows for an increased equilibrium flow rate of both air and cut material. Large accumulations of clippings, which raise power requirements and degrade performance, are thereby avoided. Field tests indicated that the mower in fact has the potential for a much higher material processing rate, although more work is required to improve the aesthetic appearance of the mowed lawn.

Before presenting details of the design, some background material will be covered to define the process of mulching and explain the motivation for developing a new mulching mower. Next, some preliminary research will be described which led directly to each of the major concepts in the design. This research was driven by the original project goals, but it also helped to refine and focus them by illustrating the limitations of current multi-spindle technology. A chapter is then devoted to some of the design concepts considered for the final solution and the rationale behind the concepts which were ultimately chosen. Finally, the design solution itself is presented, followed by the field test program, conclusions, and recommendations for further work.

1.2 Background

The Rotary Mower

The most commercially-important type of lawn mower is the rotary mower. The rotary mower cuts by high-speed impact of the grass blades with one or more cutting blades whose axes of rotation are perpendicular to the ground. A typical rotary mower blade is shown in Figure 1.1 below. The up-turned sections, or wings, at each end are designed for the dual purpose of lifting grass into an upright position and transporting cut material. Although the exact mechanism by which the grass is lifted in not well understood, it is known that the wings create a partial vacuum beneath the mower and improve cutting ability [1]. Blade tip speeds are commonly in the range of 12,000-16,000 fpm, with the ANSI upper limit being 19,000 fpm [2].

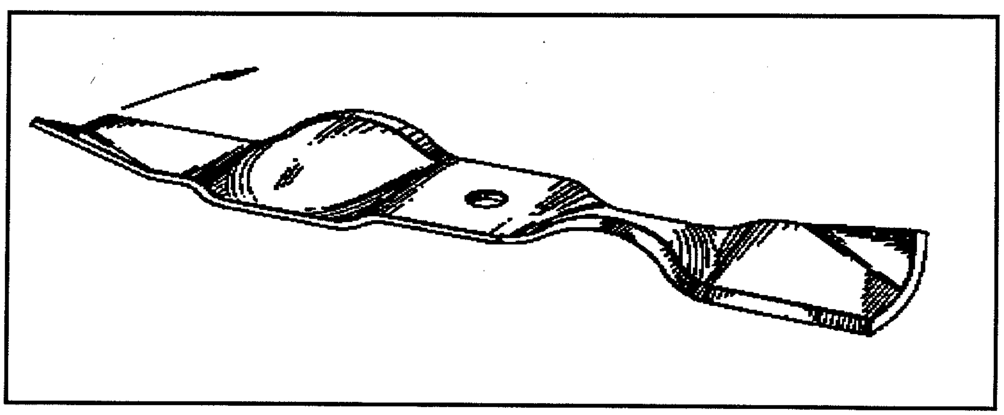

Figure 1.1 Rotary mower blade designed for mulching.

Rotary mowers usually have one, two, or three spindles. Each spindle drives one or more blades, which are housed for safety in an enclosure called the deck. The design of the blades, together with the deck enclosure, is critical to mower performance. On multi-spindle mowers, the spindles are either staggered fore and aft, or aligned with rotational timing to achieve complete coverage of the cut width. For example, Figure 1.2 shows the John Deere 44" mower, with 44-inch cut width and three-spindle staggered arrangement. Material for the blades and deck is typically steel.

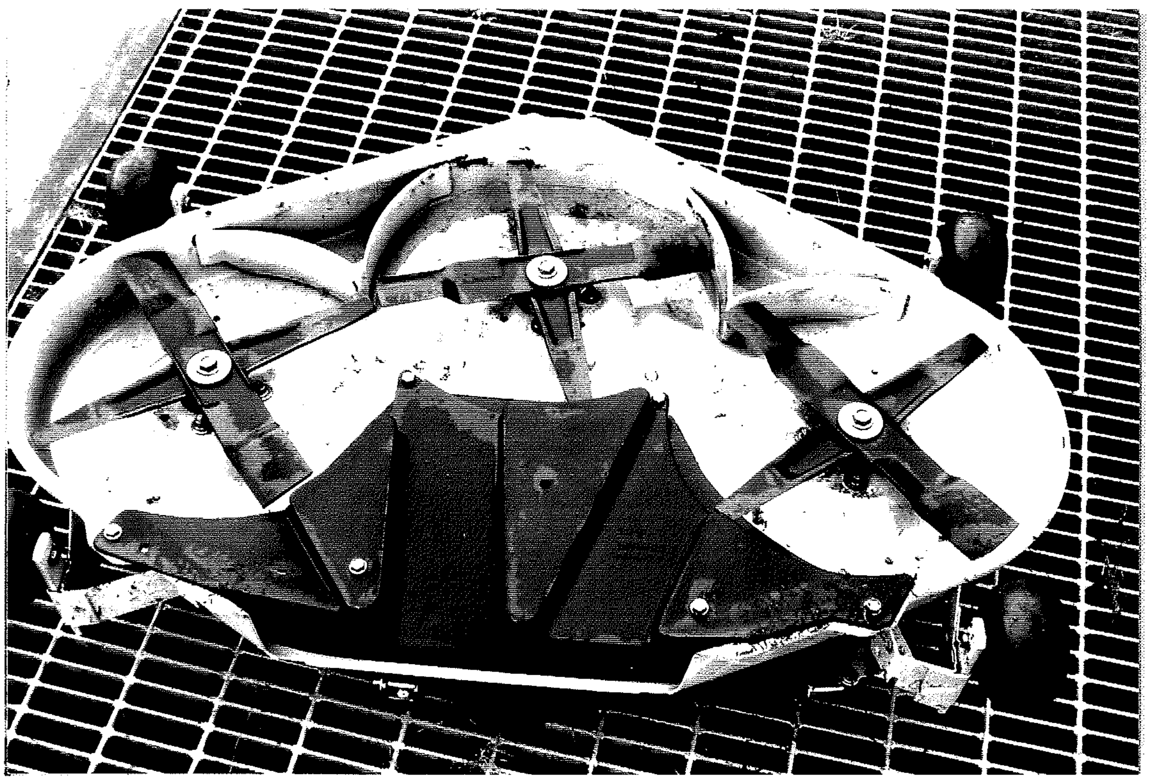

Figure 1.2 View underneath production 44" deck with cylindrical cutting chambers.

Rotary mowers are further classified according to how they deposit the grass after it is cut. Discharge mowers allow the cut grass to be simply thrown or blown out of the deck through a single discharge chute, which can be to the side or rear. No attempt is made to cut the grass clippings more than once, but a wide dispersion of the clippings on the lawn is desired. Collection mowers are similar to discharge mowers except that a receptacle is placed over the chute to collect the clippings for later disposal. Mulching mowers, lastly, are supposed to chop the grass into small particles and deposit these beneath the deck. The clippings must be chopped finely enough to be hidden in the lawn, where they decompose and become fertilizer. Many of the rotary mowers sold today have the capacity to discharge, collect, or mulch. Increasingly, however, manufacturers are offering mowers dedicated to mulching alone, in order to meet a growing consumer demand for them. As landfill space becomes more scarce and expensive, viable alternatives to collection and disposal of grass clippings become more attractive. Elimination of the collection function saves labor for individuals as well as for municipalities and lawn care professionals. Ecologically, mulching can lead to better lawn health and appearance, although the costs associated with higher power consumption and increased cutting frequency must be examined and eliminated if possible.

Until the recent popularity of mulching, rotary mowers were designed almost exclusively for discharge or collection. Over a period of many years mowers evolved to perform these two functions, and the resulting designs were not necessarily well-suited to good mulching performance. In fact, many side or rear discharge mowers were converted to mulching mowers with little prior thought or expense, simply by blocking the discharge chute to retain the clippings in the deck for repeated chopping. The result was inadequate air flow though the deck, poor dispersion of clippings, and very limited capacity to mulch tall or wet grass. More recently, as manufacturers have produced equipment especially designed for mulching, the performance has improved somewhat. A "conventional" mulching mower design has evolved, but a large gap still exists between customer expectations and actual performance.

Mulching Mower Performance

Mulching is defined as the process of chopping grass clippings into fine particles and hiding these particles in the lawn where they rapidly decompose. One question that arises is how fine the clippings must be chopped. According to turfgrass scientists, from the standpoint of lawn health the rule for clipping size is "the smaller the better" [3,4]. The smaller the clippings, the more surface area and released fluids there are to promote decomposition. However, this criterion conflicts somewhat with a criterion based solely on considerations of power requirement and aesthetics. Extensive chopping requires power, and the resulting release of fluids causes the clippings to acquire a paste-like consistency. In such a state they are difficult to disperse and tend to lay on the surface of the lawn instead of falling beneath it. Thus, one of the design requirements to be determined is the maximum acceptable clipping size.

While it is important to chop the clippings sufficiently small, it is equally important for the mowed lawn to have an aesthetically pleasing appearance. All of the grass in the path of the mower should be cut at the same height and the clippings should be uniformly dispersed and hidden. Cutting all the grass at an even height with a tractor-mounted deck is a function of 1) how the mower attaches and interacts with the traction unit, and 2) how the mower interacts with the grass. In this project we looked exclusively at mower-grass interaction. Achieving uniform dispersion depends on using the blade in concert with the deck to appropriately move and distribute the air and clippings. Whether the clippings are adequately hidden depends on their size and the manner in which they are deposited.

Since by definition mulching mowers have no discharge chute, clippings can readily build up within the deck. If the accumulation continues without relief, the mower will eventually lose speed and bog down, forcing the engine to stop. Thus, to make cuts greater than a certain depth, either a larger engine is required or the deck must handle the grass more efficiently.

Based on the preceding discussion, considerations of performance for mulching mowers may be divided into three areas:

1) **Cut Quality** - As with all lawn mowers, the most important function of a mulching mower is to cut all the grass in its path at an even height and with a clean cut.

2) **Mulch Quality** - This refers to the degree to which clippings have been dispersed across the width of the swath and hidden in the lawn. The goal is for the lawn to be neat in appearance, as if a collection mower had been used.

3) **Power Requirement** - The mower should be able to cut in tall, thick, or wet grass conditions with a relatively small engine. A convenient measure of the power requirement for a mulching mower of a given cut width is the maximum depth of cut it can make, at a given speed, without completely loading with clippings. When the deck becomes fully loaded, the

power requirement increases sharply and the mower tends to bog down. The maximum depth of cut is only an approximate measure and depends on the type, thickness, and moisture level of the grass.

In addition to the three areas above, there are other mower performance issues, such as noise generation and trimming ability, which received lesser emphasis in this work.

Limitations of Current Mowers

There are several problems customers associate with current mulching mowers. The first is poor mulch quality that results from making deep cuts. Mower manufacturers now recommend a "1/3 rule", specifying that no more than 1/3 of the nominal length of grass should be cut off [5]. The rule follows from the inability of mulching mowers to adequately disperse and hide the clippings when deeper cuts are attempted. The majority of the clippings are seen lying on the surface of the lawn, often in unsightly windrows or clumps. A side result is that users are inclined to cut more frequently, causing increased engine emissions which potentially negate the environmental benefits of mulching.

Secondly, mulching mowers tend to have inferior cut quality relative to discharge and collection mowers. Mulching mowers seem less able to lift grass that is bent over or pushed down. The result is patches and "stripes" of grass cut at a greater height than intended or not cut at all. Inadequate lift is believed to occur when there is inadequate flow of air and material out of the deck, or when the flow is in a direction that pushes the grass down. Another cause of stripes, affecting tractor mounted mowers, is depression of the grass by the front tires. In wet conditions, grass in the tire tracks can be especially difficult to pick up.

A third problem is the tendency of the mower to bog down in tall, thick, or wet grass conditions. Although it may not be realistic to expect good mulch quality in such conditions, the mower must at least be able to cut all the grass without forcing the engine to stop. Customers routinely expect to cut ten-inch grass down to three inches without having to slow down or mow in stages. To meet this requirement, mulching mowers are typically powered by larger engines than discharge or collection mowers. A rule of thumb is that 10 hp is required for every 30 inches of cut width [5].

1.3 Objectives

The primary objective of this project was to design a multi-spindle mulching mower which has the following benefits:

- Superior cut and mulch quality to comparable mowers. This goal amounts to extending the 1/3 rule to a 1/2 rule or beyond.
- Increased capacity to cut tall, thick, or wet grass without bogging down. Specifically, a deck design is desired that requires 8 hp for every 30 inches of cut width.

Additionally, there were several secondary but related objectives for the project:

- To understand the processes by which grass is either lifted or pushed down by a rotary mower.
- To characterize the movement of air and grass clippings in a typical mulching deck. This includes observations of the actual motion as well as models which attempt to explain or predict the motion.

- To develop and apply appropriate methods of evaluating mower performance.

1.4 Scope of Design

The research in this project was limited to rotary mowers with blades of some kind. Other methods of cutting grass were not considered. The scope was further narrowed to include only the mulching mower deck, and not the drive unit to any significant extent. Although it is conceivable to cut a wide area using only one spindle, considerations of space led us to assume that the deck design would have multiple spindles. With these initial constraints in place, the remaining design task consisted of specifying the complete geometry and materials for the deck and blades, as well as the blades' rotational speeds.

The specific mower deck used as the basis for the preliminary study was the John Deere 44" three-spindle production mower with mulching attachments (Figure 1.2). This mower deck was operated underneath a John Deere GT242 lawn tractor with a 14 HP gasoline engine. Eventually this deck was used as the basis for the new design, allowing us to easily incorporate some of the ideas generated during the preliminary investigation of mulching.

2.0 ANALYSIS OF THE PROBLEM

2.1 Review of the Literature

Literature dealing specifically with mulching mowers is practically nonexistent. There is considerable literature on discharge and collection mowers, however, as well as work on certain aspects of the mowing process, which is helpful. In addition there have been numerous patents granted for mulching technology, although explanations of the principles of operation are often sketchy. The patents are useful primarily as a catalyst to the generation of new ideas.

One study concerned with the biological aspects of mulching recommends the following clipping size distribution to achieve an acceptable balance between lawn health and mower performance [4]:

0-0.2 inch	60% of clippings
0.2-0.4 inch	30% of clippings
Over 0.4 inch	10% of clippings

Although a complete distribution could be specified, including mean and variance, in this project we chose to design for a single target clipping size of 0.25 inch.

It is important to know the minimum blade tip speed at which impact cutting of grasses can occur. In the absence of other limitations, this value sets the lower limit on blade speed for the machine. The values for minimum speed found in the literature vary somewhat, since they are determined experimentally and depend on a number of factors, including grass conditions, blade shape, and blade sharpness. Persson [6], in a very comprehensive compilation of previous work on plant cutting, quotes speeds as low as 8000 fpm. Boast [7] observed impact cutting at speeds as low as 70 fps (4200 fpm). This was the lowest speed found anywhere in the literature. However, mower design engineers at John Deere have found that a speed of 12,000 fpm seems to be necessary for adequate cutting in a wide range of conditions [5].

Several studies have suggested that as a percentage of the total power delivered to the mower, the power required for actually cutting the grass is quite small [1,8,9]. One study estimated this percentage at just 5%, as compared to 50% for moving cut grass, 35% for air movement, and 10% for drive-train losses [8]. In any case it is clear that the power required at the blade to accelerate clippings and overcome friction between clippings and the deck is a large portion of the total. This is especially significant in mulching, since most mulching mowers rely on high clipping dwell time to accomplish the necessary chopping.

Work by Loewer [10] showed that excessive clippings in the deck can cause stripes of uncut grass. Loewer made high-speed photographs of the grass cutting process and showed how material can build up where the opposing motion of neighboring blades creates a dead zone. It was proposed that material in the dead zone pushes down uncut grass. The films also showed that the wing angle of the blade is very important in determining the trajectory of clippings. For discharge mowers, wing angles approaching 90 degrees were suggested, in order to throw clippings more horizontally toward the discharge chute. With lesser angles, the films showed that the clippings were repeatedly thrown against the ceiling of the deck before being discharged. Loewer found that near the deck ceiling, the velocity of the clippings is at least several times less than the velocity near the level of the blade, due to aerodynamic drag on the particles.

Litherland [11], beginning with a mathematical analysis based on a number of simplifying assumptions, developed a computer program to predict how the wing angle of the blade affects the trajectory of clippings. He also produced experimental results in the form of high-speed photographs to confirm the predictions of his analysis. Litherland's work has direct application to the design of discharge and collection mowers, but it can also be applied to advantage in work with mulching mowers. Having an idea of the speed and trajectory of clippings as they leave the blade allows the designer to devise more efficient means to chop and deposit them. The design variables in the computer program were blade radius, tip speed, wing angle, and wing height. The grass-on-steel friction coefficient was assumed to be 0.70.

An important result from Litherland's work was that clippings have a very high tangential velocity component as they leave the blade - often as high as 60% of blade tip speed. The axial component, by comparison, is roughly a quarter of blade speed, while the radial component is one tenth. These ratios apply for blades having wings angled at 30 degrees from horizontal, which is common for mulchers. One implication is that in a conventional mulching mower, a grass clipping will likely travel a substantial distance around the deck before falling into a position to be recut.

The air flow created by the blades is evidently highly turbulent [1] and may include prominent vortices shed from the blade tips. The graph in Figure 2.1 shows that a region of downward flow is present just above the blade wings [12]. This flow could be the result of shed vortices similar to those observed behind fixed wing aircraft during landing.

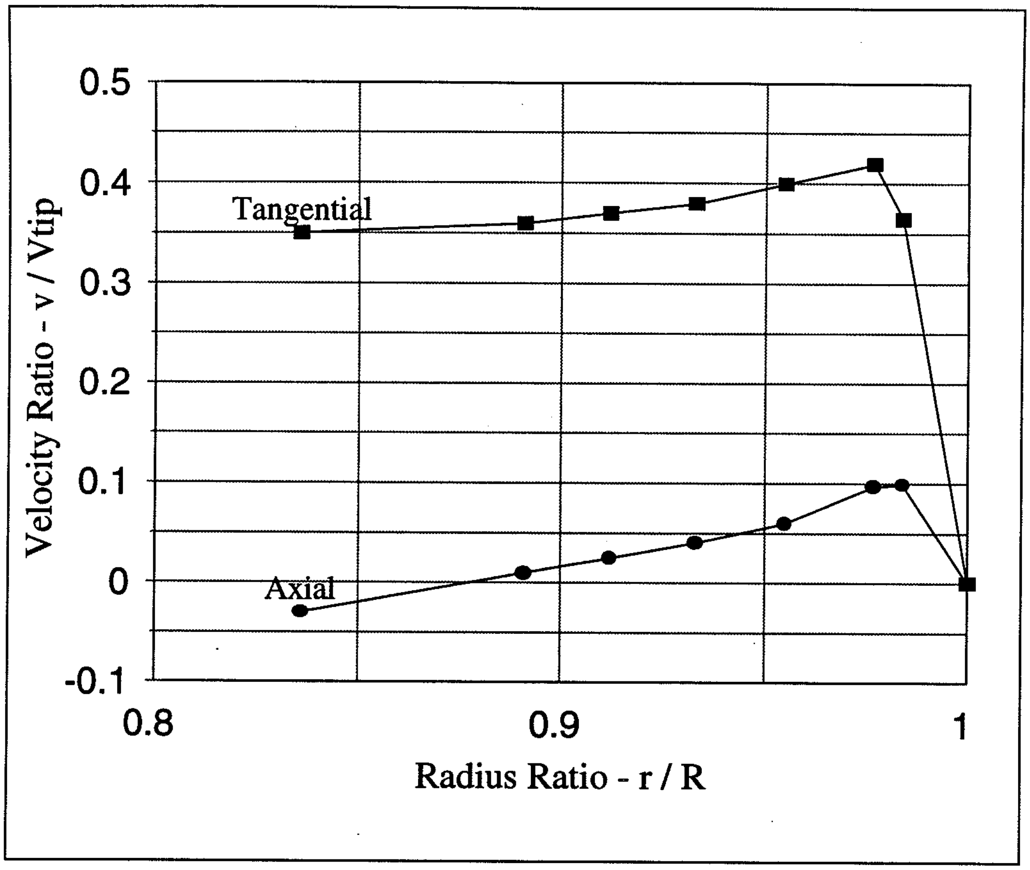

Figure 2.1 Air velocity distribution 1.5 inches above a mower blade. Data from [12].

With regard to noise generation, there has been extensive publication [12,13,14]. Several workers have demonstrated that blade speed has the strongest effect on mower noise. It is thus desirable to lower the blade speed, if this can be done without compromising performance. Another significant factor is the shape and frontal area of the blade wing. Streamlining is advantageous for reducing noise. Again, however, the effects on performance must be weighed with the benefits of a quieter machine. This theme occurs frequently when dealing with rotary mowers, as there are always benefits (less noise and aerodynamic drag) associated with reduced blade speed or frontal area, but the costs in performance are often too high.

2.2 Current Art

In principle a mulching mower can be obtained from any discharge mower by simply blocking the discharge chute. As manufacturers have found, however, this approach yields performance which is far from optimal. Therefore, as the number of models dedicated to mulching has increased, a conventional design with several common features has evolved.

The conventional mulching deck consists of adjacent torus-shaped chambers, each of which houses one mulching blade and sometimes an additional chopping blade (see Figure 2.2). The mulching blades have an outer wing section and an inner "mulching hump" on each end (Figure 1.1). Although the clearance between the blade tips and the deck skirt varies from mower to mower, it is usually within the range of 1/8-1/4 inch. It is thought that with this combination of deck and blade shape, a circulatory flow of material is generated in which grass is lifted and cut by the wing section and recut and deposited by the mulching hump. High-speed films taken by John Deere reveal that a toroidal deck shape does in fact utilize the vertical momentum of clippings to direct them in a spiral path along the ceiling and toward the inner wall of the torus.

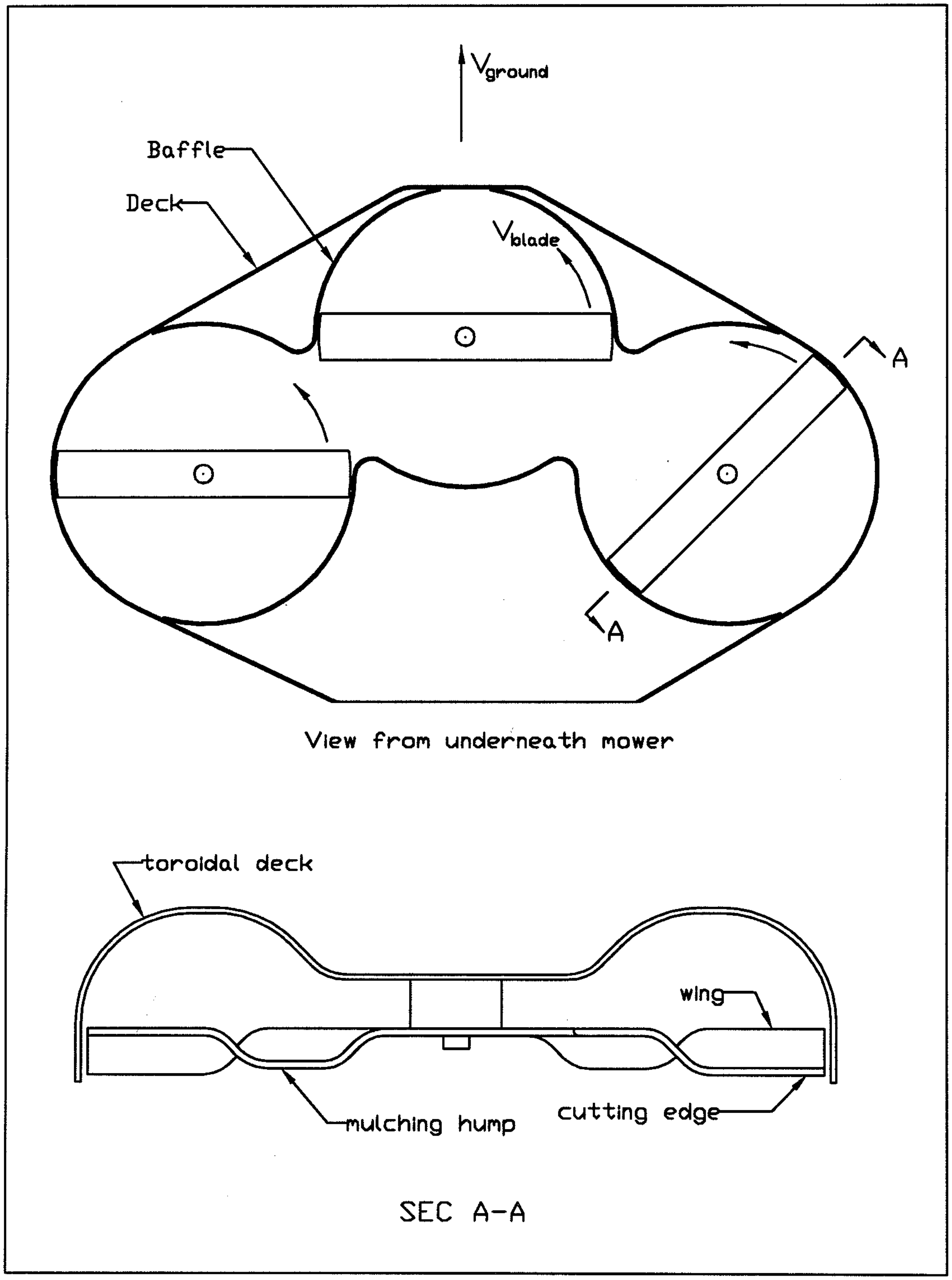

Figure 2.2 Conventional mulching mower.

At least one manufacturer has added to this basic design a means of deflecting material back into the path of the blades. The two-spindle mower shown in Figure 2.3 has wedge-shaped "kickers" attached to the ceiling of the deck for that purpose. This mower has proved very effective, in moderate conditions, at hiding its clippings in the lawn.

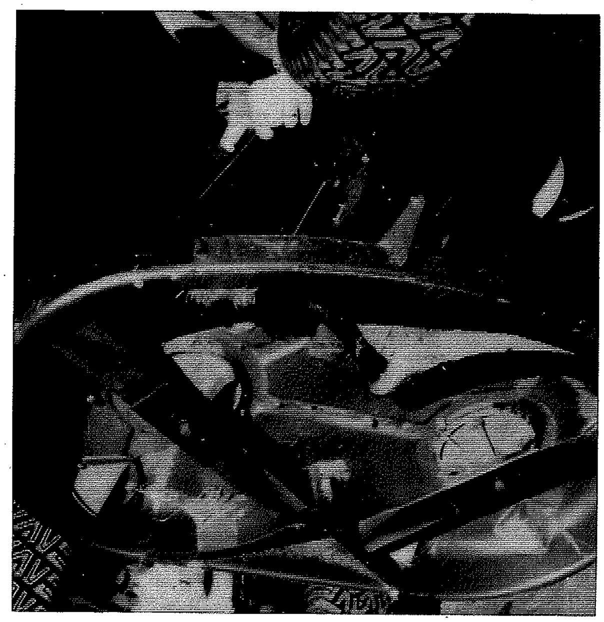

Figure 2.3 Two-spindle mulching mower with kickers for deflecting grass clippings.

Very recently, more mower designs have appeared with in-line spindles rather than a staggered arrangement. Expanded tip clearances around the rear skirt have also become more popular.

2.3 Preliminary Mowing Tests

In order to gain more insight on the problem before proceeding with the design, extensive mowing was done with production equipment. Specifically, we desired to learn more about the flow of air and material through the deck and to better understand what causes performance to degrade. The mower tested was the John Deere 44", which could be run in discharge mode or in mulching mode. In mulching mode, either cylindrical (Figure 1.2) or toroidal (Figure 2.4) cutting chambers could be used.

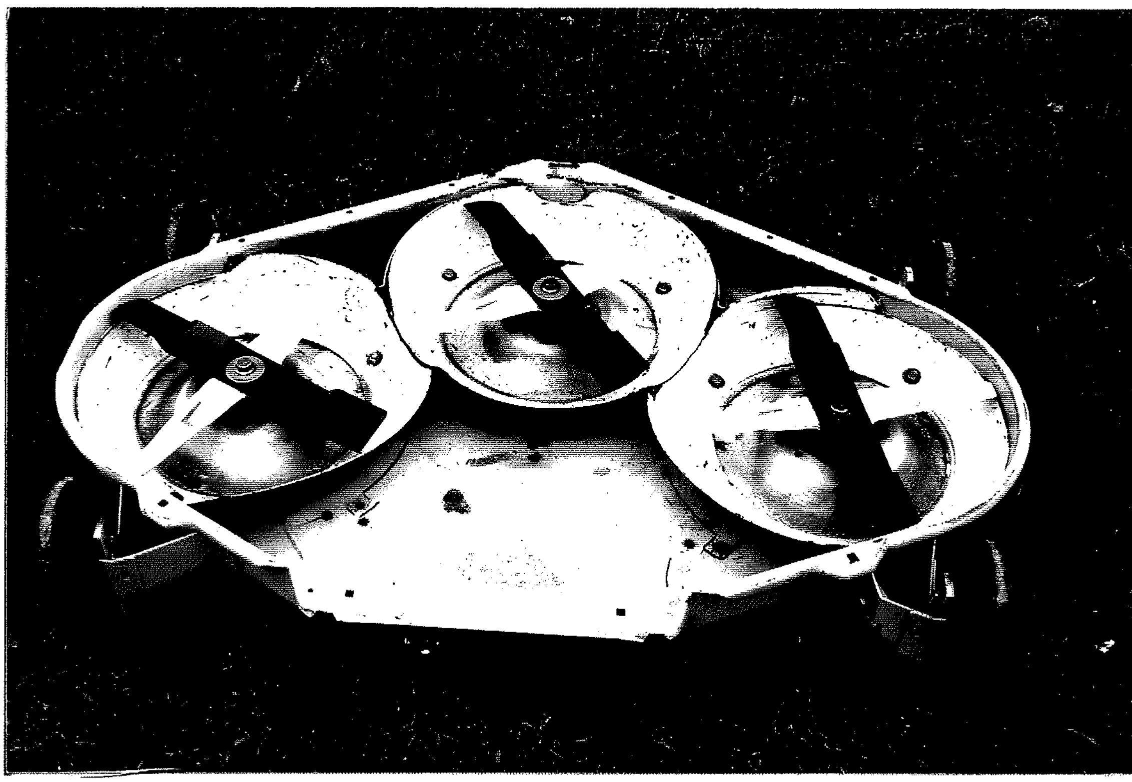

Figure 2.4 View underneath production 44" deck with toroidal cutting chambers.

Air Flow

Since air flow is thought to be very important for generating lift and transporting material, we decided to further investigate the characteristics of the air flow, such as flow direction and the effect of deck geometry.

In simple experiments with a one-spindle side discharge mower, a trend was noticed which seemed to apply to other mowers as well. In the side discharge unit, air flowed into the deck (underneath the cylindrical skirt) where the tip clearance was small. Air flowed out of the deck where the tip clearance was relatively large. The presence of a sufficiently small tip clearance apparently caused suction to develop, whereas a larger clearance allowed air to spill over the end of the blade. It is interesting to ask where air would flow into and out of a deck with identical tip clearances all around. For example, imagine a one-spindle deck in the form of a half-cylinder. In the absence of other effects, the rotating blade would seem to cause only a swirling motion of air inside the deck but no net flow.

In conventional mulching mowers there is no direct path for air to leave the deck. This presents a problem for achieving lift on the grass. If there is no net air flow, any local lift created will have to be balanced somewhere by a corresponding downward flow. In fact, since the wings of the blades displace air upwards, it follows that behind the blades there is likely to be downward motion of air. In this case the grass would actually be pushed down before the blade encountered it again. The problem is intensified by large accumulations of clippings that tend to develop in conventional mulchers. A heavy mass of swirling material inhibits any lifting action the blades might otherwise generate.

There are several ways to solve the problem of creating lift. The challenge is to generate high air flow through the deck without allowing the clippings to escape before getting chopped. One alternative is to retain a limited discharge opening, but use many blades per spindle to ensure that the clippings are chopped before being discharged. The extra blades can be in the form of a turbine device or simply additional conventional mower blades. In the latter case the required cuts are made simultaneously at the time of initial impact.

Multiple Cutting Edges

To test the idea of making multiple cuts on a leaf of grass simultaneously, three sets of blades were fabricated and stacked on each spindle of the production deck. Each set consisted of a lifting blade as well as up to three additional flat blades stacked above it. (See Appendix B for drawings of these blades.) The vertical spacing between the cutting edges was set at 0.30 inch, while the angular orientation could be varied infinitely. The blades were run in mulching mode, with both the toroidal and cylindrical chambers, as well as in discharge mode.

Several things were noticed immediately. First, operating with three or four blades per spindle caused a sharp increase in the noise level, especially at higher frequencies. Second, although the wing on the lifting blade was very small and the additional blades had no wings at all, a very strong flow of air was produced. It was clear that this flow was primarily tangential. Also, as expected, the added inertia of the blades caused belt slippage during starting and stopping.

Many combinations of blade count and angular orientation were tested, but in all cases using additional blades appeared to reduce the size of the clippings deposited by the deck. It was evident, however, that with each blade added, the marginal reduction in clipping size was less. That is, when increasing from one blade to two blades per spindle, a large reduction in clipping size was observed. But when three blades was increased to four, there was hardly a noticeable difference. This was true whether the deck was configured for mulching or discharging. We also found that aligning the cutting edges radially was preferable to having them oriented 90 degrees apart. This implied that the grass plants were in fact being cut simultaneously by each edge in the stack.

One problem with the stacked blades was lack of lift. The cut quality with the low-profile lifter was consistently worse than with the production blades. Evidently, a blade with large frontal area is necessary for best cut quality.

Material Flow

Some important discoveries were made during our investigation of the material flow inside a mulching mower. The objective was to determine the complete path of a typical grass particle after it is initially cut. Although the motion is certainly very difficult to describe precisely, a few simple observations can reveal important general trends of the motion. We especially wanted to learn how material exits a mulching deck.

As described in the literature review, it is known that the blade wing imparts a primarily tangential but also vertical trajectory to the clipping. The wing essentially slaps the clipping toward the deck ceiling at approximately a 25 degree angle. Then, depending on the shape of the deck chamber and the amount of material already present, the clipping will slide along the ceiling, lose speed due to drag, and eventually fall back to the level of the blade. If the clipping has spiraled sufficiently toward the center of the chamber, the mulching hump will recut the clipping and deflect the bottom half toward the ground. If the clipping has moved a lesser amount toward the center, it will be deflected upwardly again by the wing. Finally, if the clipping remains at the periphery of the chamber (along the outer wall), it will be deposited through the tip clearance. Clippings too large to pass through the clearance will probably be recut or thrown against the outer wall.

A number of simple experiments were performed to verify all or part of the above description. First, a mulching blade was painted white so that grass stains would record the impact of clippings. The inside of the yellow deck was completely scoured of foreign material so that impact on the deck would also be evident. After cutting for several minutes, markings on the blade revealed that impact was occurring on both the blade wing and the mulching hump, although the higher-speed flow at the wing scoured some of the paint and most of the stains away. Markings on the deck showed evidence of the spiral motion discussed previously. It was also noticed that clippings from one chamber were being thrown against the inner wall (near the spindle) of the adjacent chamber.

Migration of clippings from one chamber to another was verified by painting the grass before cutting and then observing where the painted clippings were deposited. In the three-spindle mower tested, where the blades all rotate in a clockwise direction (as viewed from above), the clippings tended to migrate to the right hand chamber.

To find the exact areas in the deck where clippings were deposited, the deck was loaded with clippings and run for 3 minutes while positioned above a large piece of cardboard. The resulting pattern is shown in Figure 2.5. It reveals several things. First, no large clippings are evident. Probably these were all chopped during the 3 minutes in the deck. Second, it was surprising to find that the majority of material was deposited just outside the blade tips, while progressively less material was deposited toward the center of each cutting chamber. Finally, an interesting pattern was produced at the overlap regions. Clearly, the open passages between chambers allowed interaction between adjacent blades. It appeared that the downward flows from adjacent blades were augmenting one another.

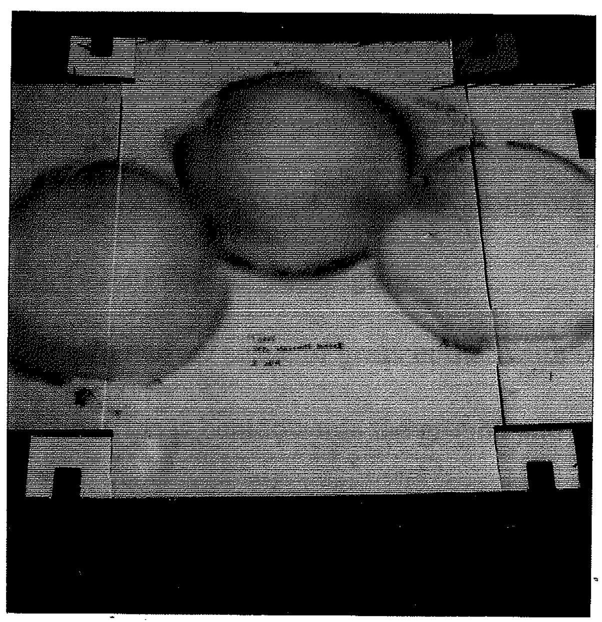

Figure 2.5 Pattern of deposited material under three-spindle mulching mower.

During the mowing tests, we observed that moisture and depth of cut had the strongest effects on power requirement. Whenever the deck became loaded with clippings the power requirement would rise steeply, as evidenced by a drop in speed. In wet conditions, the build up was caused by material sticking to the deck ceiling. However, the deck would readily saturate with clippings in dry conditions as well, if cuts deeper than about 4 inches were attempted. In this situation, two factors were at work: increased amount of material to process, and choked air flow. The bluegrass cut for the tests is characteristically thicker closer to root level, since not all the stems grow to the nominal length. During deep cuts, the grass around the skirt chokes off the flow of air and hence material.

Causes of Striping

Striping continues to be a persistent problem for mower manufacturers [5]. Therefore we were asked to consider causes and possible remedies during our investigations, with the hope of later applying our findings to a deck design.

Striping occurs when a narrow stripe of grass in the swath of the mower is not cut or is cut too high. Grass in the stripe is bent towards the ground and not raised sufficiently into the cutting plane as the mower passes. Striping is most severe when tall grass is mowed, and it tends to occur in three areas: behind the front tractor tires, in the overlap region between adjacent blades, and where each blade makes a forward sweep.

In attacking the problem the first step is to ask why the grass is bent over. For lawn tractors the most obvious reason is the front tires. The effect of the tires is greatest when mowing tall or wet grass, and at high ground speeds, because in these conditions the grass has less ability to spring back. However, since the front tires cannot be eliminated, the solution must be some method of lifting the grass before the mower passes. This may be accomplished mechanically, pneumatically, or by some other means. The solution usually attempted is to hope that the rotating blades lift the grass, either by direct suction or by contrary air flow along the ground. But to this point, the air flow produced has been inadequate to consistently lift the grass in tire tracks.

Another reason grass is bent over is that mowers must have a front skirt. To prevent injuries by thrown objects, ANSI Standard 71.4-1984 [2] sets a maximum height for the opening at the front of the deck. In practice, however, the front skirt usually extends much lower than the maximum height in order to prevent "blowout" of clippings from the deck. Thus, either the grass must be lifted after it passes under the skirt, or the skirt must be made higher without inducing blowout. On current art decks, the skirt is often raised somewhat in front, but not enough to allow the grass to pass freely underneath. The blades are then relied upon to lift the depressed grass.

A third reason grass is bent down is air flow from the blades themselves. Air flow in the deck is very turbulent, with a large component that is horizontal. This horizontal flow, if in the same direction that the grass is lying down, can actually prevent the suction of the blades from lifting the grass in time to be cut. Since the grass is almost invariably bent over in the direction of mower travel, striping tends to occur where there is a forward sweep of the blades. Of course it is impossible to have a rotary mower without any forward sweep. But by strategically choosing the directions of rotation, the forward sweep of each blade can be placed to cause the least striping.

Each blade apparently has a downward component of air flow off the blade tip, resulting from a pressure imbalance or shed vortices. This action may contribute to striping in the overlap region, because here the downwash effects of two blades add together. The relative directions of rotation of the neighboring blades is probably a factor as well. Loewer [10] found that striping in the left hand overlap region of a three spindle mower could be reduced somewhat by reversing the rotation of the center blade. This eliminated the contrary tangential flow and alleviated grass build-up in the overlap region.

2.4 Power Requirement

In attempting to reduce the power requirement of a mower, it is helpful to know what proportion of the total power is consumed by each mowing process. Estimates of these proportions have been made in previous research, as mentioned in the literature review. Figure 2.6 shows one estimate [8], which is in general agreement with others found in the literature. The important point is that the largest opportunity for reducing power is in transport of air and material. Relatively little opportunity exists in the cutting process. Thus, although issues such as blade sharpness and shear cutting are important for cut quality, they have little to do with power consumption.

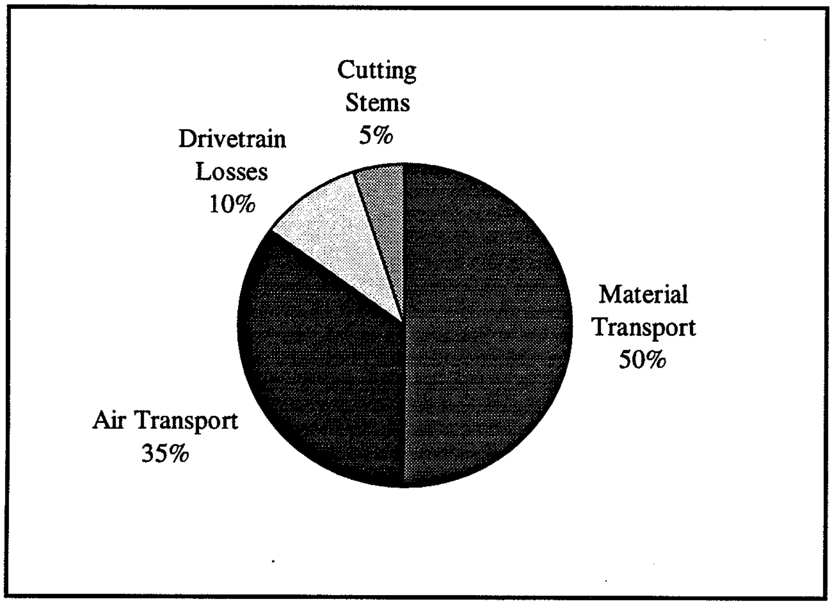

Figure 2.6 Total power required by mower [8].

The power required by a blade rotating with an angular speed of ω is

$$P = T\,\omega$$

where T is the torque exerted on the blade by grass and air. Neglecting cutting forces, which are relatively small, torque is applied to the blade in three different modes.

Initial Acceleration

Immediately after a stationary grass stem is cut, the blade wing accelerates it to a high speed. Only the tangential component of the clipping's velocity is responsible for torque on the blade. If the ratio of the r.m.s. tangential velocity of clippings to the velocity of the blade tip is designated as β, then the power consumed by initial acceleration is approximately

$$P_{acc} = m' (\beta V_{tip})^2 / 2$$

The relation is approximate because the torque is actually applied at a slightly smaller radius than the blade tip. The quantity m' is the mass flow rate of grass into the deck. Work by Litherland [11] has demonstrated that the ratio β depends primarily on the blade wing angle. Using his data, Table 2.1 shows the variation of β^2 with wing angle.

Table 2.1 Effect of Wing Angle on Velocity Ratio

Wing Angle (deg)	β	β^2
15	0.23	0.053
20	0.32	0.102
25	0.42	0.176
30	0.53	0.281
35	0.63	0.397
40	0.72	0.518
45	0.82	0.672
50	0.91	0.828

As indicated by the data, a large change can be effected in the power required for this mode of transport when the blade angle is changed.

To get an idea of the magnitude of the acceleration power, data from Persson [6] has been used to calculate a typical value of m'. The expression for m' is

$$m' = d\,\gamma\,\rho_A\,W\,V_{ground}$$

where the definition of each variable and typical values are given in Table 2.2.

Table 2.2 Mass Flow Rate into Mower

Variable	Definition	Typical Value [6]
d	depth of cut	4.0 in/plant
γ	linear plant density (wet)	0.00056 lb/in
ρ_A	area plant density	2.5 plants/in^2
W	cutting width of mower	44 in
V_{ground}	ground speed of mower	24 in/s

Substitution of these values into the expression for m' yields a flow rate of 5.9 lb/s by weight, or 0.015 lb-s^2/in/s by mass. For a 30 degree blade having a tip speed of 14,000 fpm or 2800 in/s, the resulting acceleration power is calculated to be

$$P_{acc} = 0.015 \text{ lbf-s}^2\text{/in/s } [(0.53)(2800 \text{ in/s})]^2 / 2 = 16{,}900 \text{ lbf-in/s} = \underline{2.6 \text{ hp}}$$

By comparison, the value quoted by Boast [7] for cutting power alone in comparable conditions is only 0.6 hp.

Fluid Dynamic Drag

After clippings are initially accelerated, they will begin to slow due to friction. Unless they leave the deck, they will eventually be struck again by the blade, although not from a stationary position. If the mixture of air and material in the deck can be considered to have an effective density ρ_{eff} then the power due to fluid dynamic drag on the blade is given by

$$P_{fluid} = K \rho_{eff} V_{rel}^{2} V_{tip} / 2$$

where K is a composite drag coefficient depending on both the shape and frontal area of the blade, and V_{rel} is the difference between the fluid tangential velocity and the blade tip velocity. The graph in Figure 2.1, given previously, indicates that the fluid tangential velocity is roughly 35% of V_{tip}. Inserting this relationship into the preceding equation yields

$$P_{fluid} = 0.123 K \rho_{eff} V_{tip}^{3} / 2$$

The cubic term implies that the fluid drag component of the transport power is extremely sensitive to tip speed. Values of K and effective density are determined experimentally, although this was not done in this project. As more material accumulates in the deck, ρ_{eff} will certainly rise.

Deck-Grass Friction

A phenomenon was observed during mowing experiments which demonstrated a third mode of transport power consumption. It occurred only in very heavy conditions (wet grass and very tall grass), during which the flow of material into the mower exceeded the outflow long enough to cause significant mass storage. These were situations where the space above the blade became completely occupied with material. On several occasions, after the mower bogged down, we looked under the deck and saw clumps of grass lodged between the blade and the deck. The clumps had been dragged around the deck by the blade, and when the mower was restarted in this condition, it killed almost immediately.

Apparently, as the mower tries to ingest more and more clippings, the existing clippings are compressed against the deck ceiling, creating a normal force large enough to lodge the clippings. This material is dragged around the deck, opposed by a frictional force which the blade must overcome. The power consumed by this action is

$$P_{fric} = \mu N V_{tip}$$

where μ is the grass-on-deck friction coefficient and N is the normal force. The normal force probably depends on the bulk density of material in the deck, since the material is compressed as more is added. No attempt was made to quantify the normal force.

Summary

About 85% of the total power required at the blade is due to transport. There are three modes of transport power, one of which is not always active.

$$P_{trans} = P_{acc} + P_{fluid} + (P_{fric})$$

$$P_{trans} = m' (\beta V_{tip})^2 / 2 + 0.123 K \rho_{eff} V_{tip}^3 / 2 + (\mu N V_{tip})$$

Unfortunately, we did not have time in this project to determine typical magnitudes for the last two terms. Several things can be learned from this relation, however. First, the power is strongly dependent on the blade speed. In the past, the blade speed has been kept high to ensure adequate lift, cut quality, and clipping transport. In mulching, clipping transport is not necessarily desired, so perhaps the blade speed can be lowered somewhat in a mulching mower. If a way were found to ensure lift without the use of conventional blade shapes, a very significant reduction in transport power could be made. In this case, not only could the tip speed be reduced, but the wing angle could be made smaller, affecting the important quantities K and β. Finally, the second and third terms show that it is very important to limit the bulk density of material in the deck.

2.5 Preliminary Conclusions

Based on the preliminary mowing tests and reviews of current art and literature, we were able to begin the conceptual design stage guided by a number of important conclusions. These conclusions are summarized below.

Air Flow

1. Maintaining air flow through the deck is very important for generating lift and preventing undesirable accumulations of material.
2. Tip clearance effectively controls where air and material enter and leave the deck.
3. In tall grass the flow is choked when the area underneath the skirt lip, which is the only flow path, becomes blocked.

Material Flow

1. Most of the clippings in a mulching mower are deposited just outside of the blade tips. Fewer and fewer clippings are deposited as the center of the cutting chamber is approached.
2. In current mulching mowers, clippings spend the majority of their time out of the cutting zone.

Striping

1. The blades themselves cannot consistently pick up grass that has been depressed by tractor tires.
2. Stripes tend to occur where the blades sweep forward (the direction of mower travel).
3. Striping in the blade overlap region is affected by interaction between adjacent blades.

General Conclusions

1. Current mulching mowers readily saturate with clippings. This behavior greatly increases their power requirement and reduces their grass-lifting ability.
2. To reduce the power requirement, one or more of the following quantities should be reduced: blade speed, wing angle, wing height or the amount of material stored in the deck. Reducing the last quantity amounts to increasing the equilibrium flow rate of material.
3. The use of multiple cutting edges significantly reduces the size of the clippings deposited by a mower.

3.0 DESIGN CONCEPTS

3.1 Design Approach

The design of a mulching mower is a task that lends itself well to a functional approach. Mulching can be viewed as a process made up of several sub-processes or functions which must be performed. There are six primary functions:

1. Lift grass
2. Cut grass
3. Chop clippings
4. Deposit clippings
5. Disperse clippings
6. Hide clippings

It is interesting that in most mulching mowers, the blade plays a central role in accomplishing all six of these functions. The role of the deck is to enhance the performance of the blade. For example, for the function of chopping, the deck prevents the clippings from being discharged too soon. In more advanced mowers, the deck would also be designed to direct the clippings back into the cutting region.

A sensible approach to the design task is to examine each function in detail and ask what is the best way to accomplish it. The blade may or may not be an important part of the result. Then, as conceptual solutions are found for each function, they must be combined into a feasible overall solution. The combination process may reveal that some concepts are mutually exclusive or inclusive. Such constraints, along with intuition and judgment based on mowing experience, narrow the large number of combinations down to a manageable size.

Table 3.1 is a summary of the design functions and possible solutions, where the solutions ultimately chosen have been highlighted. The remainder of this chapter discusses in more detail each of the six functions and some of the concepts considered for them. The emphasis is on the rationale behind the concepts chosen for the final design. In each case, the chosen concept followed directly from conclusions drawn during the preliminary study of mulching.

Table 3.1 Design Functions and Concepts

Function	Concept					
LIFT grass	blade wing	separate blower	rake or comb mechanism	roller with brushes		
CUT grass	three spindles aligned	two spindles aligned	two spindles staggered	three spindles with middle spindle forward	three spindles with outer spindles forward	three spindles, staggered diagonally
CHOP clippings	direct clippings back into cutting blade	use additional chopping blades	turbine or shredder	vertical oscillatory motion	tilted deck (higher in front)	fixed blades (use clipping velocity)
DEPOSIT clippings	tip clearance	mulching hump	discharge chute			
DISPERSE clippings	optimum tip clearance distribution	mulching hump	chute with dispersing surface	discharge chute with diverging flow		
HIDE clippings	downward flow from blade tip	mulching hump	chute with deflecting surface	downward air jet behind deck	comb or mat drug behind deck	

(Highlighted entries indicate concepts chosen for final design solution.)

3.2 Generating Lift

During the preliminary mowing tests, the blades often had difficulty lifting the grass to be cut. Part of the problem is that mulching mowers develop a small volume of air flow. However, even discharge mowers sometimes experience difficulty lifting grass. Thus, it seems reasonable to ask if an alternative to the blade wings would be desirable for generating lift. One initially attractive idea is a roller with brushes in front of the mower. The brushes would have to be driven at a higher speed than the ground speed in order to brush up grass that is laying over in the direction of travel. Another interesting idea is a separate blower mounted on the deck to create high vacuum underneath. Blowers are sometimes used on collection mowers to increase the collection capacity.

In the past, the lifting function has usually been left to the blade because this is most convenient. The added cost and complexity of other lifting mechanisms have discouraged their use. As the blade must already have a relatively high speed to make impact cuts, the addition of a wing provides a ready source of lift. Although we felt that there were potential advantages in using a separate lifting mechanism, we decided that designing and building such a device was beyond the scope of the project. The main advantage of separate lifting means is that the drag on the blade can be reduced, because a smaller wing and slower speed are required of a blade used for cutting but not for lifting. Hopefully, the power saved from drag reduction would not be exceeded by the power required for the auxiliary device.

Once we decided to rely on the blades for lift, the task was to maximize their lifting ability, keeping other performance constraints in mind. First of all, it was clear from tests with production equipment that the area under the standard skirt was simply not a reliable path for air flow. Even if the rear of the mower remained unblocked, when the front skirt became blocked by thick grass the flow was effectively choked. For this reason we concluded that an alternate path for incoming air was needed.

One path considered was through the top-center of each cutting chamber, near the spindle. The advantage of this arrangement is that the blades act as a centrifugal fan, drawing air in through the center of the deck ceiling [12]. This type of flow could be very effective at preventing material build-up. However, we desired incoming flow at the front of the mower, because this is where most of the grass is initially cut. There was some question whether the centrifugal arrangement would generate sufficient vacuum up front, at the grass height. The centrifugal fan idea was therefore rejected and the problem was further narrowed to one of using the blades to create suction at the front of the deck.

One way to enable more air to flow into the front of the mower would be to raise the front skirt. As specified in ANSI Standard B71.4-1984 [2], the maximum height allowed for the front skirt opening is 1.25 inches. Designs seldom come close to this maximum, however, since otherwise there is blowout of grass from the deck. Our proposed solution to this problem was two-fold. First, to maintain lift, air would be supplied to the mower via a duct at the top of the front skirt. Second, to minimize blowout, the blade wing would rotate inside a raised baffle. A low-drag blade with no wing would rotate underneath the baffle to achieve the desired cut height. Details of this solution, along with the complete design solution, are presented in the next chapter.

3.3 Cutting the Grass

Impact cutting using rotating blades was assumed from the outset, so that the only issue to be determined was relative spindle placement. For reasons of cost, a limit of three spindles was imposed. The various possible placements are shown in Figure 3.1. The three-spindle, middle-forward arrangement was eventually chosen, because it is spatially efficient and allows the cutting chambers to be isolated from one another. Isolation was desired to lessen blade interaction (which contributes to striping) and to reduce clipping migration between chambers (which works against dispersion).

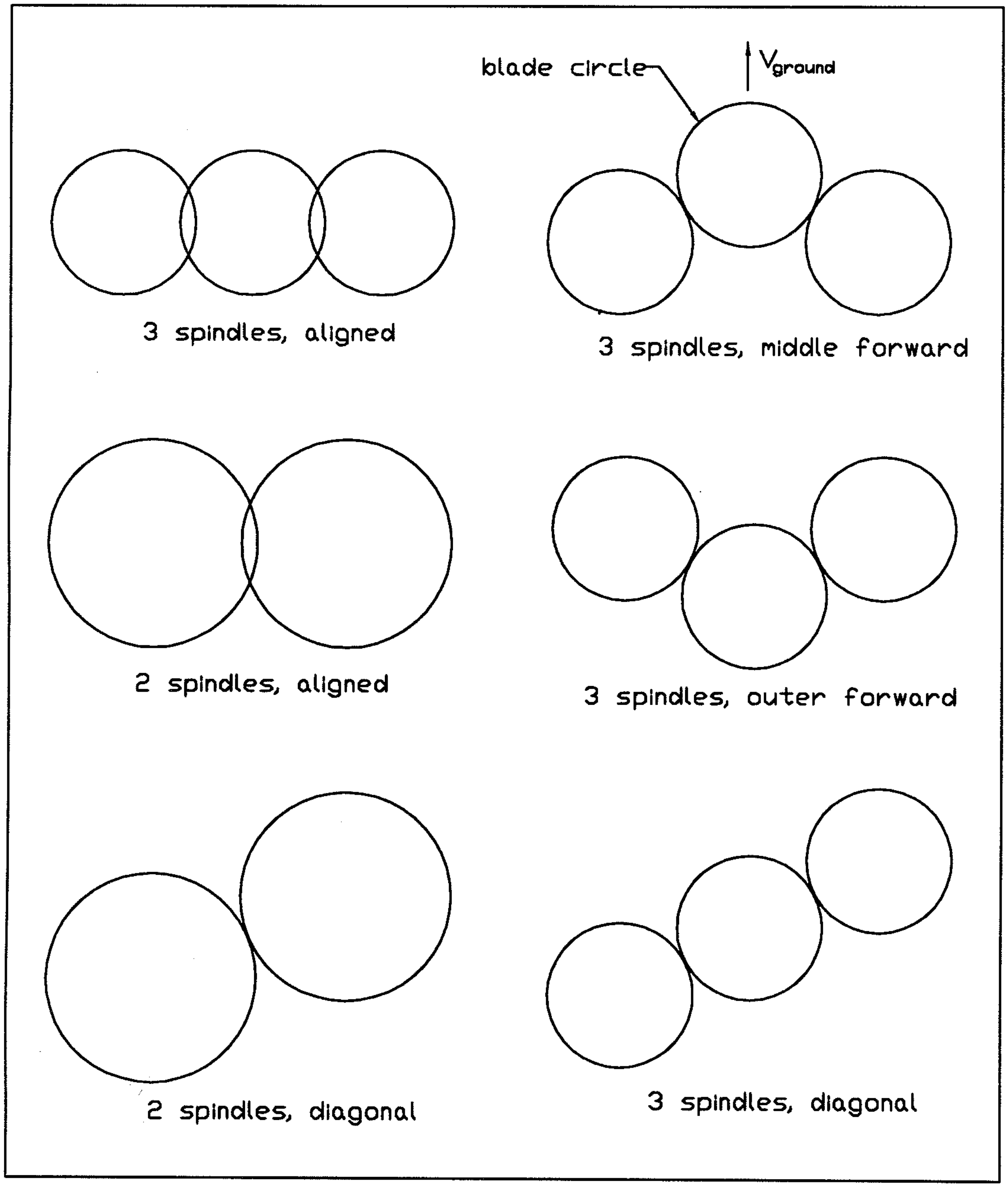

Figure 3.1 Spindle arrangements for 44-inch mower.

3.4 Chopping the Clippings

Chopping is the defining function of a mulching mower. Without the ability to chop grass clippings, the mower cannot produce an aesthetically pleasant or healthy lawn. Conventional mowers facilitate chopping by closing off the deck and encouraging the clippings to circulate in the deck for a relatively long time. The deck ceiling is designed to direct the clippings inwardly, toward the mulching hump of the blade. Thus, the time the clippings spend in the cutting region (in the path of the blades) is relatively small. As has been stressed, the results of large clipping dwell time are accumulation of material, high power requirement, and poor dispersion in heavy conditions.

Since an impact cut is most readily made when the grass plant is stationary and its location is known, a good strategy is to make as many cuts as possible simultaneously, at initial impact. An obvious way to do this is with a gang of stacked cutting edges. A second way is to tilt the deck back slightly, such that the front is perhaps an inch higher than the rear. Although the cuts will not be exactly simultaneous with a titled deck, the successive cuts will very quickly slice the stationary grass leaf into small pieces.

To move the deck design in a direction where it processes material more continuously, we chose to implement stacked edges in combination with a deck ceiling that deflects material into the path of the blades. Such a design move is not as radical as using a turbine or shedder attached to the deck, but it retains the original economy and simplicity of the rotary mower without assigning the chopping function to only one blade.

3.5 Depositing the Clippings

Preliminary tests with a gang of stacked blades indicated that the clippings could not be simply discharged through a chute. Otherwise not all the grass would get chopped, and very little would be hidden in the lawn. Therefore, even with multiple cutting edges per spindle, some dwell time is required. The challenge is to achieve the optimum balance between the need for a high processing rate and the need to adequately chop the clippings. We felt we could best find this optimum by designing an adjustable rear skirt and depositing the clippings through the rear tip clearance. We already knew that we could control the flow rate of material by adjusting the tip clearance.

3.6 Dispersing the Clippings

Once the choice was made to use the tip clearance for deposition, the remaining question was how to allocate the clearance around the rear circumference of the blade circle. An optimum distribution was desired. Using somewhat idealistic assumptions, the optimum distribution was found to be crescent-shaped, as shown in Figure 3.2. A crescent shape of variable size is easily generated with a semi-circular skirt moved fore and aft. (See Appendix A for a development of the optimum tip clearance.)

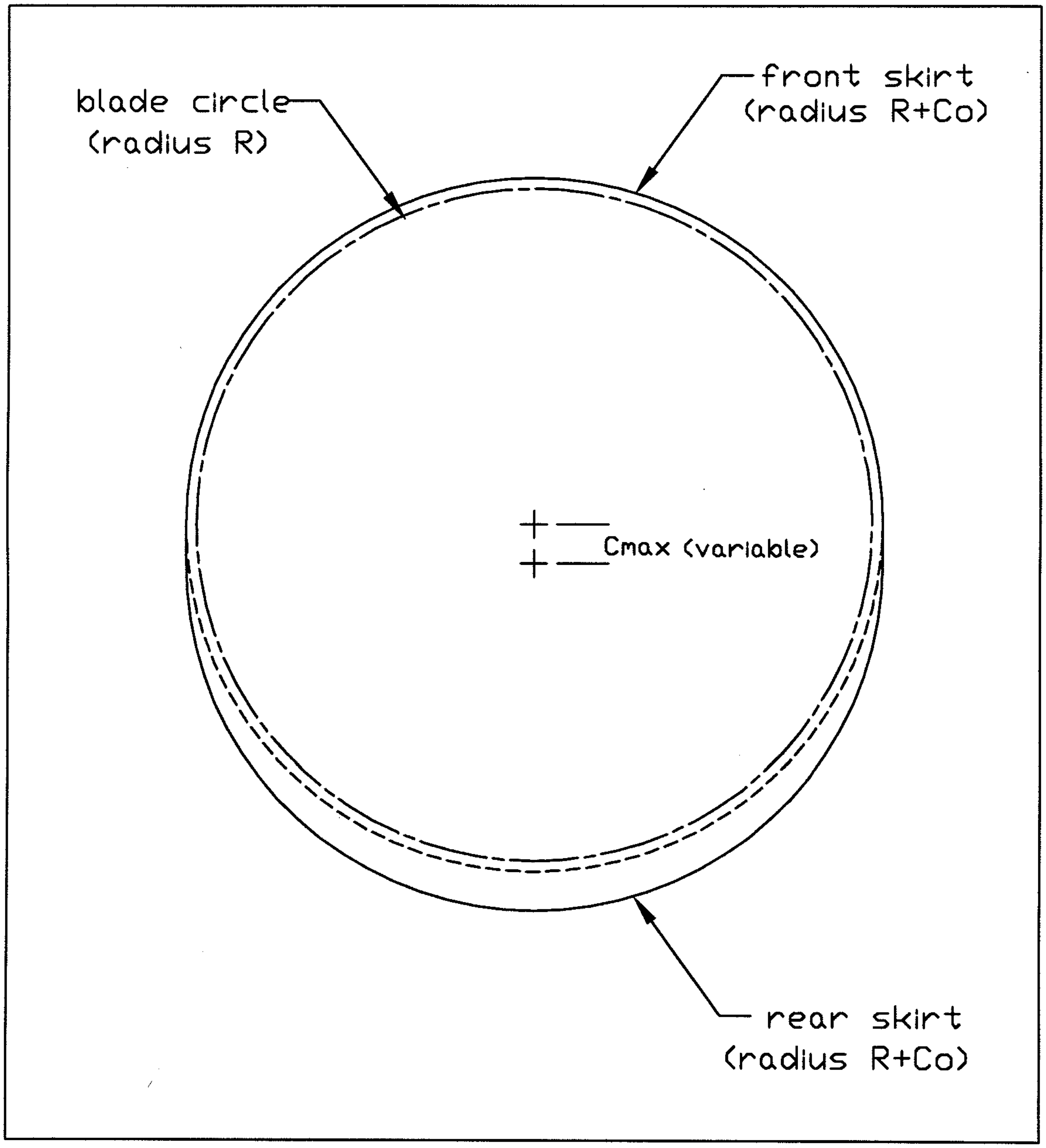

Figure 3.2 Optimum tip clearance distribution in rear of cutting chamber.

Two other design concepts that improve dispersion by preventing migration of clippings from one side of the deck to another are 1) physical isolation of the cutting chambers, and 2) counter-rotating spindles. For the second concept, the left spindle was chosen to rotate oppositely to the center and right spindles. Not only was this intended to improve dispersion, but it was also supposed to eliminate striping at the far left side of the swath. Without counter-rotation, the left blade has a forward sweep in this area.

3.7 Hiding the Clippings

The mulching hump of a conventional mulching blade is effective at hiding clippings, but relatively few clippings reach the area of the hump. If they do reach this area, it is only after the mower has ingested much more material. Another possible method for hiding is to utilize the downward flow that apparently exists from the blade tips. Since this flow also has a tangential element, hiding can be improved by giving the rear skirt a downward incline. Clippings then deflect off of the skirt and towards the ground. It may be possible to design a skirt such that air passes underneath, while the inertia of the deflected clippings carries them into the lawn. These ideas were implemented in the design solution.

One novel idea which was not implemented, but which should be considered, is a downward air jet behind the mower. Also, many walk-behind mowers marketed today have a mat that drags behind the mower to help any escaped clippings settle into the lawn. A similar addition to a multi-spindle mulching mower might prove helpful.

4.0 DESIGN SOLUTION

4.1 Baseline Features

With conceptual solutions chosen for each mulching function, the next task was to combine them into an overall solution and begin specifying the details. When the collection of individual solutions was considered in its entirety, we noticed that the production mower used for initial testing could serve as a platform on which to build the new design. This strategy had the great advantage that it allowed the use of stock power transfer elements. It also avoided the lengthy process of fabricating an entirely new deck shape from scratch. The existing deck shape of the John Deere 44" three-spindle mower was created by production tooling.

Similarly, for convenience, and for the ability to directly compare mower performance, we planned to mount the new design to the same tractor used for testing of the production design. This decision permitted us to use the existing mounting fixtures and hardware. Thus, the attachment points, most of the power transfer elements, and many of the basic dimensions were already determined. We had only to design our features into this platform. If we desired to vary the blade speed, this could be accomplished by using variously-sized belt sheaves, some of which were stock items. Other sizes could be fabricated if necessary.

Figure 4.1 shows the underside of the prototype mower fully assembled. The remaining sections of this chapter describe the major features of the design.

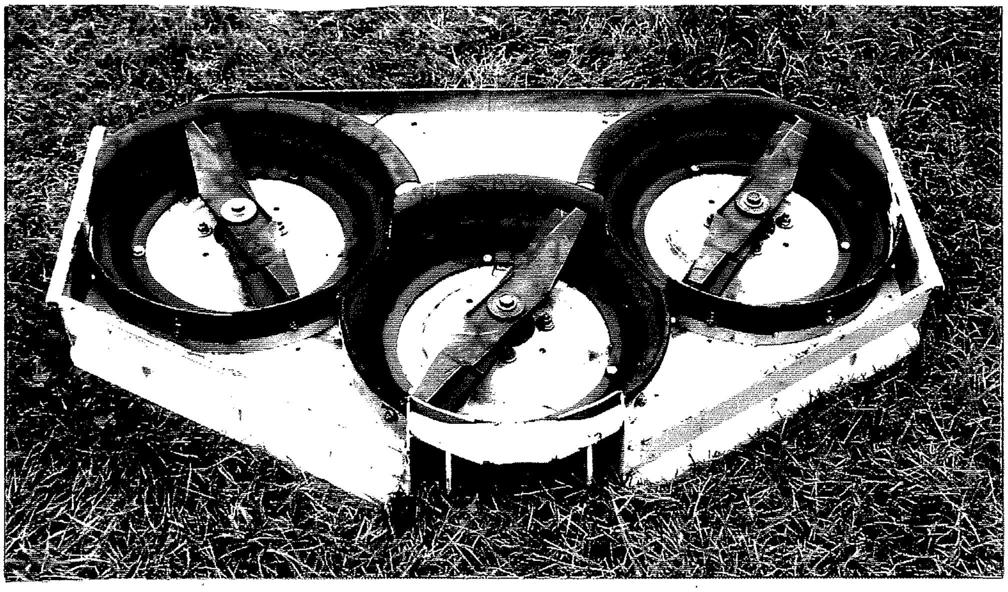

Figure 4.1 View underneath prototype mulching mower.

4.2 Ducted Front Skirt

The most distinctive feature of the prototype mower is the front skirt. A schematic of the front of one of the cutting chambers is shown in Figure 4.2. As indicated, we have moved the front skirt forward but maintained a small tip clearance by placing a baffle just outside the top blade. The baffles are adjustable vertically and can be raised much higher than the skirt, allowing air to flow underneath. To minimize blowout, we have used narrow, low-drag blades at the cut height and just above it. The top blade has a wing for generating lift. Air is supplied to the mower via the opening at the top of the skirt.

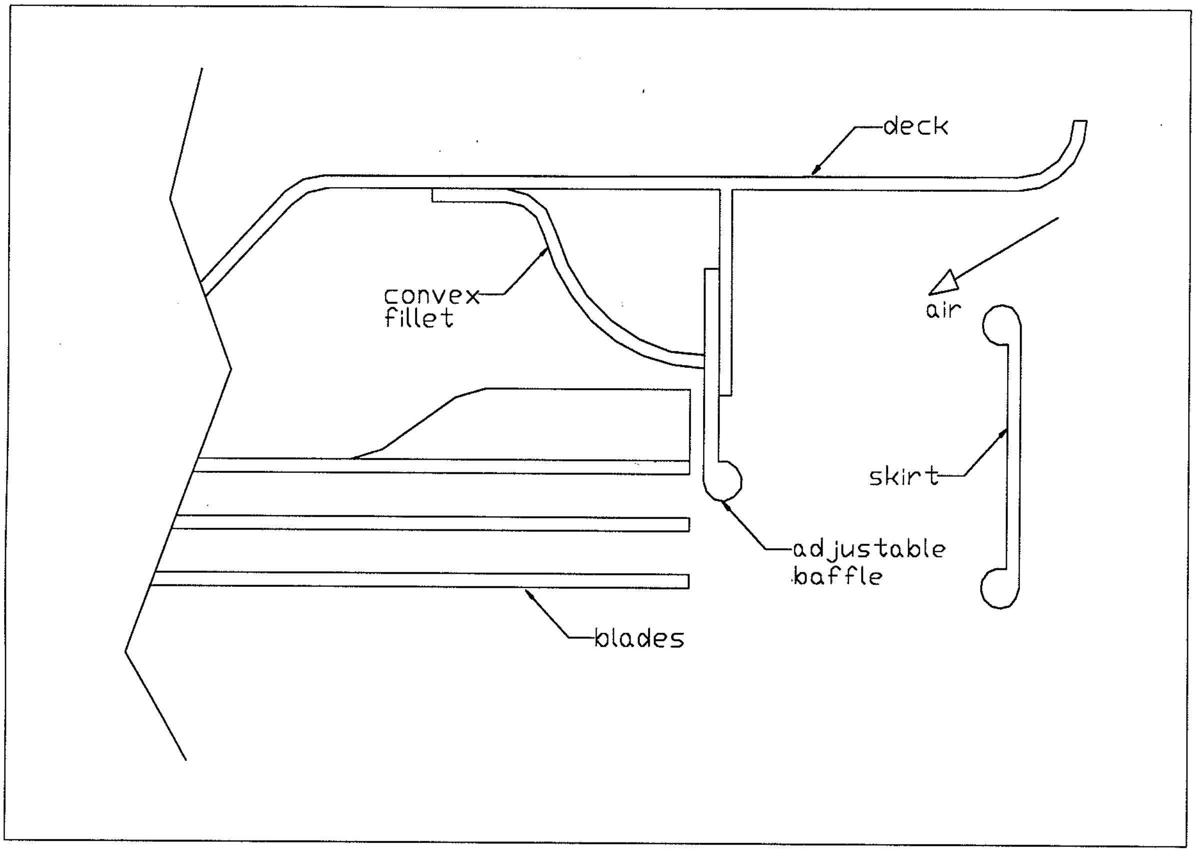

Figure 4.2 Schematic of front of cutting chamber.

4.3 Multiple Blades

Figure 4.3 is a close-up of the left cutting chamber, showing the three blades installed. The relative angular positions of the blades are infinitely variable. During testing, the lift-generating blade, which is normally mounted highest in the deck, could be switched to the bottom. The two narrow blades were then mounted above it. In addition, one of the narrow blades could be removed if desired. (Dimensioned drawings of the blades and all other design components are provided in Appendix B.)

Figure 4.3 Close-up of left cutting chamber, with adjustable rear skirt in foreground.

For the lifting blade two different designs were fabricated and tested. End views of these designs are pictured in Figure 4.4. The first blade is similar to a standard discharge blade and has a wing angle of 30 degrees. The second blade, which has a 45 degree wing angle, is a more novel design. It is supposed to deflect clippings into the ground while still providing lift with an upturned wing. Thus, a single shape at the end of the blade performs the same functions as the mulching hump and wing on a conventional blade. The bottom surface of the blade has a smooth contour to help keep fluid drag low.

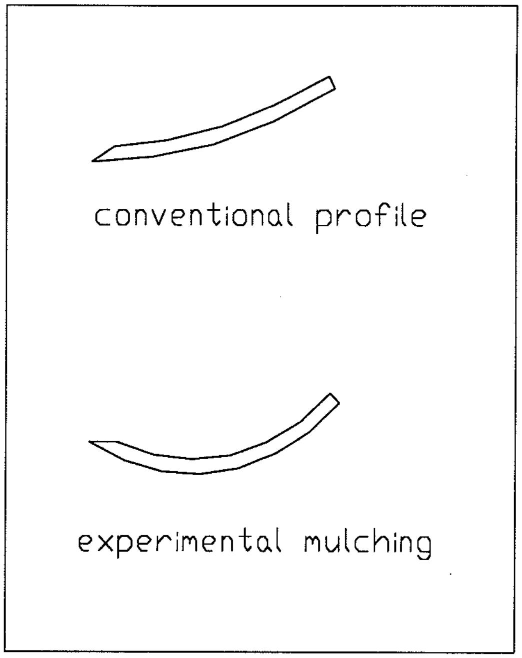

Figure 4.4 End views of two mulching blades tested.

4.4 Deck Ceiling

Figure 4.3 also shows the fillet, or convex torus, installed around the entire upper circumference of each cutting chamber. During testing this fillet could be replaced with a conventional concave fillet for comparison. The function of the convex fillet is to deflect material back into the cutting zone, by occupying the same volume where the clippings would ordinarily be sent by the blade. There is some question whether a large deck volume or small deck volume is more beneficial in this region. A large volume is said to permit the blade to generate more lift and reduce the tendency of the deck to plug. However, as described in the chapter on field testing, our work showed that plugging occurred more readily with the concave (large volume) fillet.

4.5 Overlap Region

Originally we wanted to completely isolate the three cutting chambers from each other. We felt that by decoupling the chambers, we could reduce one complex problem down to three simpler ones. Furthermore, earlier investigation had revealed possible adverse effects of blade interaction in the overlap region (the region midway between spindles). The simplest way to isolate the chambers would be to place a barrier between them. However, this was not possible with our spindle arrangement, because the tip-to-tip clearance between blades was less than 0.125 inch. Although the blades could have been shortened, this would have harmed cut coverage. Ultimately, the only isolation we achieved was provided by the corner fillets, which extended down from the deck ceiling approximately 2 inches. This was enough to provide at least some barrier to interaction.

4.6 Counter Rotation

The power transfer elements used to achieve counter-rotation of the left spindle are shown in Figure 4.5. The middle and right spindles (middle and left in the figure) rotate clockwise as viewed from above. By means of the two idlers at the right of the figure, the double-sided belt drives the left spindle (right in the figure) counter-clockwise as viewed from above.

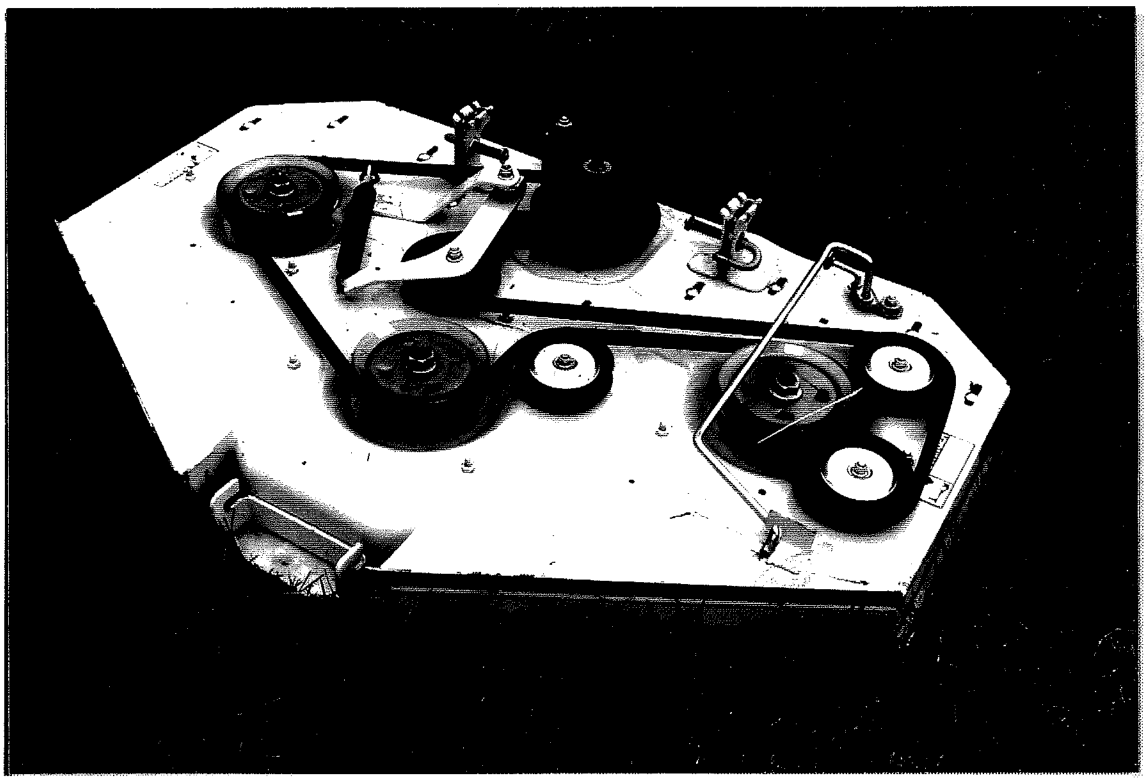

Figure 4.5 Power transfer elements on prototype deck, with skirt opening in foreground.

4.7 Adjustable Rear Skirt

A schematic of the rear of one the cutting chambers is shown in Figure 4.6. To allow the flow area to be adjusted in two ways, the rear skirt has two degrees of freedom. Either the crescent-shaped tip clearance can be adjusted, or the skirt height can be changed. These changes can be made independently. The rounded shape of the skirt lip is supposed to allow the maximum amount of air to flow underneath while still deflecting clippings into the lawn.

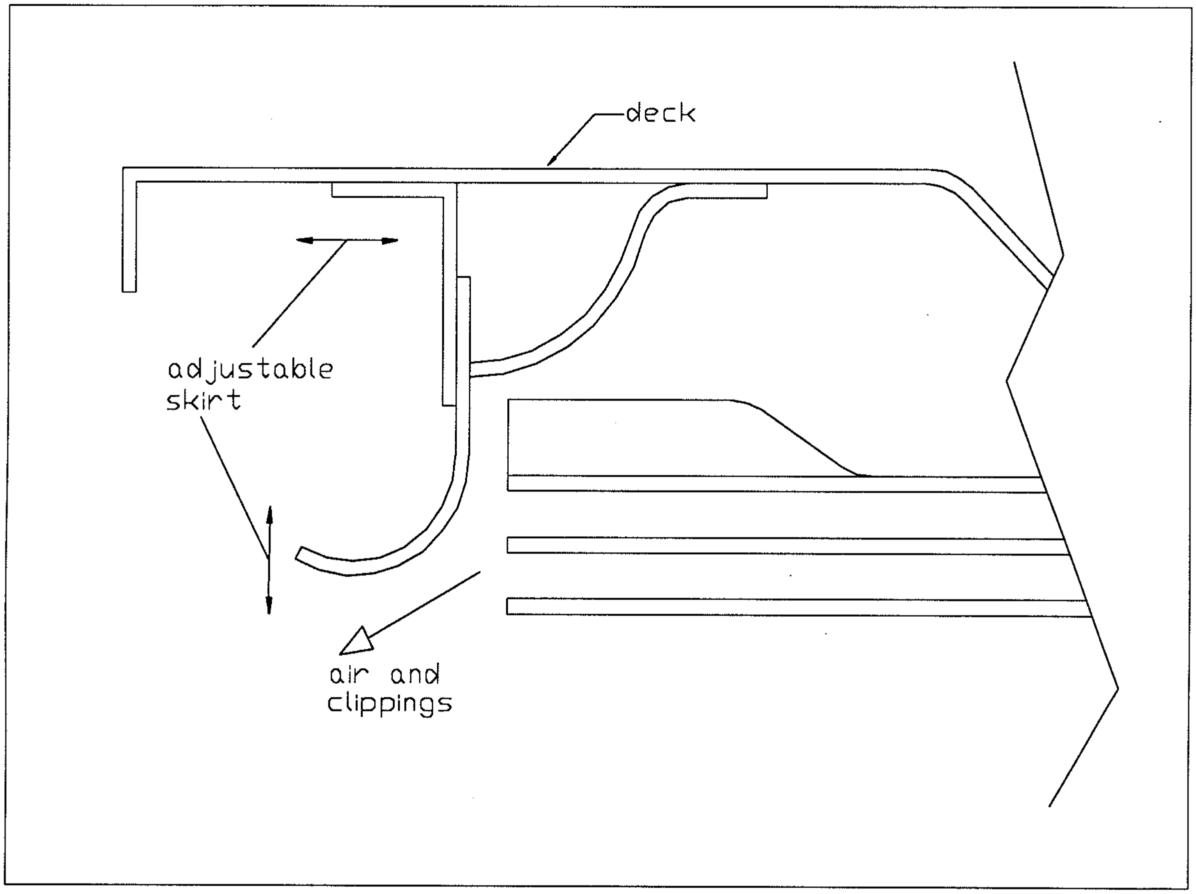

Figure 4.6 Schematic of rear of cutting chamber.

5.0 FIELD TESTING

5.1 Testing Objectives

The main objective of the test program was to determine which, if any, design features had a positive effect on performance. More generally, we wanted to answer the question of whether the prototype deck design had a lower power requirement and better cut and mulch quality than comparable machines. To provide a basis for comparison, the production 44" mower was used as a control during testing of the prototype unit. This allowed judgments of performance to be based on a consistent standard, independent of grass conditions.

Another goal of testing was to characterize the way in which the prototype mower handled material and air. We had theories about the effects that certain design features would have, but these effects needed to be verified.

A third goal was to make progress in the difficult area of mower evaluations. It is notoriously difficult to quantify mower performance in a repeatable fashion. (One exception is power, where, with appropriate instrumentation, good numerical results are often possible.) Although the final and most important evaluation is made subjectively by the customer, for design purposes quantification is very important. Mower design is for the most part an incremental process. Relatively few breakthroughs occur. Therefore, to make continuous improvement, the designer must be sensitive to small changes in performance and know whether they are the result of design features, grass conditions, or simply random variation. Numerical measures are helpful in making these determinations.

The testing phase of the project was begun by posing the following questions:

1. How does the prototype mower compare to the production mower with respect to cut quality, mulch quality, and power requirement?
2. Does the mower draw air through the opening in the front skirt, as intended?
3. Does the mulching blade (Figure 4.4, bottom profile) improve mulch quality without harming cut quality?
4. What is the best orientation of the blades for lift and simultaneous cutting?
5. What is the effect of the convex fillet as opposed to the concave fillet?
6. Does counter-rotation improve dispersion and reduce striping?

To answer these questions, a series of factorial tests was devised. These are tests in which a number of design factors are varied simultaneously, but their individual effects can be determined separately. Several one-factor tests were also performed to resolve ambiguities and supply information not provided by the multi-factor tests. But first, an initial proving period was covered to work out bugs and gain familiarity with the cutting characteristics of the mower. This work took place at the O.J. Noer Turfgrass Facility, west of Madison. The proving period revealed a number of important things about the mower. Later, the factorial tests were run at the John Deere Horicon Works test facility, in Horicon. The tractor used to drive the mower for all the tests is shown in Figure 5.1.

Figure 5.1 Prototype mower installed under lawn tractor for field testing.

5.2 Proving Period

After receiving the completed deck, several weeks were spent attempting to achieve the clearances and adjustability originally intended for the design. The radii of the front baffles were manufactured too small, and the baffles had been welded to the deck too close to the spindles. The result was interference between the blade tips and the baffles. As a remedy the blades were shortened somewhat, and the adjustable portion of the baffle was moved from the inside to the outside of the fixed portion. Despite these changes, a continuous and completely accurate front clearance was never obtained. Another side effect was that the fillets had to be installed farther back in the deck, interfering with horizontal adjustments of the rear skirt. Later, this hindered the testing program, because the rear tip clearance could not be reduced as much as desired.

Once mowing began, the first thing noticed was blowout underneath the skirt on both sides of the mower. The blowout occurred because the lowest blade in the stack was actually slightly below the side skirt lip. Eventually, an ad-hoc baffle was attached to each side skirt to effectively lower the lip. The blades were also heated and bent up slightly. Together these changes eliminated most of the blowout.

Another initial observation concerned how the mower handled heavy grass conditions. One area of the test plot was allowed to grow to a height of ten to twelve inches. The prototype mower never failed to make it through the high growth, whereas the production mower would usually bog down. This ability to continue mowing in heavy conditions was evident throughout the testing and is discussed in further detail later.

To determine if air was being drawn into the skirt opening, a smoke generator was placed alongside the mower while operating over grass. The amount of suction created was rather disappointing. Air was clearly being drawn in, but not to the degree previously imagined. During mowing, when the front baffles were raised to their highest position, a steady stream of very small clippings could be seen exiting the skirt opening. This implied that whatever incoming flow did exist had to be quite small.

The preferred angular orientation for the blades was also determined during the proving stage. We found that having the blades closely aligned produced a better mulch than a distributed or star arrangement.

5.3 Factorial Tests

Multi-Factor Tests

Table 5.1 summarizes the five design factors which were varied. Counter-rotation was not included as a factor because of the excessive time required to change the belt system. Rear skirt position was not included due to the interference difficulty mentioned earlier. In the blade orientation factor, the top two blades were aligned, while the lower blade either trailed or led these two by five to ten degrees. Other factors are self-explanatory.

Table 5.1 Design Factors Tested

Factor	"+" Setting	"-" Setting
Fillet	convex	concave
Skirt	open	closed
Lifter	top	bottom
Front Baffles	up	down
Blade Orientation	lowest trails	lowest leads

The specific combinations and sequence of the tests are given next, in Table 5.2. In all, 10 of 32 possible factor combinations were tested. These combinations were selected as part of a fractional factorial design that was not completed. The sequence was obtained by random drawing.

Table 5.2 Sequence of Tests

Test	Fillet	Skirt	Lifter	Front Baffles	Blade Orientation
1	-	-	+	-	-
2	+	+	+	+	+
3	+	-	-	+	-
4	-	+	-	-	+
5	Control				
6	-	-	-	+	-
7	+	+	+	+	+
8	-	-	+	-	+
9	+	+	-	-	-
10	Control				
11	+	-	+	-	-
12	+	-	-	+	+
13	-	+	+	+	-
14	-	+	-	-	+
15	Control				

As indicated in the table, there were three groups of five runs each. The fifth run in each group was the production mower. It was important to divide the tests into small groups for two reasons. First, five runs is about the limit for accurate judging. If more runs than this are judged simultaneously, the judges lose track of the runs and have trouble distinguishing between them. Secondly, grouping of runs, if done appropriately, will minimize the effects of changes in grass conditions and judging biases during the testing. Conditions can vary enough within one day to markedly change results. Similarly, drifting biases of the judges can alter patterns in scoring. However, the use of small groups (blocks, in statistical terminology) will tend to cause these unwanted effects to cancel when the factor effects are computed. The theory is that conditions will be about the same in each individual group, although they may vary over the experiment as a whole. If, for instance, the grass is wet during the first group tests, all the scores in that group should reflect this. If the grass later dries, the scores in subsequent groups all reflect that as well. Since each factor in a group has the same number of "+" and "-" settings, the effects of grass wetness will tend to cancel out of the total effect for that factor.

It is also important that each group contain a control run, as was done with the production mower in these tests. Using a control allows ratings of performance to always be based on comparison with an invariant design. If changes in conditions or biases affect the design being tested, they will probably also affect the control.

Grass Conditions

The first group was run on a morning, in unusually wet conditions. Bluegrass at heights of 5-6 inches was mowed. The last two groups were run in the morning and afternoon of one day. Again, the grass was damp in the morning, but it dried substantially before the second group was finished. Grass lengths for the last two groups were 10-12 inches. In all cases the tractor was driven in third gear and the cut height was set at 3 inches.

5.4 Results

Evaluations of Performance

Three aspects of performance were evaluated: cut quality, mulch quality, and apparent power requirement. Although the hope had been to develop objective, quantitative measurement techniques, as it turned out all evaluations were primarily subjective. In order to compare results numerically, scores were attached to human judgments. These scores consisted of perceived differences between the prototype mower and the control.

Evaluations of power requirement were made in two ways - first, by listening for any drop in engine speed. Obviously, if the mower came close to killing the engine, then this was noted. Note was also made of approximately how much grass had accumulated in the deck by the end of the run. Mulch quality was evaluated by visual inspection of the swath, where both dispersion and visibility of clippings are important. To gage cut quality, the grass was brushed up in several spots and examined for cleanliness of cut and uniform cut height. Locations of uncut grass were also noted.

Multi-Factor Test Results - Cut and Mulch Quality

Table 5.3 shows the scores for the cut quality and mulch quality portions of the tests. The numbers in parentheses are the differences between the control and prototype scores for each group. These are the values used to find the effects of the design factors. The rating sheet we used in the field to record the original data is given in Appendix A.

Table 5.3 Mower Test Scores

Test	Scores (1-10, 10 is best)		
	Cut Quality	Dispersion	Hiding
1	3 (-2)	6 (+2)	3 (-3)
2	3 (-2)	6 (+2)	3 (-3)
3	5 (+0)	5 (+1)	4 (-2)
4	4 (-1)	5 (+1)	4 (-2)
5	5	4	6
6	3 (-1)	4 (-1)	2 (-3)
7	3 (-1)	4 (-1)	2 (-3)
8	3 (-1)	4 (-1)	2 (-3)
9	4 (+0)	4 (-1)	2 (-3)
10	4	5	5
11	3 (-1)	4 (+1)	2 (-1)
12	4 (+0)	4 (+1)	2 (-1)
13	4 (+0)	4 (+1)	2 (-1)
14	3 (-1)	4 (+1)	2 (-1)
15*	4	3	3

* Control bogged down before end of run

There is not much difference in many of the scores. This is borne out by Table 5.4, which shows the effects of each factor, calculated using the differences between the control and prototype scores in each group. The effect for a factor is really the difference between the average score at the "+" setting of the factor and the average at the "-" setting. Since tests 2 and 7 were replicates, as were tests 4 and 14, the averages for each setting include only five terms.

Table 5.4 Factor Effects - Cut and Mulch Quality

Factor	Cut Quality	Dispersion	Hiding
Fillet	0.50	0.10	0.30
Skirt	0.50	-0.30	0.90
Lifter	-0.70	0.50	-0.10
Front Baffles	0.50	0.10	0.30
Blade Orientation	0.10	-0.30	0.90

It is difficult to draw conclusions from these effects since a good estimate of the experimental error is not available. However, because two of the factor combinations were replicated, the standard error of each effect can be estimated as follows. First, the variance of the replicated tests is estimated using their score differences. The variance estimate for the replicated cut quality tests is

$$s^2 = \frac{[-2-(-1)]^2 + [-1-(-1)]^2}{2 \cdot 2} = 0.25.$$

As explained in books on experimental statistics such as [15], the standard error for each cut quality effect is then

$$\text{s.e.} = \sqrt{\frac{4 \cdot s^2}{10}} = 0.32$$

Proceeding in a similar fashion for dispersion and hiding gives their standard errors as 0.95 and 0.32, respectively. The significance of these numbers is that they provide a limited statistical basis for drawing conclusions about the factor effects. For instance, none of the dispersion effects is statistically significant since each falls below 0.95. Contrariwise, all cut quality effects, except that for blade orientation, are said to be significant. Only the skirt and blade orientation significantly affect hiding. The sign (positive or negative) of the effects indicates which factor settings were more beneficial. Thus, having the lifter on the bottom was more beneficial to cut quality than having it on top.

It is important to note that conclusions drawn about the factor effects can only be tentative, as not enough runs of the full factorial experiment were made to separate single-factor effects from two-factor interactions. It is probable that some interactions are operative.

Looking at the scores individually for a moment, one trend stands out which should be noted. The prototype mower often had superior scores for dispersion but inferior scores for hiding clippings. In fact, this behavior was obvious before compiling the data. It is a characteristic of the prototype mower that it disperses the grass very well but does not hide it. The mower may be too far on the rear-discharge end of the mower spectrum. To move it towards the mulching end, more experimentation with the rear skirt is needed. There is likely an optimum balance between power reduction and clipping dwell time which should be achievable with the current configuration. During testing the mower seemed to be weighted too much in favor of reduced power.

Multi-Factor Tests Results - Power

For power requirement evaluations, numerical scores or data were not obtained. Observations made during each test revealed some important results, however. The most striking result was the effect of the convex fillet. There was noticeably less material built up within the deck when the convex fillet was used. The concave fillet, on the other hand, seemed to encourage build-up. The explanation may be that the convex shape deflects material immediately back towards the ground, whereas the concave shape provides space and a smooth path for the grass to slide around the deck ceiling. The convex shape appeared to cause an almost random spraying of the material which deflected off of it. This material could be seen exiting the sides of the deck. Further, the prototype mower never stalled in tall grass. With the concave shape it would sometimes lose a good deal of speed, but it did not stall. A much smaller drop in speed occurred with the convex fillet.

By contrast, the production mower obviously carried many more clippings with it as it mowed. This caused it to bog down more readily. However, since in most cases the production mower was cutting more of the grass, it was handicapped somewhat in a power comparison. The prototype mower left more uncut grass, reducing its material flow load.

Single-Factor Tests

To confirm that the skirt had little effect on cut quality, a series of four runs were made with the skirt alternately open and taped shut. The runs were made in 12 inch grass, with the first two runs cutting it down to 2.5 inches, and the second two cutting it down to 2 inches. The skirt was the only design factor changed. Although the mower successfully traversed the deep grass, the skirt opening had no perceptible effects on either power or cut quality.

Other Results

Regarding the novel mulching blade design, cut quality was generally poor when either lifter was run as the top blade in the stack. Since the new design could not be run as the bottom blade, a definite judgment as to cut quality would be difficult to make. The new blade design was able to hide clippings slightly better than the other lifter, but this was not quantified in the test results.

The first time the convex fillet was installed, it seemed to cause noise characteristics which were noticeably different than those of the concave fillet. No other changes had been made to the mower, but the sound became more agreeable after the switch. Although the effect was not verified with instrumentation, it seemed less pronounced during the latter stages of testing. A controlled test in a sound room should probably be performed to determine whether a convex fillet can in fact reduce mower noise.

Finally, mention should be made of the counter-rotation feature. Unfortunately, its effect on dispersion was not measured in any way. Since the prototype design does have good dispersion, it is tempting to believe that there is a positive effect. One effect which was observed directly was a reduction in the stripe behind the left tire. However, the cut quality elsewhere was poor enough to perhaps outweigh the improvement in the left tire track.

5.5 Summary

The prototype mower required less power to mow in heavy conditions than the production mower. The dispersion was often excellent, but the cut grass did not get hid. With work to increase the clipping dwell time slightly, and with additional means to better hide clippings, the design could move the state of the art forward significantly. The idea of a convex fillet in the deck has the potential to provide a number of advantages. Further work with the idea is warranted.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This project has focused on ways to reduce the power requirements of mulching mowers. An explanation of the modes of power consumption has been given, and this has led to a design which has the potential to extend the state of the art. The design already has demonstrated the characteristics of close-to-uniform dispersion and efficient processing of cut grass. What remains is to improve the ability of the mower to hide its clippings in the lawn, since this is essential for customer satisfaction. The changes to effect the desired improvement may be as simple as modifying the rear skirt profile.

Despite the foregoing benefits, there are other areas which require improvement. No significant progress has been made on the problem of generating lift. As long as winged blades are used, lift will be necessary to ensure good cut quality. Lift is in turn dependent upon air flow. An attempt was made with an original front skirt design to develop a solution to the air flow dilemma. However, for several reasons the effort was not a success. Part of the problem lay with tip clearances that did not meet design requirements. Having accurate clearances is apparently critical to generating the right flow. The design itself may have serious problems as well. Although blades much narrower than normal were used below the raised baffling in front, this did not prevent the flow from moving opposite to the direction intended. It might be worthwhile to try even lower-drag blades, in order to allow the lifting blade above to do its work.

The idea from this design which has the most promise is an alternative deck shape - specifically, a convex corner fillet. The effect of that specific shape was to dramatically reduce the tendency of this mower to accumulate material. Of all mulching mower characteristics, the most harmful to efficiency and cut quality is rapid build-up of grass clippings. A major conclusion of this project has been that there are better ways to chop clippings than to simply suspend them above a blade. The use of multiple cutting edges in combination with a grass deflecting surface - the method used in this design - is one such way.

At the beginning of this project, the emphasis was on research to understand the mulching process, and the mowing process in general. Later, the focus shifted to design. If a research program is to have the best opportunity to be useful, the goals should be clearly stated and understood at the outset. One of the paths not chosen in this project was extensive laboratory-type experimentation. Techniques such as high-speed photography, flow visualization, and scaled modeling could prove very useful, however, if the results are correlated to real hardware.

There are likewise many opportunities for advancement on the design side. Examples include surface treatments and alternative materials for wet conditions; utilization of exhaust gases; a centrifugal fan type deck and blade; spinning disks to prevent adhesion; auxiliary fans, blowers, and shredders; and so on. There may be opportunities to employ more advanced analytical techniques as well, to provide insight that cannot be gained otherwise. As has been seen in the past, however, care must be taken to ensure that the models used are not so far divorced from reality as to be useless. Finally, the design ideas developed in this project should be re-examined. With further development, the basic concepts of the present design can be utilized with success in a commercial mulching mower.

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My sincere thanks also go to my adviser, Professor Frank Fronczak, whose insight and guidance always proved to be exactly what I needed. He encouraged me to think more practically about engineering problems as well as many aspects of life.

Thanks to the professors and staff at the O.J. Noer Turfgrass Facility, for giving generously of their time and equipment for the benefit of this project.

Finally, I would like to express my appreciation to my mother, for her support during the past nineteen months, and to Sami Eyskens, for her enduring encouragement.

APPENDIX A

Miscellaneous Experiments, Analyses, and Data

Computational Fluid Dynamics

Early in the project we investigated the possibility of using computational fluid dynamics (CFD) to analyze the flow in a mulching mower . The objective would be to augment intuition and observation with a computer prediction of the flow field under the mower deck. For several reasons, however, we decided the time investment required was not justified by the expected benefits. The flow is three-dimensional, turbulent, and two-phase. This is a situation very difficult to model accurately. Creation of the mesh can take up to several months and, with the software currently available, cannot be changed significantly without substantial effort. Therefore, "what if" studies of the effects of geometry changes on flow are not practical. No further work with CFD was planned after our investigatory study.

Separation Experiment

In the typical mulching mower, which has no discharge chute, clippings are retained until they have been chopped finely enough to be forced out of the deck. These small clippings probably pass below the cutting plane at the tip clearance or near the mulching hump. Since it is desirable to increase the maximum flow rate of small clippings out of the deck, we investigated the possibility of separating clippings based on size. If such separation were possible, the smaller clippings could be deposited while the larger ones were retained to be chopped.

A simple experiment was designed and carried out to test the feasibility of separation. The method of separation chosen was air velocity, since this would be the method most likely used in a mower. (Separation with screens and so forth was seen as impractical, due to the tendency of clippings to clog small openings.) A vertical, diverging wind tunnel was constructed and mounted on an axial fan (see Figure A.1). Theoretically, the air velocity decreases linearly with increasing height, since the area of the rectangular tunnel does also. We hoped to achieve suspension of different size clippings at distinct heights in the tunnel. Although we experienced problems obtaining uniform velocity at any height, it was apparent that separation of the clippings into distinct groups was probably not feasible. The differences in suspension velocities, although not measured, were evidently very small compared to the velocities in a mower. Thus, the air velocity in a mower would have to be controlled very accurately for distinct separation. Such control would be difficult to achieve given the turbulent, swirling nature of the flow generated by the blades. For this reason the idea of separation was abandoned.

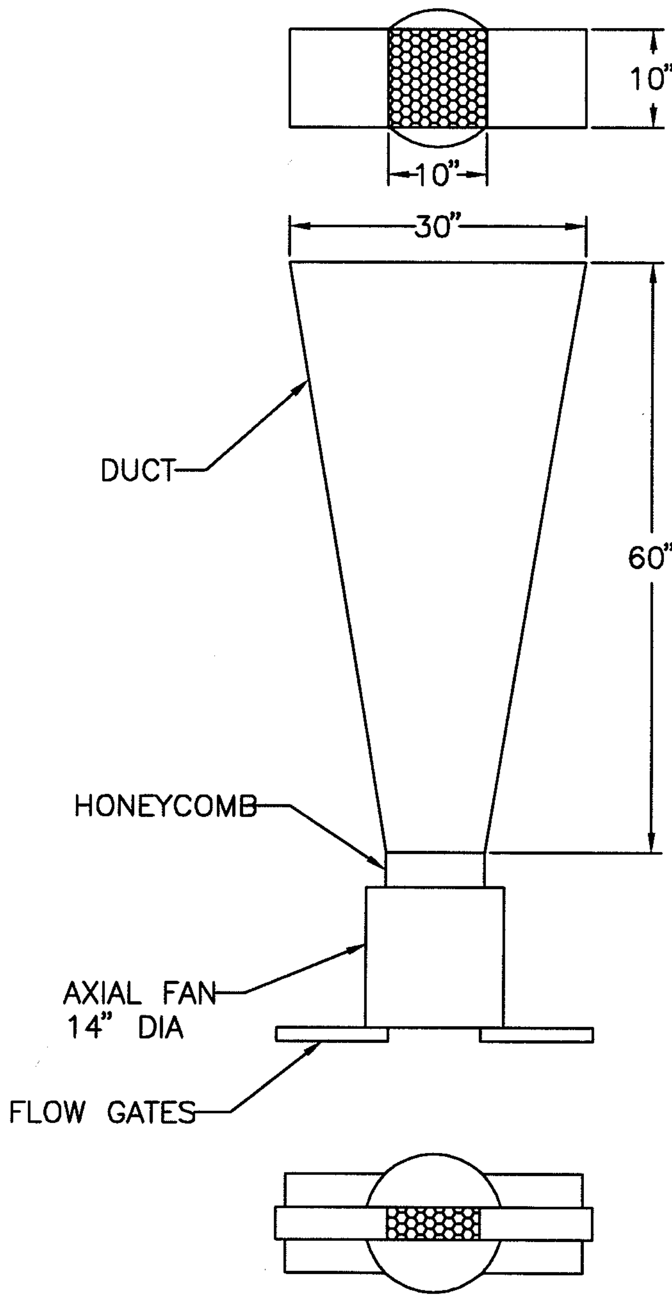


Figure A.1 Apparatus for separation experiment.

Optimum Rear Tip Clearance

A distribution of the tip clearance around the rear of the cutting chambers was desired which would result in uniform dispersion across the width of the swath. To find this optimum distribution, it was assumed that the clippings are deposited through the tip clearance at a rate which is proportional to the clearance area. This assumption leads to the requirement that the cumulative area should increase linearly across the swath.

Referring to Figure A.2, a function f(x) is sought which satisfies the following relationship for the cumulative area at any X.

$$A = \int_0^X [f(x) - g(x)]dx = kX$$

It is seen by inspection that a value of f(x) equal to g(x)+k satisfies the requirement. Thus, f(x) should be circular, with the same radius as the blade circle, and centered at (0,k).

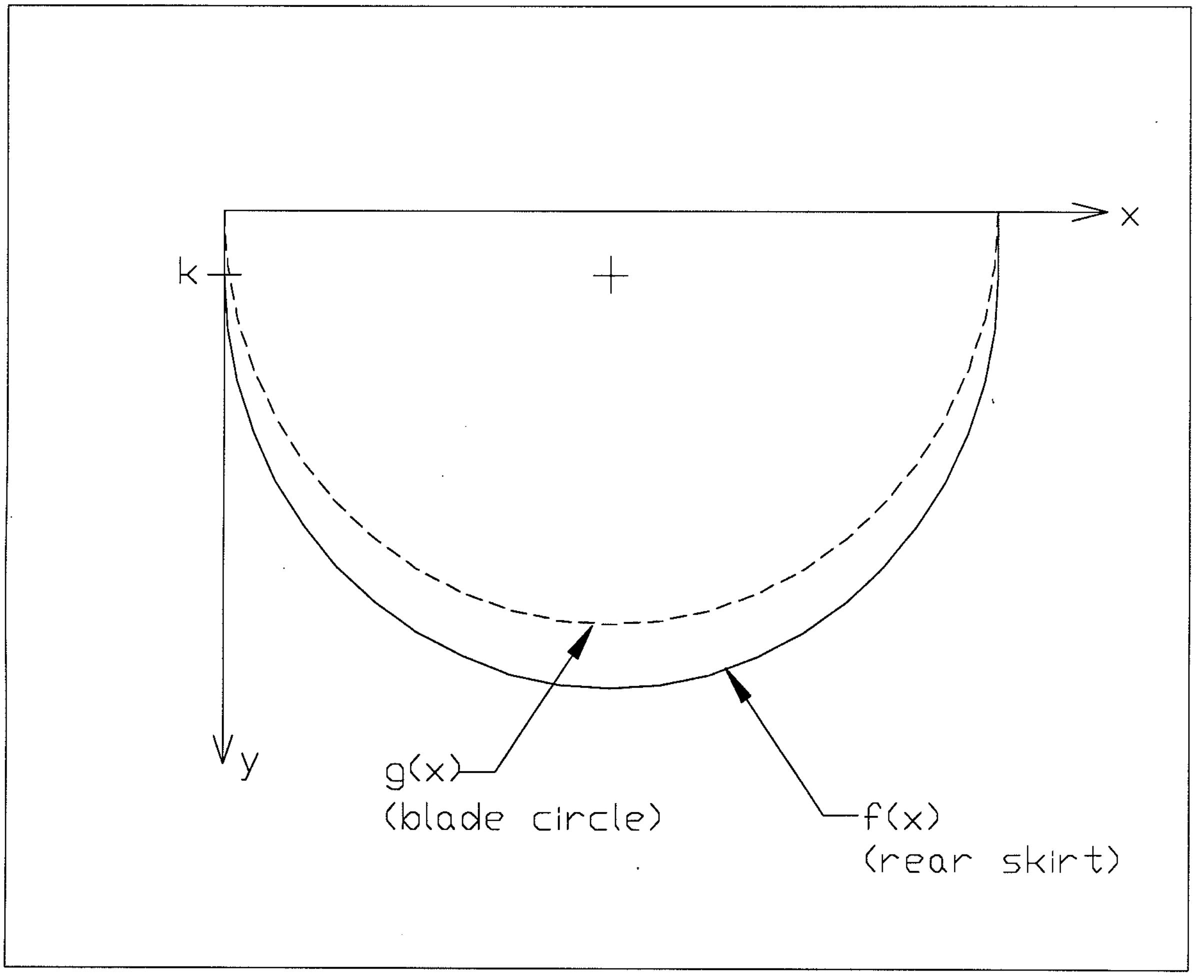


Figure A.2 Diagram for determining optimum tip clearance

Rating Sheet Used for Field Tests

DOX RATING SHEET

Date/Time____________________________ Cut No.____________

CUT QUALITY	1	2	3	4	5	6	7	8	9	10
MULCH QUALITY										
dispersion	1	2	3	4	5	6	7	8	9	10
hid clippings	1	2	3	4	5	6	7	8	9	10

COMMENTS

____

____

POWER

rpm drop____

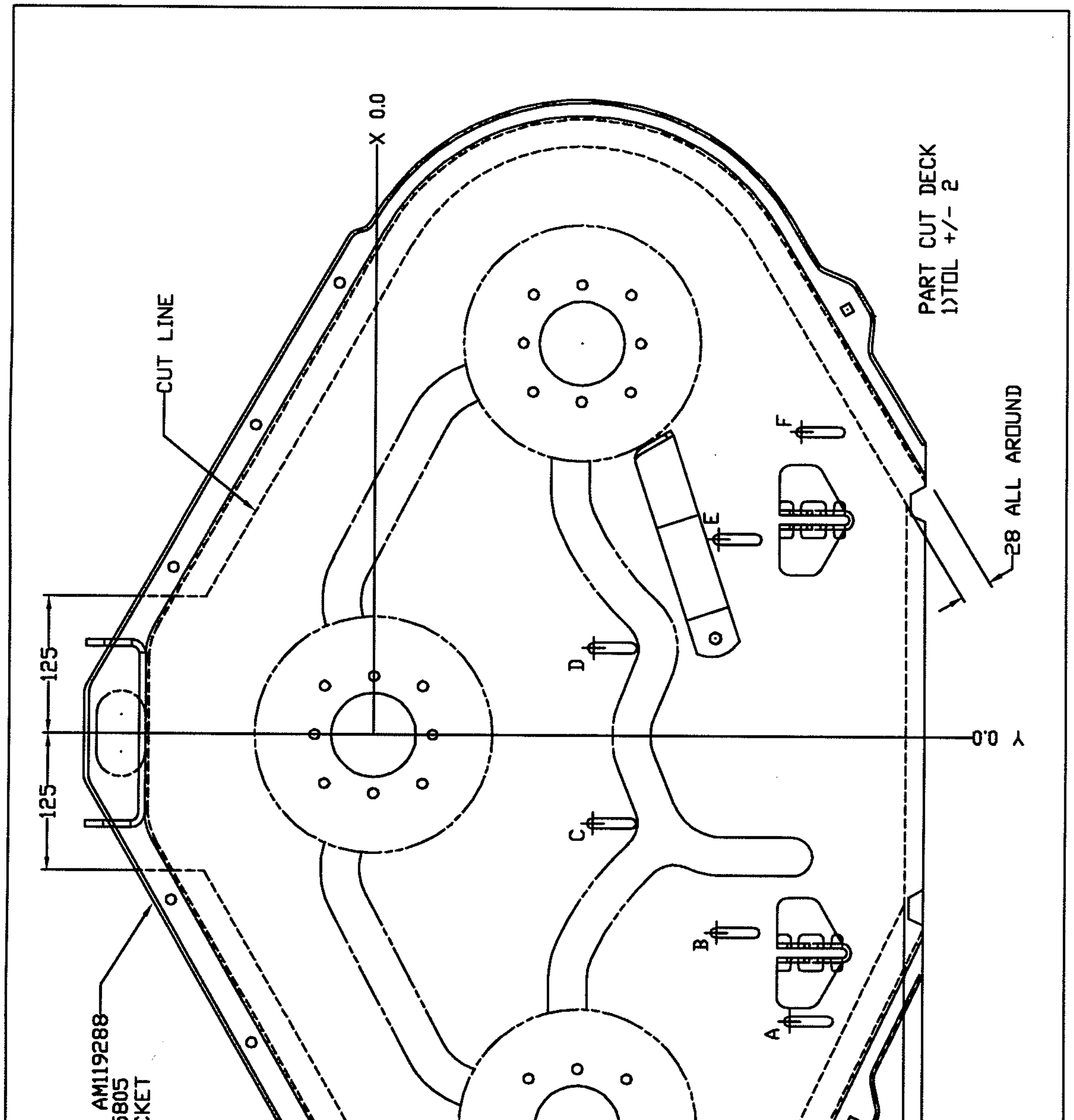
stop dump____

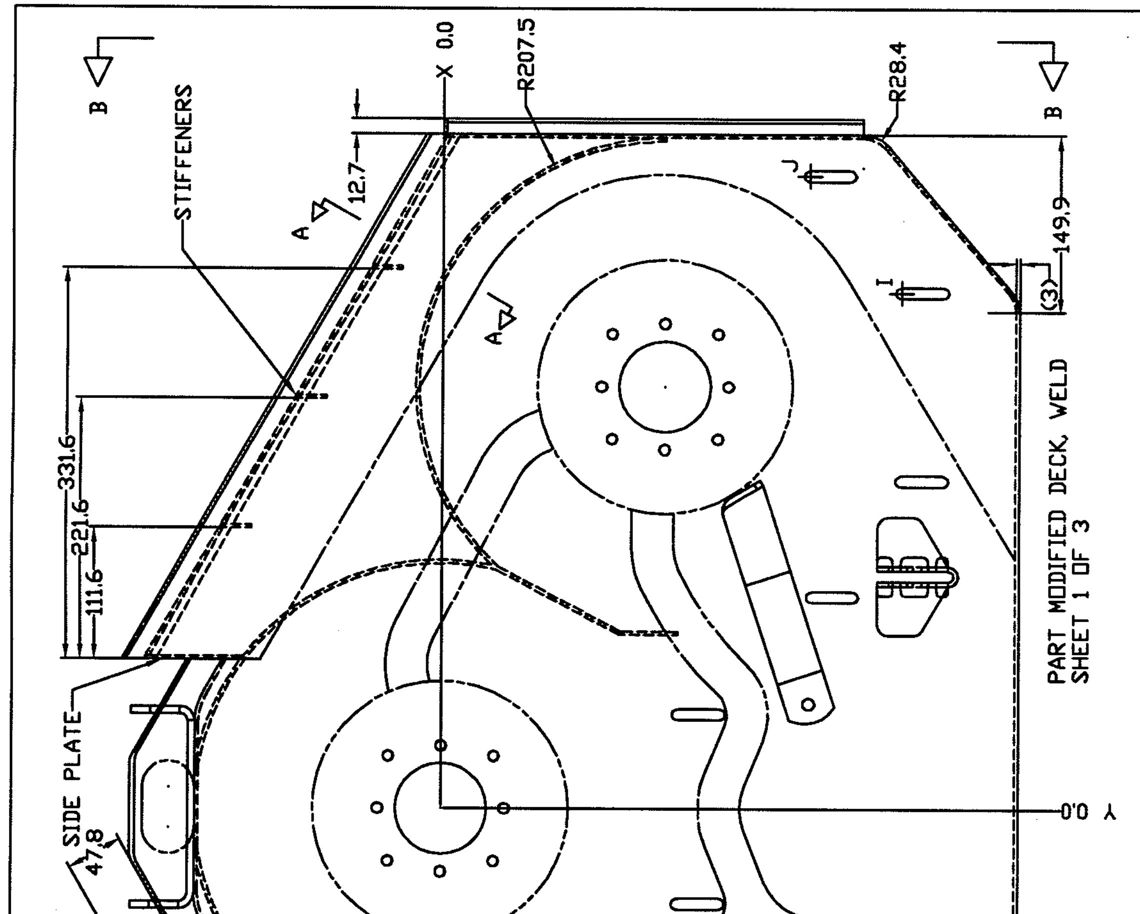
APPENDIX B

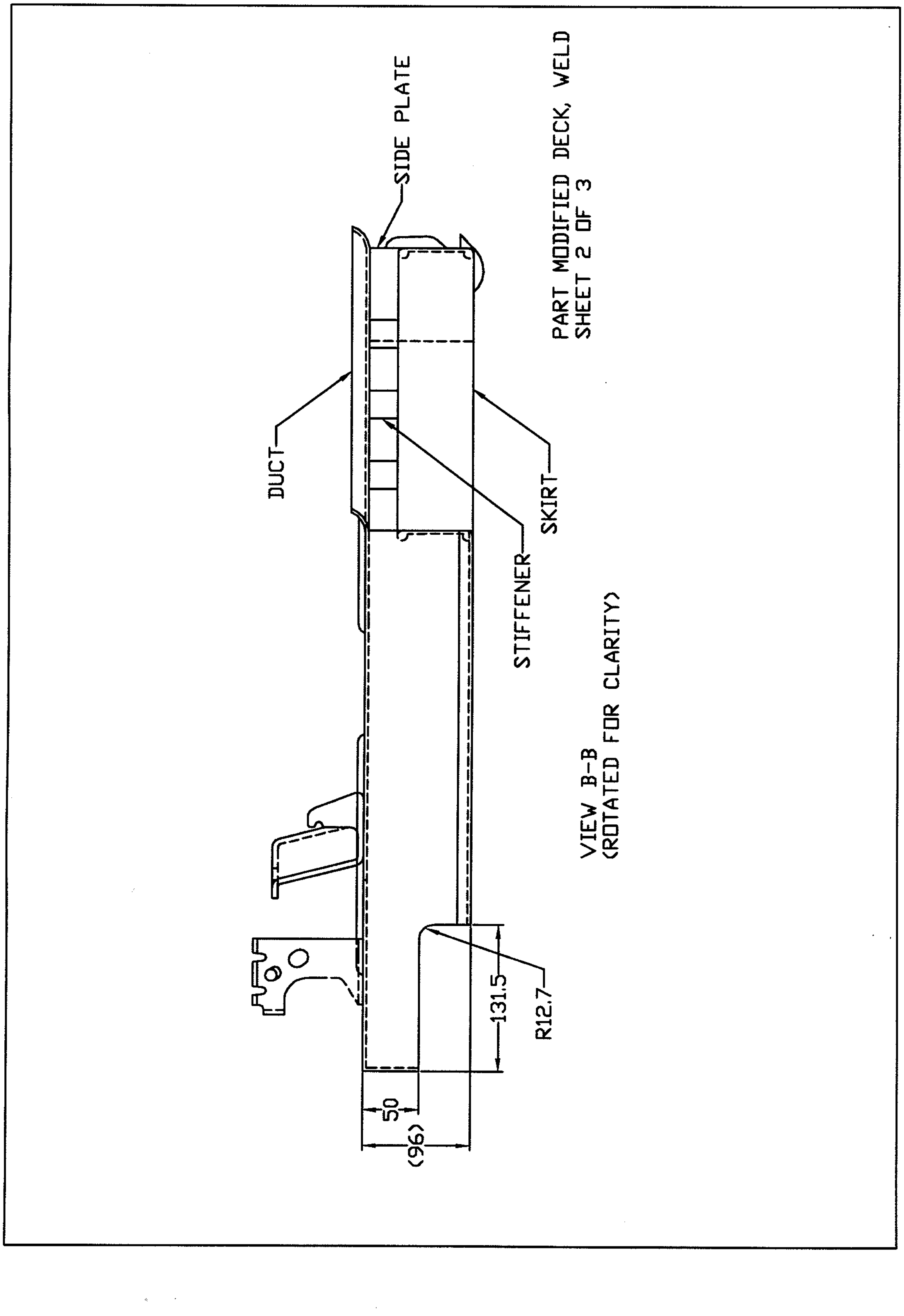
Design Drawings

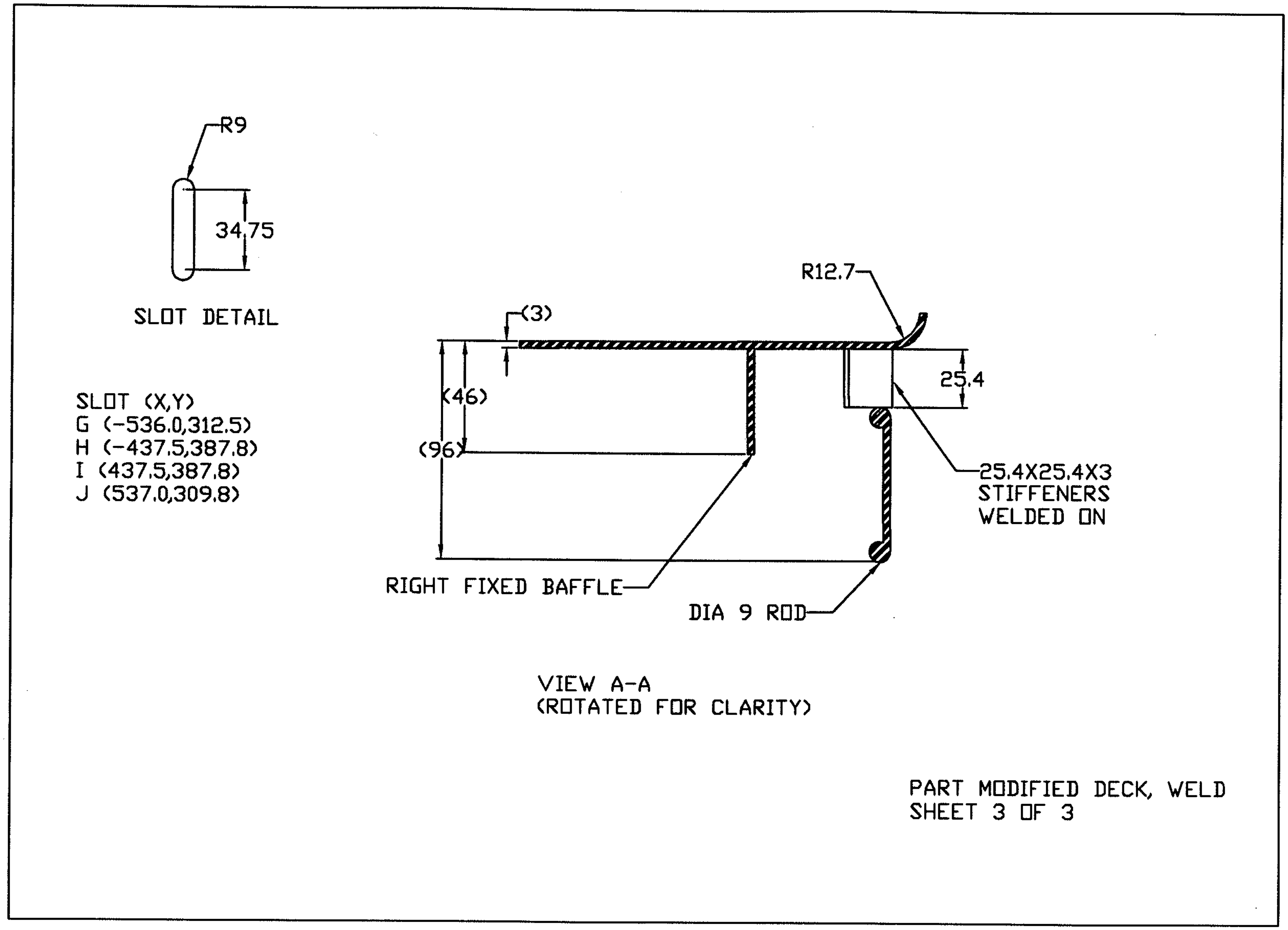
The following drawing package was used for fabrication of the prototype mower by John Deere Horicon Works. All dimensions are in millimeters. Where dimensions are not given, the configuration is covered by existing John Deere drawings. The prototype deck was constructed by first cutting the skirt off of a production 44" deck, and then welding material to the remaining structure according to the prototype plans.

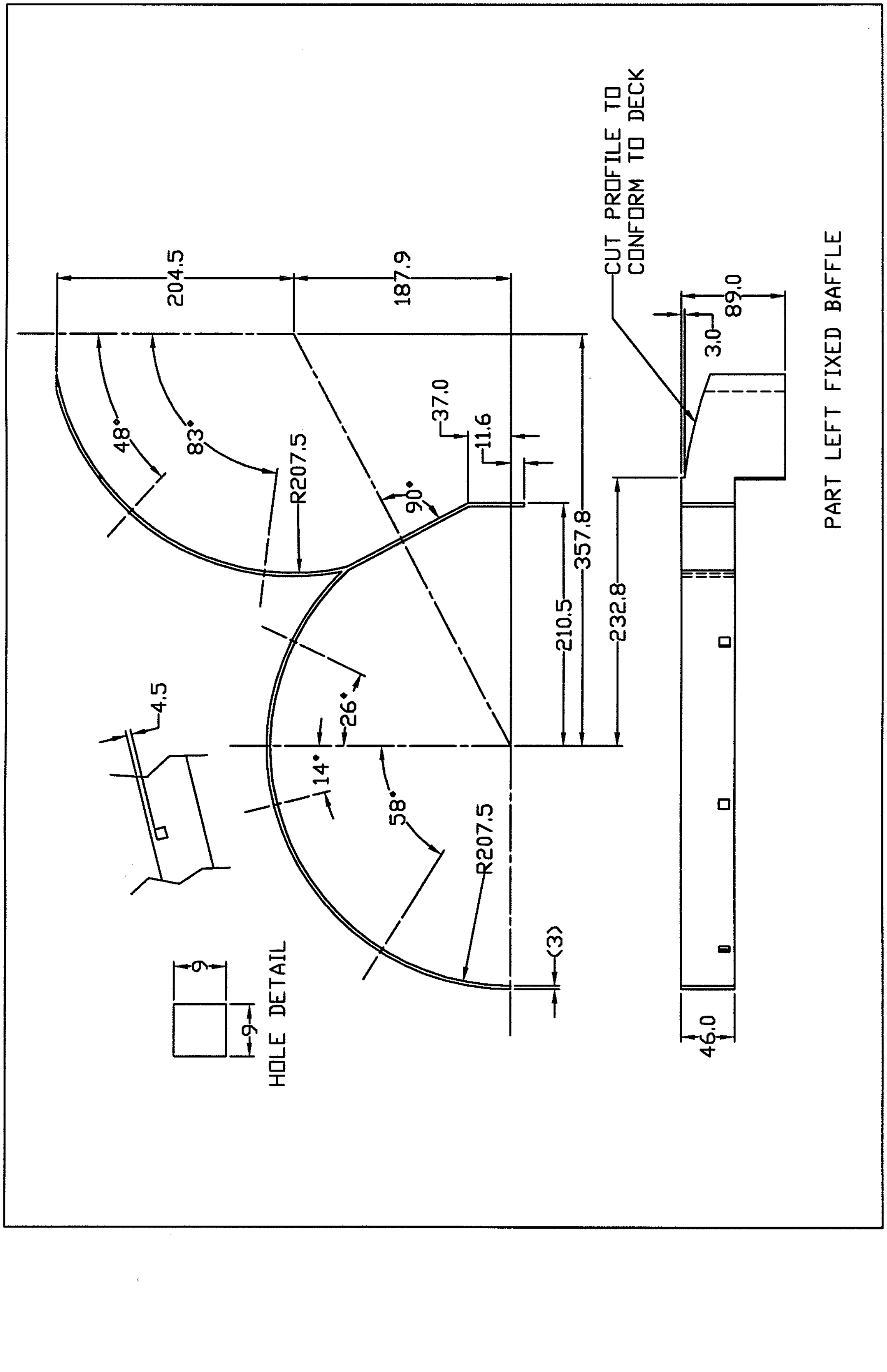
The final two drawings in the package show the blades used for the simultaneous cutting experiment discussed in Section 2.3 of the text.


44" DECK P/N AM119288
NO BAFFLE M115805
NO WHEEL BRACKET
CUT LINE
X 0.0
Y 0.0
125
125
A
B
C
D
E
F
PART CUT DECK
1)TOL +/- 2
28 ALL AROUND
16.75
R9
34.75
SLOT (X,Y)
A (-260.1,380.1)
B (-179.5,312.5)
C (-80.0,199.9)
D (80.0,199.9)
E (179.5,312.5)
F (278.0,387.8)

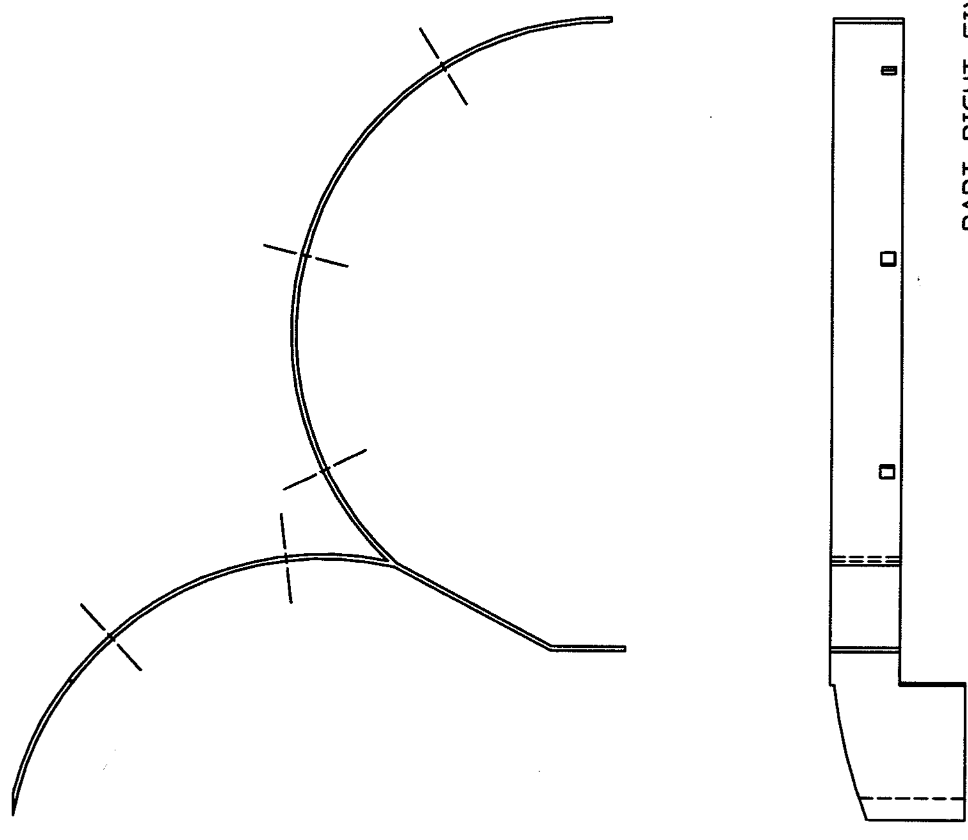

PART MODIFIED DECK, WELD
SHEET 1 OF 3
STIFFENERS
SIDE PLATE
DUCT
SKIRT
WELD LINE
BRACKET
LEFT FIXED BAFFLE
FLUSH WITH CEILING
OF DECK
X 0.0
Y 0.0
R207.5
R28.4
12.7
331.6
221.6
111.6
47.8
115.8
149.9
(3)
149.9
189.8
167.0
131.5
A
A
B
B
G
H
I
J


SIDE PLATE
PART MODIFIED DECK, WELD
SHEET 2 OF 3
DUCT
SKIRT
STIFFENER
VIEW B-B
(ROTATED FOR CLARITY)
131.5
R12.7
50
(96)

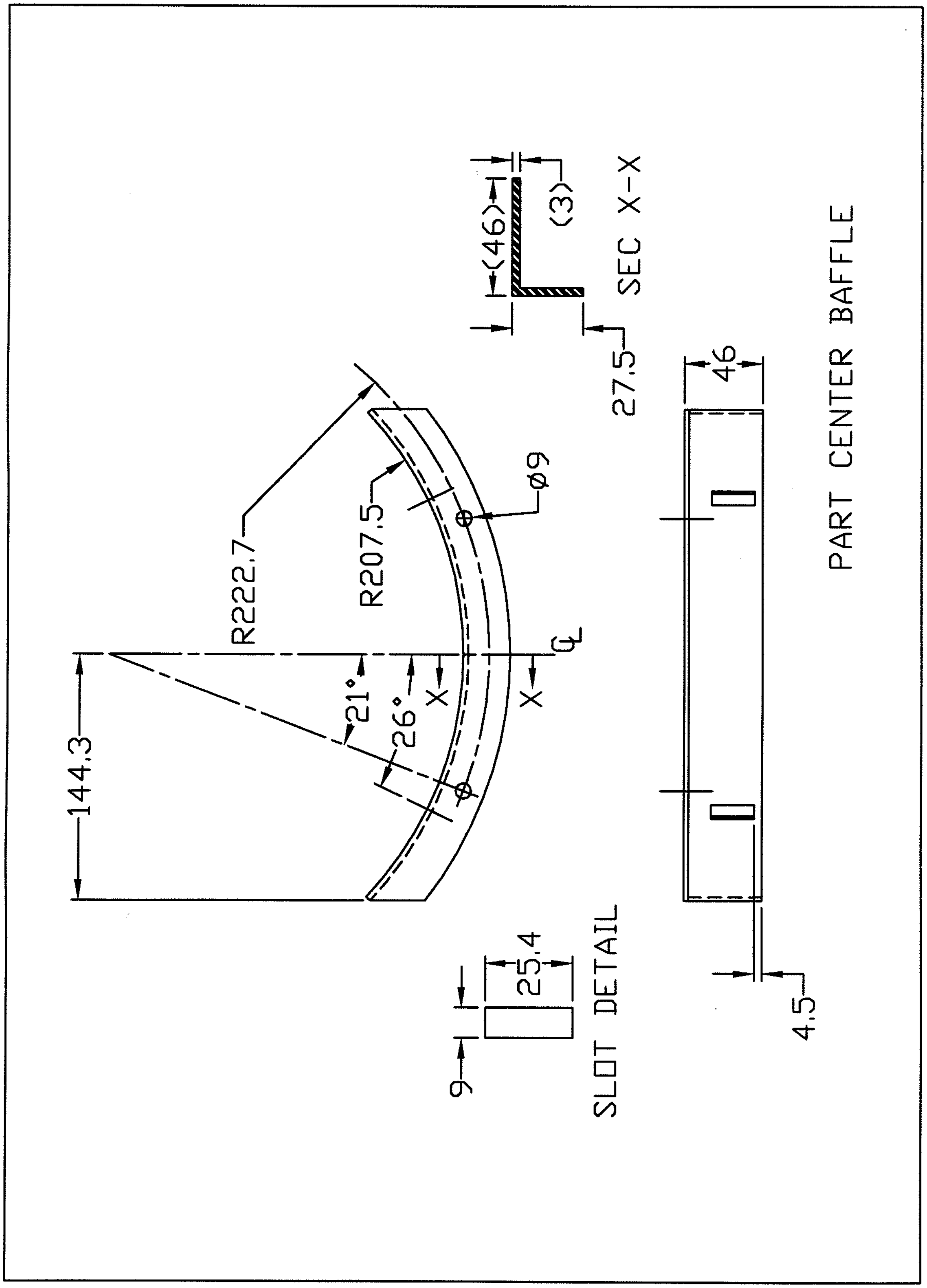

R9
34.75
SLOT DETAIL
SLOT (X,Y)
G (-536.0,312.5)
H (-437.5,387.8)
I (437.5,387.8)
J (537.0,309.8)
R12.7
(3)
(46)
(96)
25.4
25.4X25.4X3
STIFFENERS
WELDED ON
RIGHT FIXED BAFFLE
DIA 9 ROD
VIEW A-A
(ROTATED FOR CLARITY)
PART MODIFIED DECK, WELD
SHEET 3 OF 3



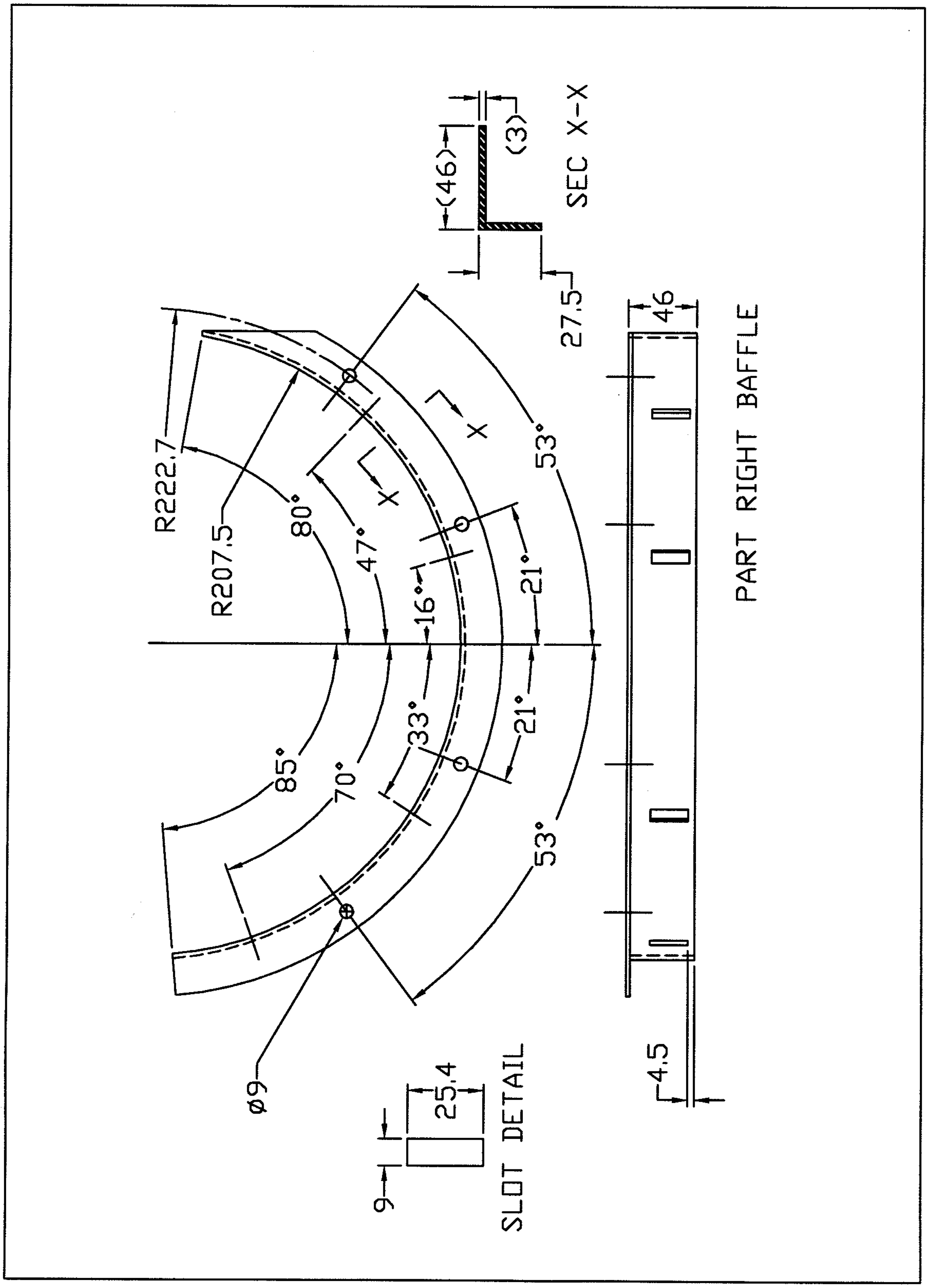
204.5
187.9
48°
83°
R207.5
37.0
11.6
90°
357.8
210.5
232.8
26°
14°
58°
R207.5
4.5
(3)
9
9
HOLE DETAIL
CUT PROFILE TO
CONFORM TO DECK
3.0
89.0
46.0
PART LEFT FIXED BAFFLE

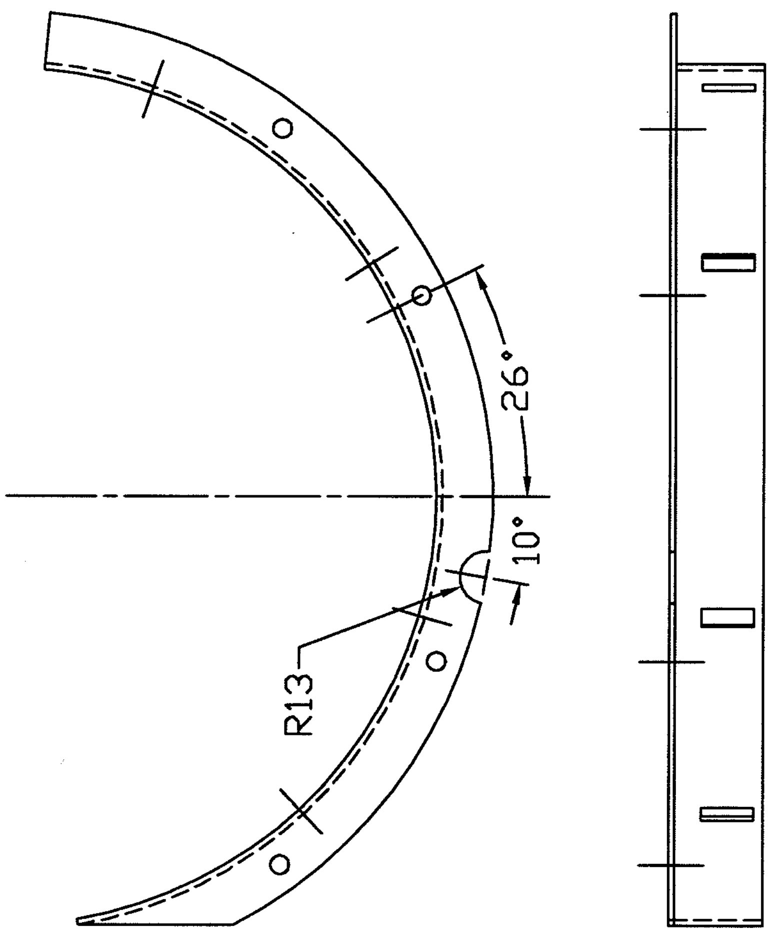


PART RIGHT FIXED BAFFLE
(MIRROR IMAGE OF PART LEFT
FIXED BAFFLE)

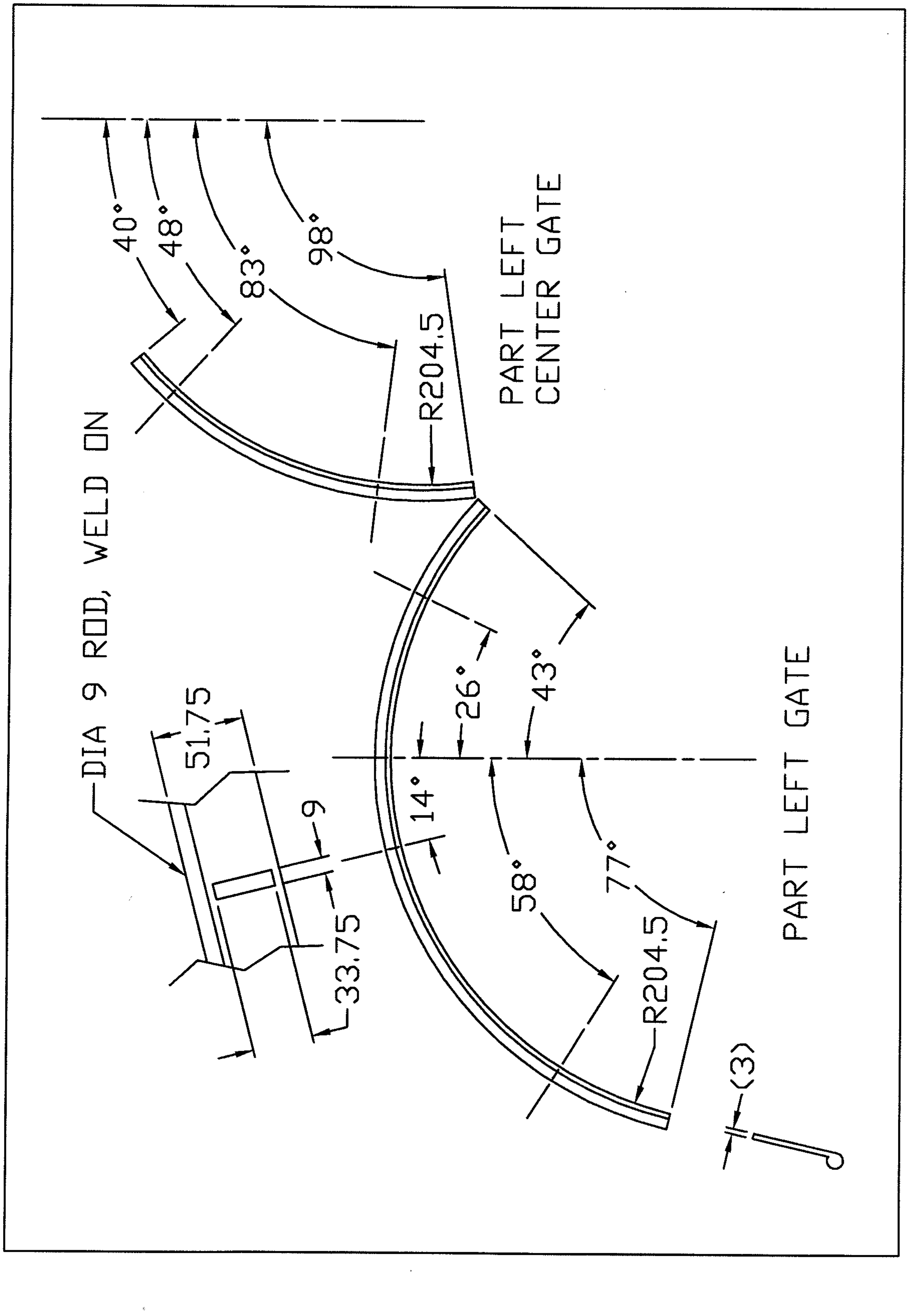


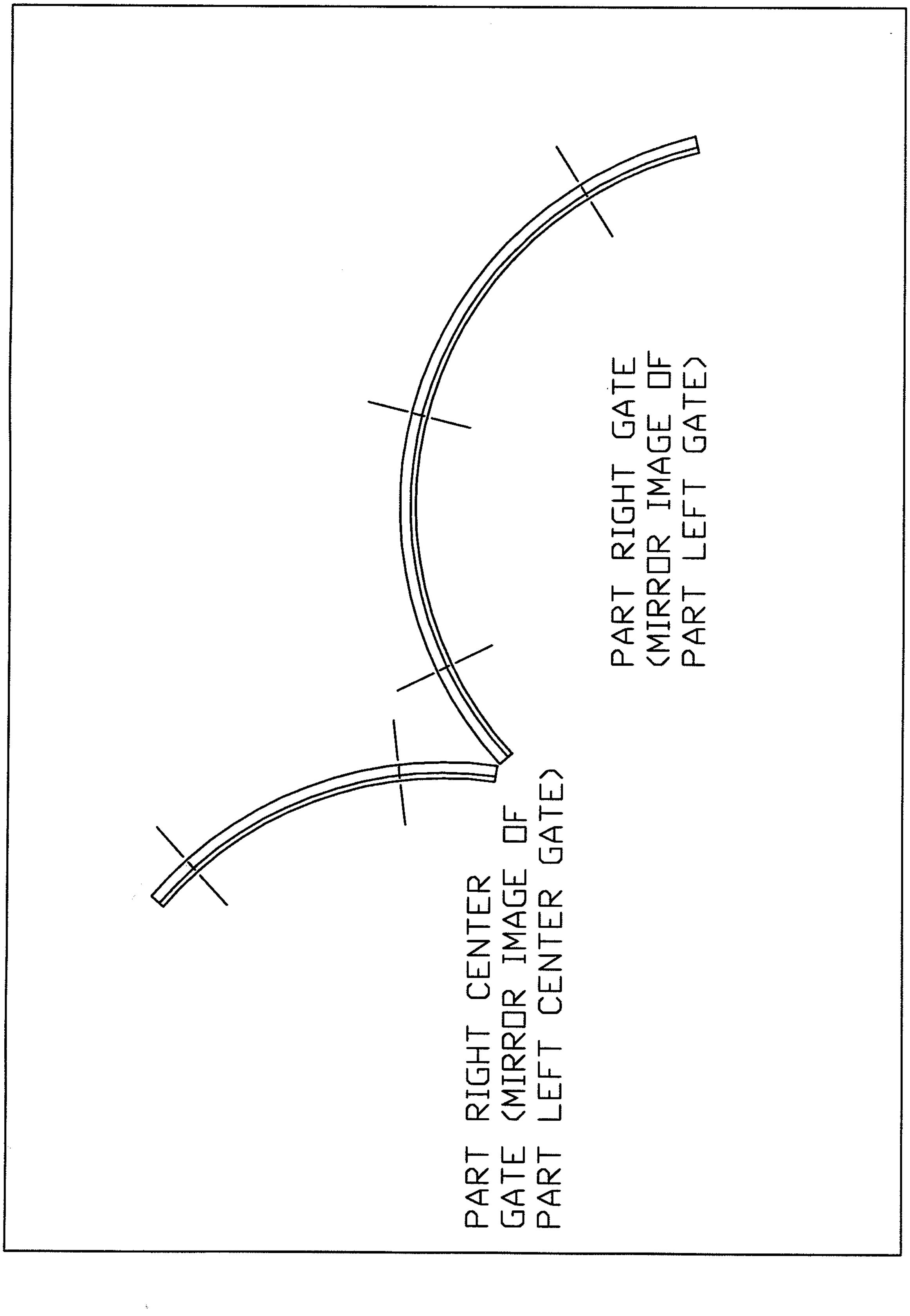
PART CENTER BAFFLE
R222.7
R207.5
ø9
144.3
21°
26°
X
X
℄
SEC X-X
(46)
(3)
27.5
46
4.5
SLOT DETAIL
25.4
9

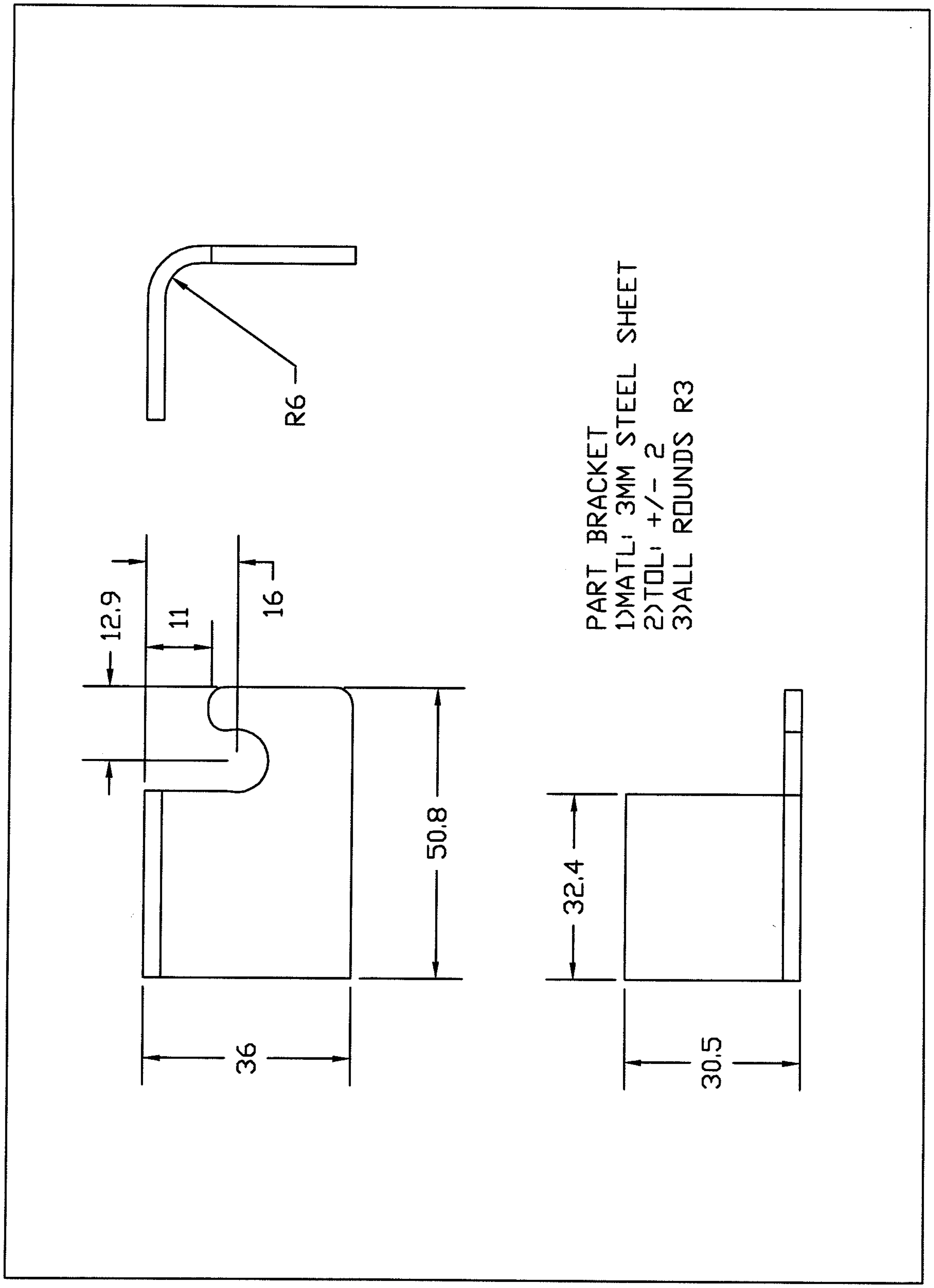

SEC X-X
(46)
(3)
27.5
46
X
R222.7
R207.5
80°
47°
16°
21°
53°
85°
70°
33°
21°
53°
Ø9
25.4
9
SLOT DETAIL
4.5
PART RIGHT BAFFLE

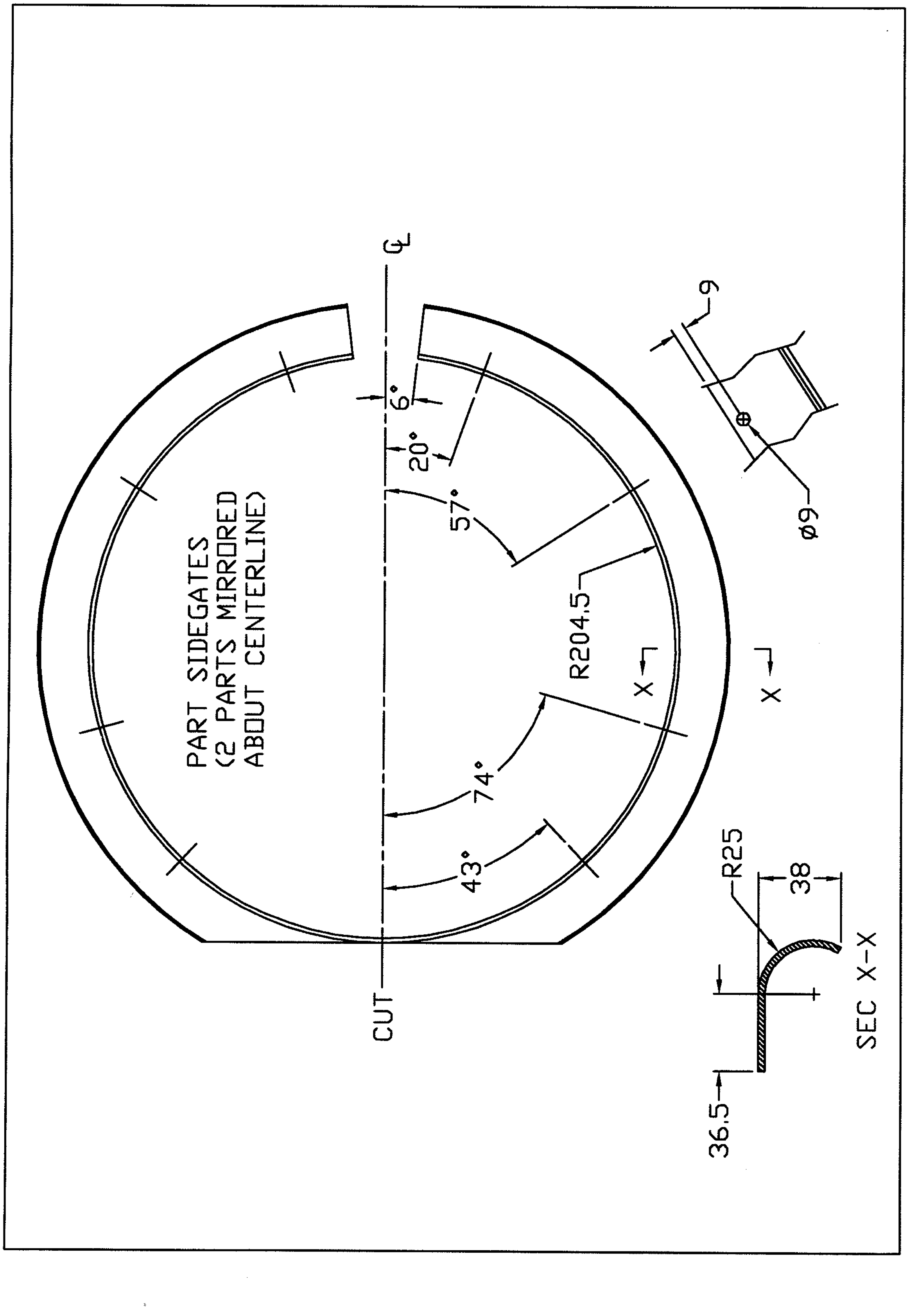


PART LEFT BAFFLE
(MIRROR IMAGE OF RIGHT BAFFLE
EXCEPT FOR DIMENSIONS SHOWN)

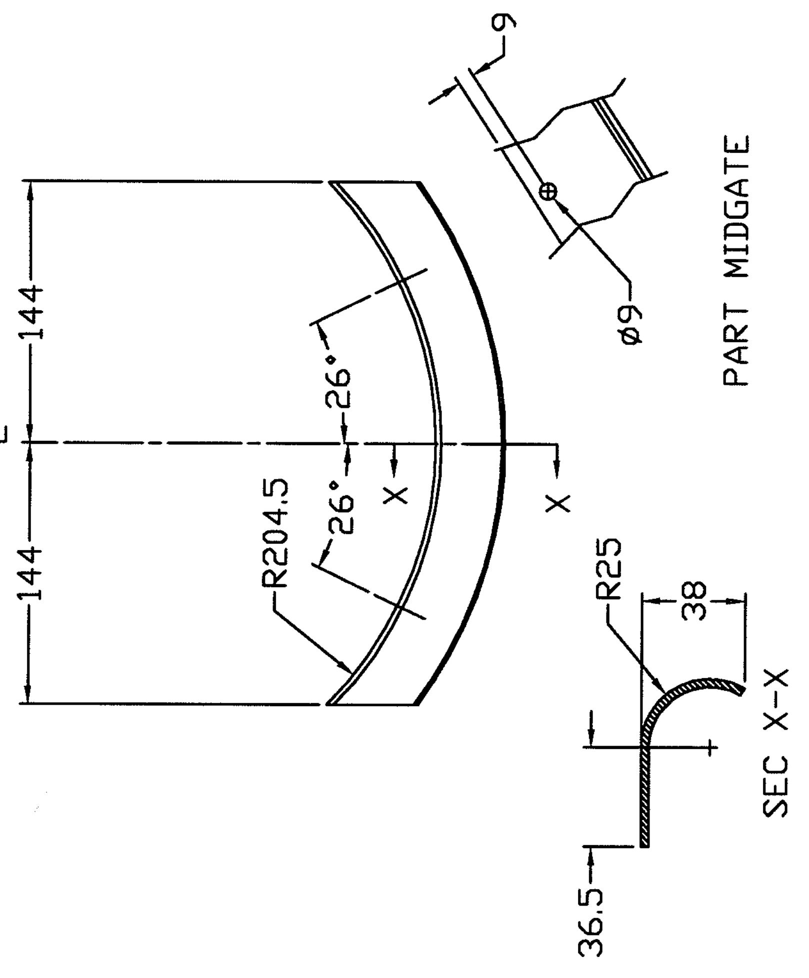

DIA 9 ROD, WELD ON
51.75
9
33.75
14°
26°
43°
58°
77°
R204.5
R204.5
40°
48°
83°
98°
PART LEFT
CENTER GATE
PART LEFT GATE
(3)

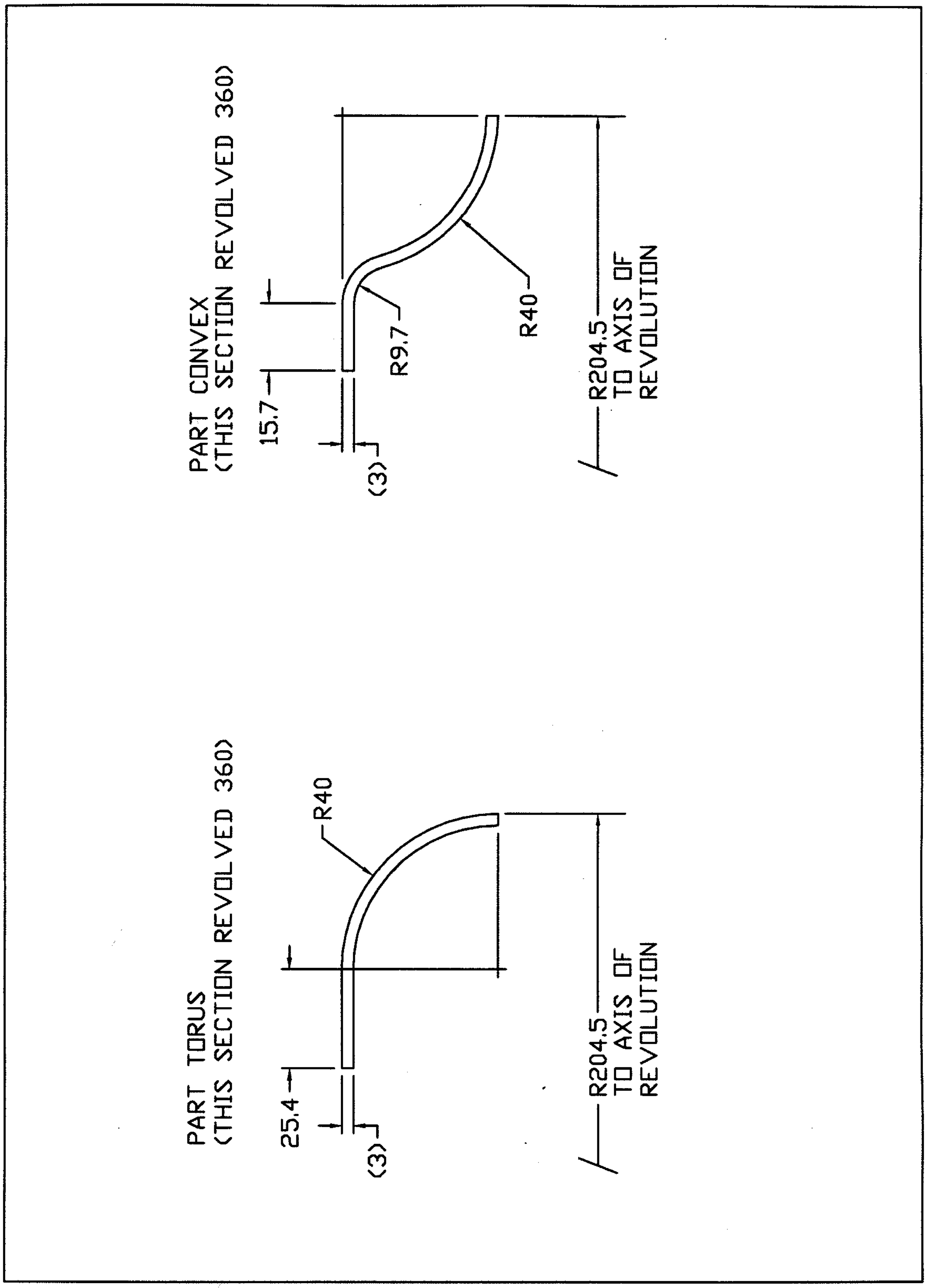

PART RIGHT CENTER
GATE (MIRROR IMAGE OF
PART LEFT CENTER GATE)
PART RIGHT GATE
(MIRROR IMAGE OF
PART LEFT GATE)

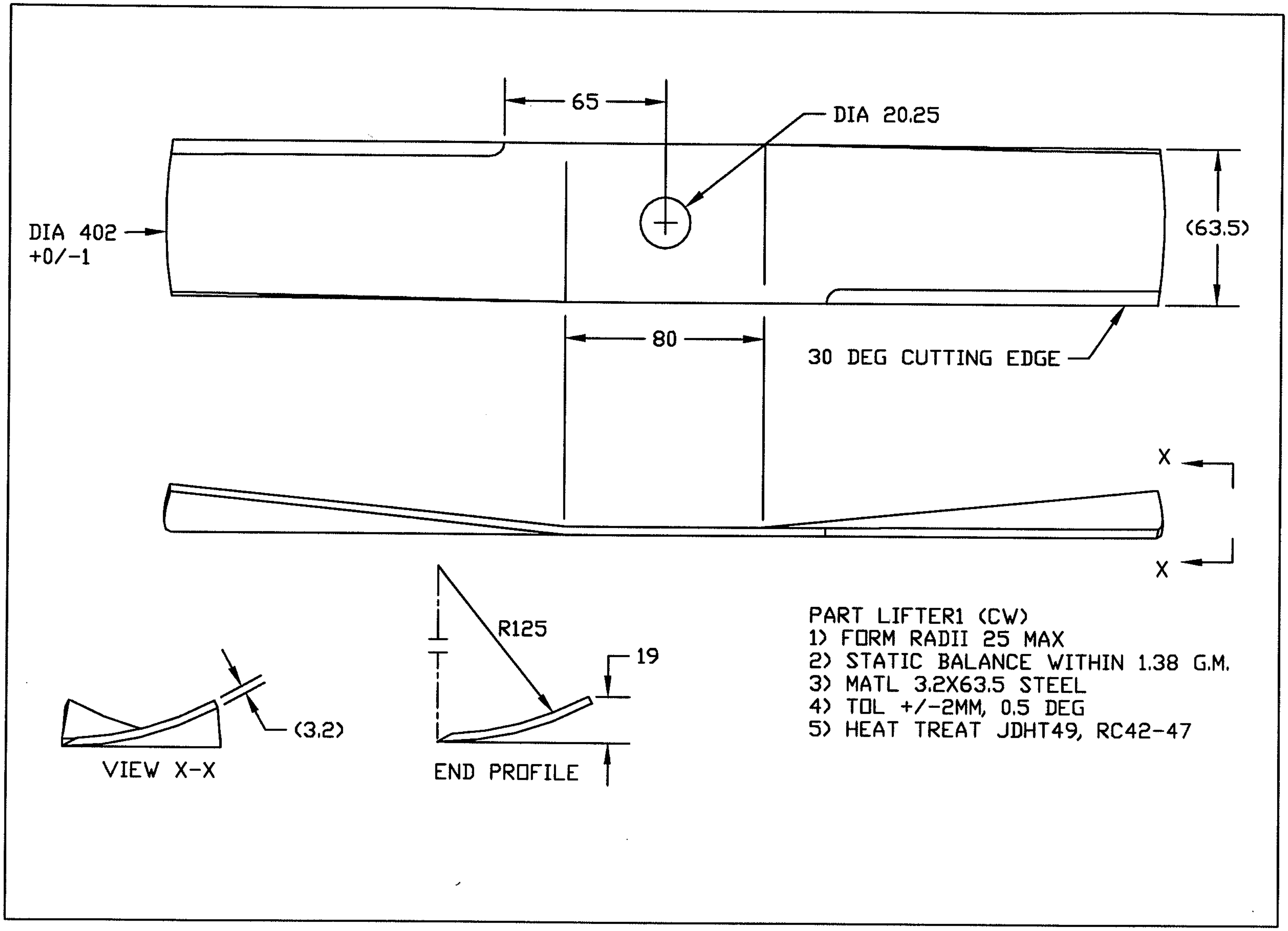

12.9
11
16
R6
50.8
32.4
36
30.5
PART BRACKET
1)MATL: 3MM STEEL SHEET
2)TOL: +/- 2
3)ALL ROUNDS R3

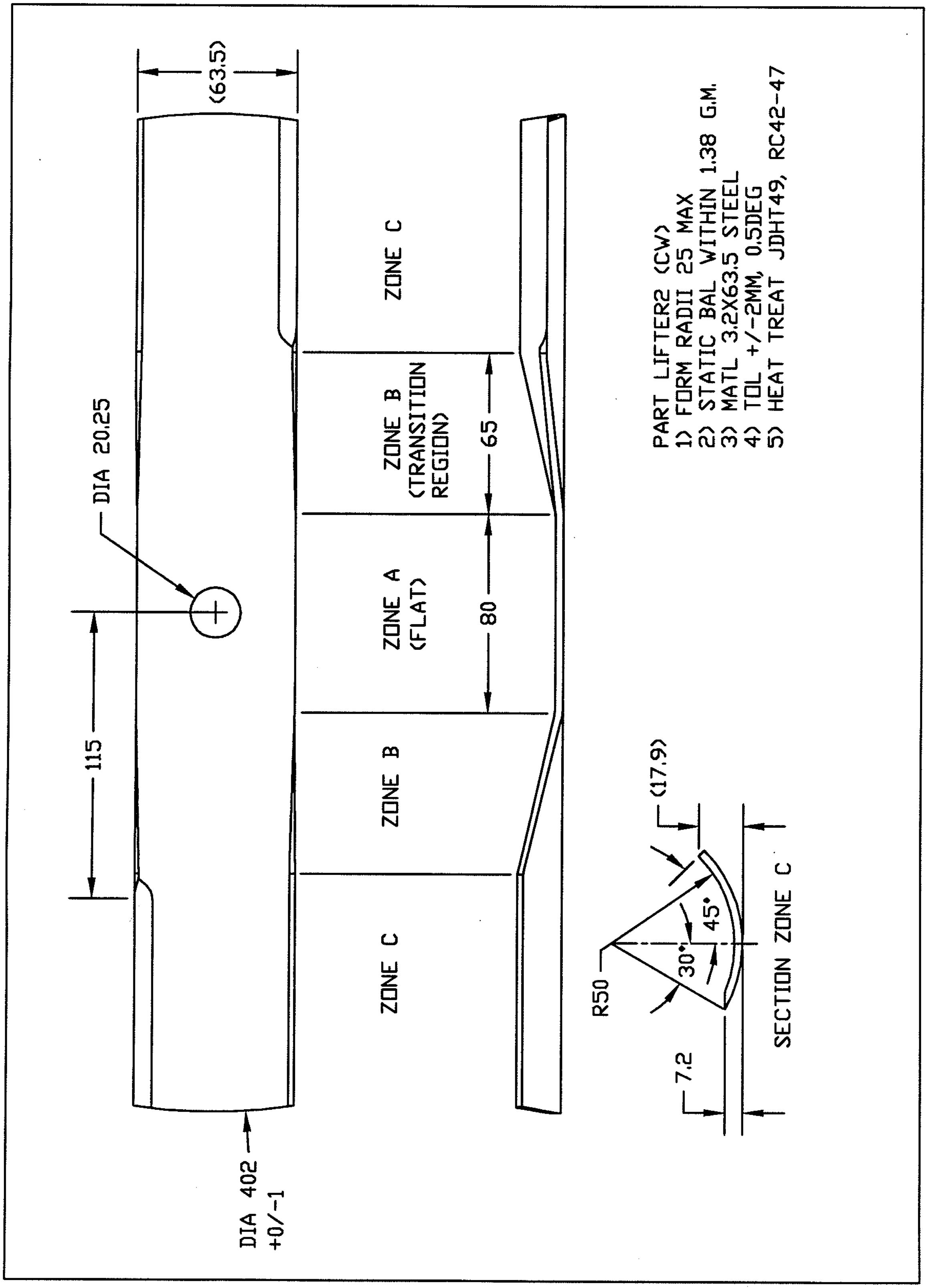


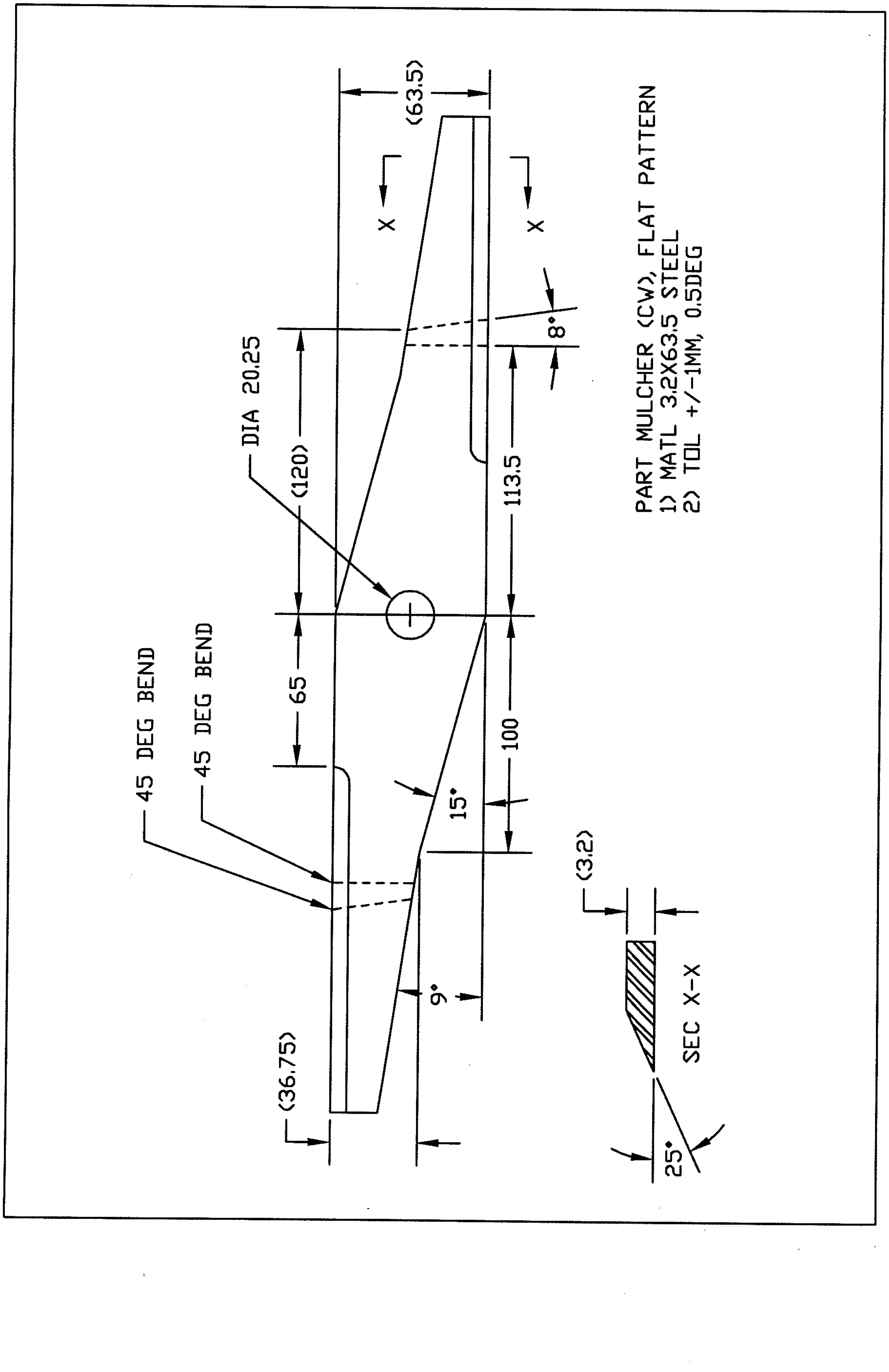
PART SIDEGATES
(2 PARTS MIRRORED
ABOUT CENTERLINE)
℄
6°
20°
57°
R204,5
X
X
74°
43°
CUT
R25
38
SEC X-X
36,5
9
ø9

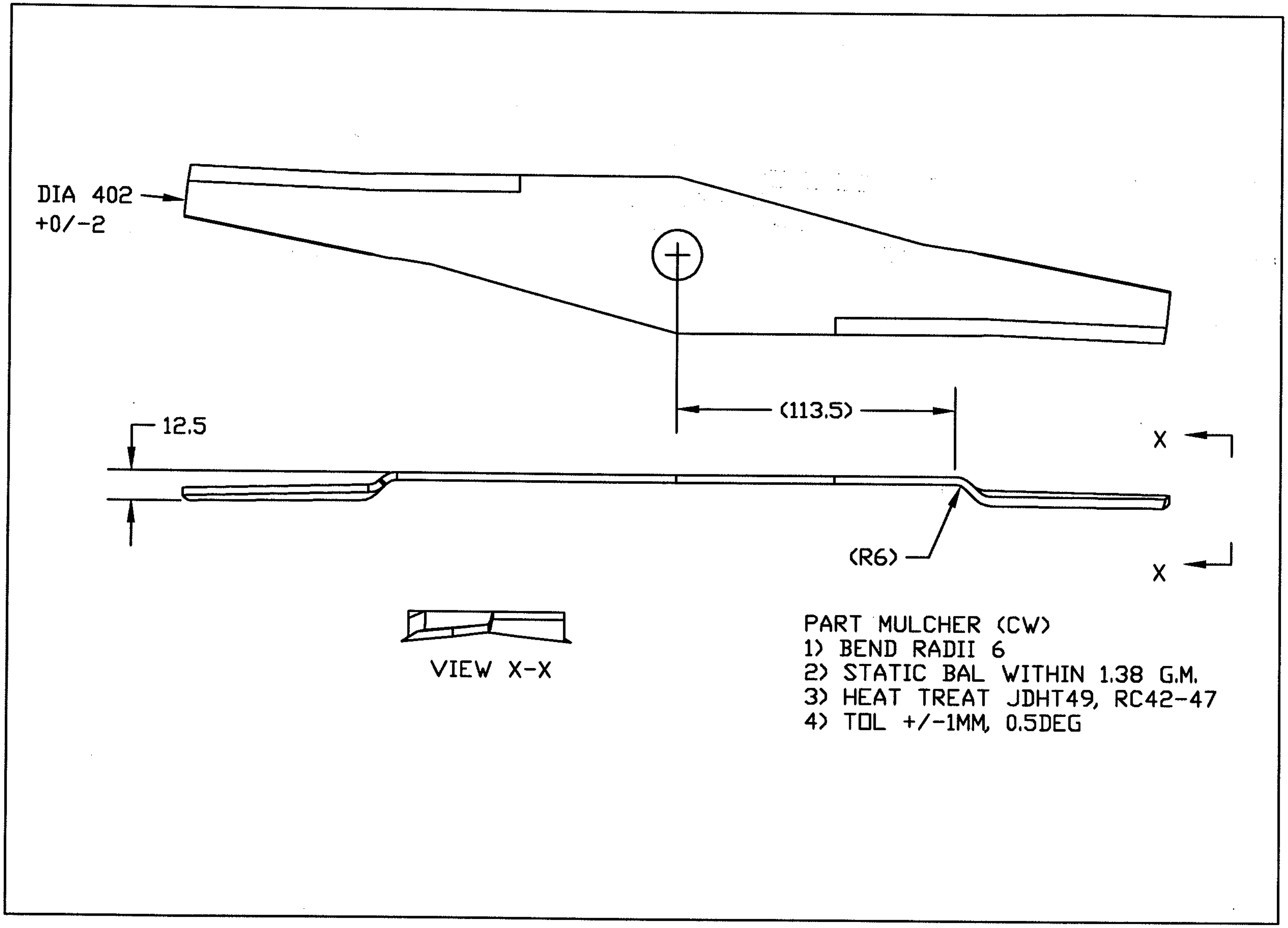

144
144
℄
26°
26°
R204.5
X
X
9
Ø9
PART MIDGATE
R25
38
36.5
SEC X-X

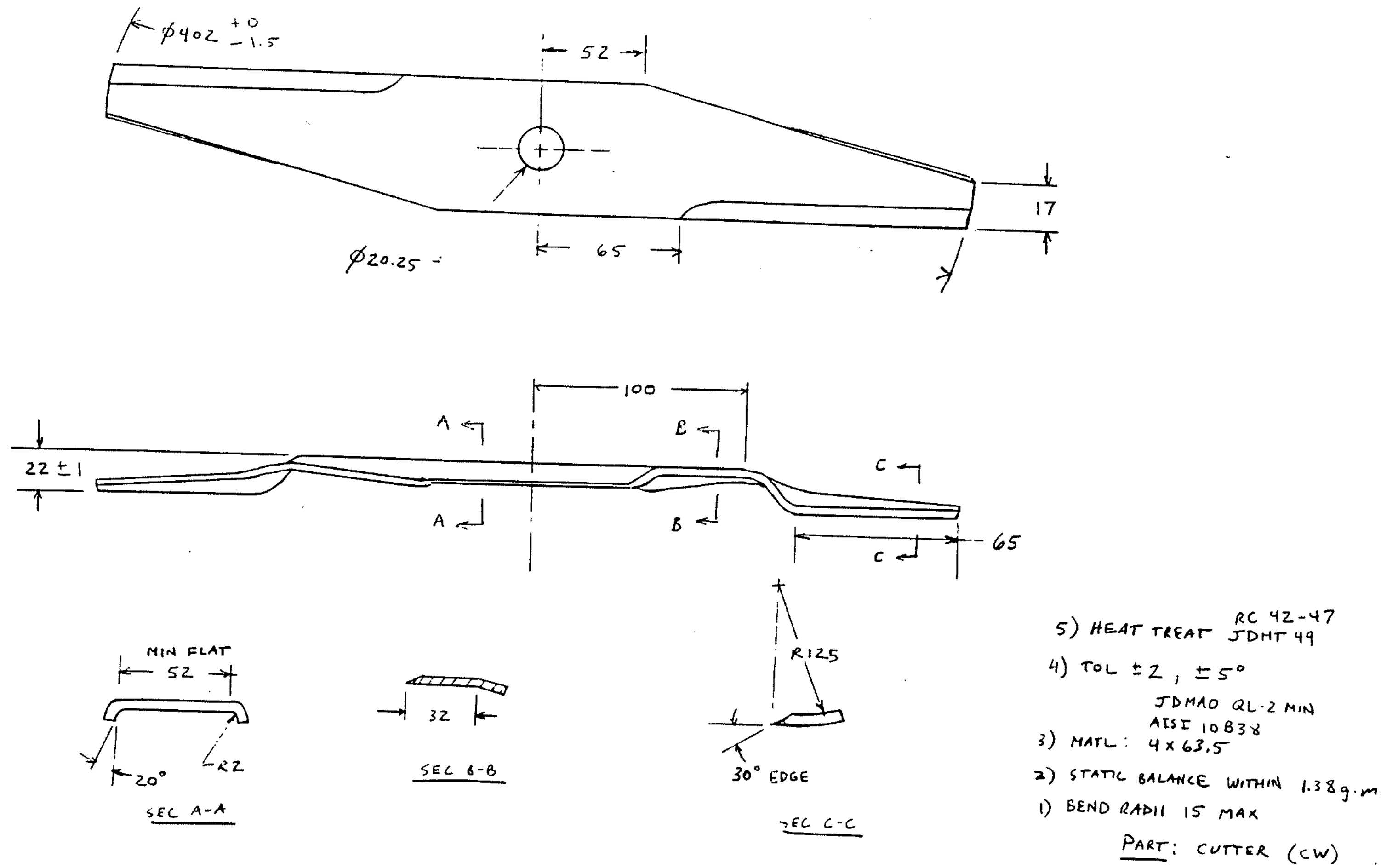

PART TORUS
(THIS SECTION REVOLVED 360)
R40
25.4
(3)
R204.5
TO AXIS OF
REVOLUTION
PART CONVEX
(THIS SECTION REVOLVED 360)
15.7
(3)
R9.7
R40
R204.5
TO AXIS OF
REVOLUTION

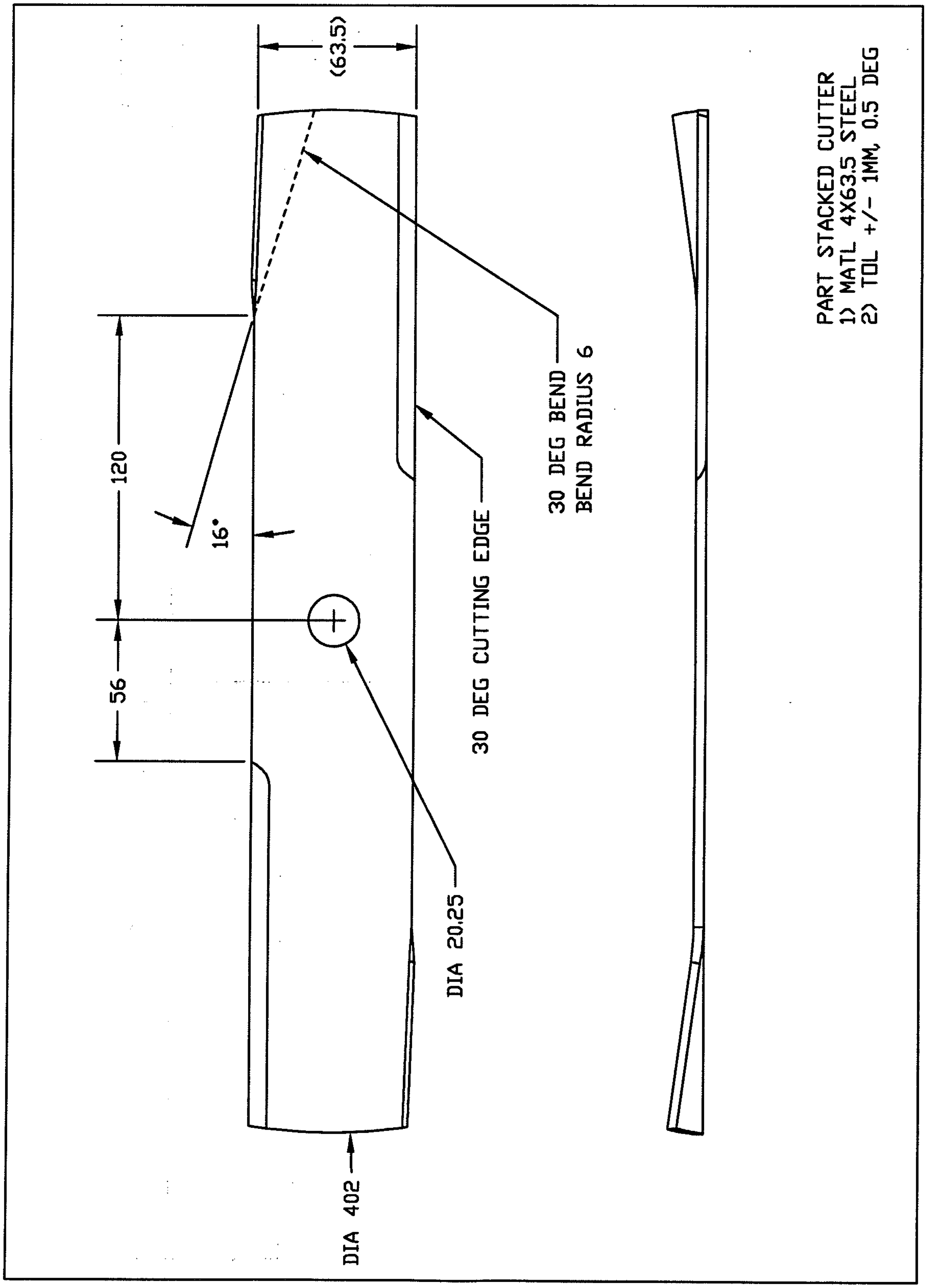

65
DIA 20.25
DIA 402
+0/-1
(63.5)
80
30 DEG CUTTING EDGE
X
X
R125
19
(3.2)
VIEW X-X
END PROFILE
PART LIFTER1 (CW)
1) FORM RADII 25 MAX
2) STATIC BALANCE WITHIN 1.38 G.M.
3) MATL 3.2X63.5 STEEL
4) TOL +/-2MM, 0.5 DEG
5) HEAT TREAT JDHT49, RC42-47

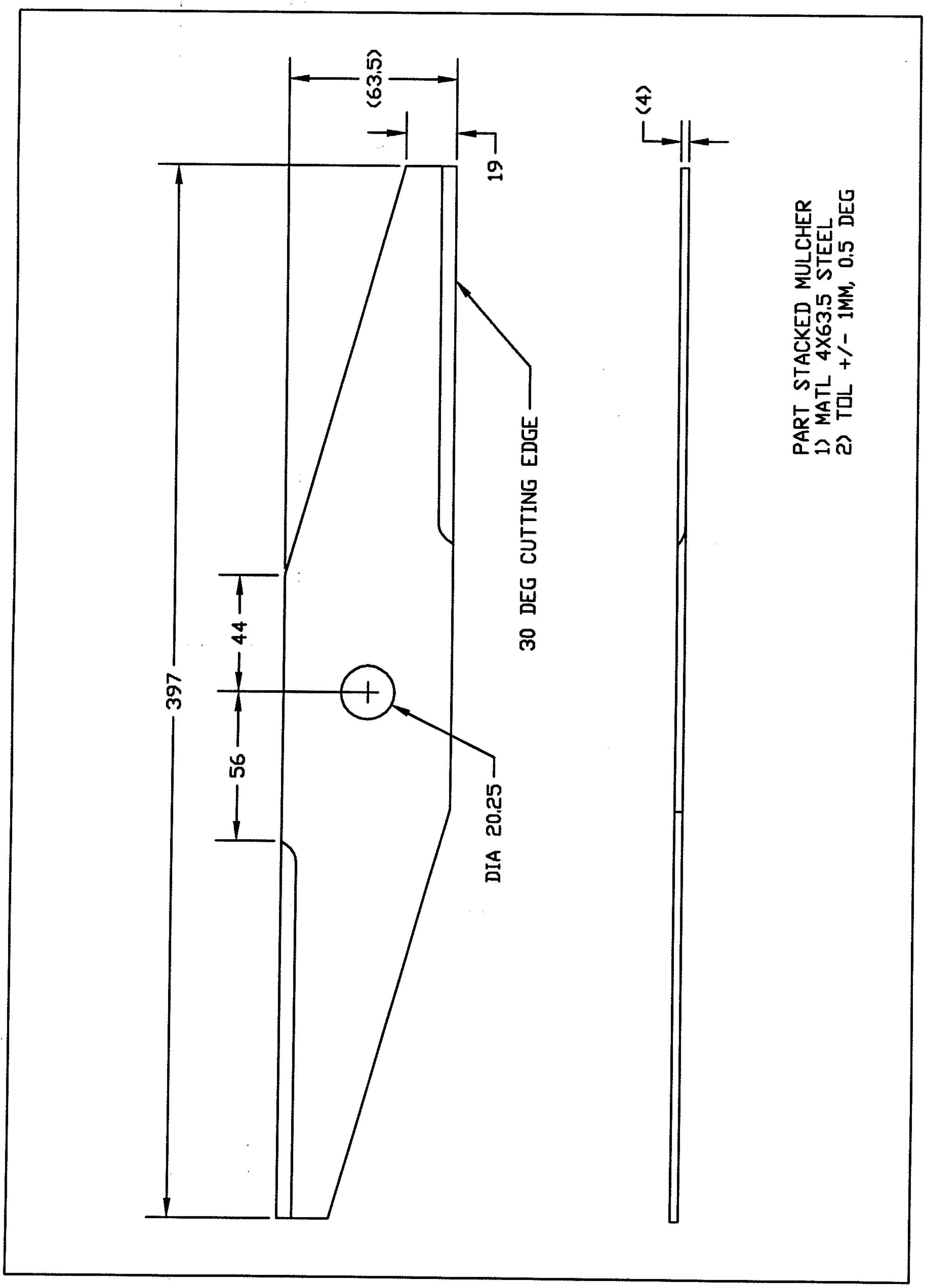

(63.5)
DIA 20.25
115
ZONE C
ZONE B
ZONE A
(FLAT)
80
ZONE B
(TRANSITION
REGION)
65
ZONE C
DIA 402
+0/-1
R50
30°
45°
(17.9)
7.2
SECTION ZONE C
PART LIFTER2 (CW)
1) FORM RADII 25 MAX
2) STATIC BAL WITHIN 1.38 G.M.
3) MATL 3.2X63.5 STEEL
4) TOL +/-2MM, 0.5DEG
5) HEAT TREAT JDHT49, RC42-47


PART MULCHER (CW), FLAT PATTERN
1) MATL 3.2X63.5 STEEL
2) TOL +/-1MM, 0.5DEG
(63.5)
DIA 20.25
(120)
113.5
65
100
45 DEG BEND
45 DEG BEND
15°
8°
9°
X
X
(36.75)
(3.2)
SEC X-X
25°


DIA 402
+0/-2
12.5
(113.5)
(R6)
X
X
VIEW X-X
PART MULCHER (CW)
1) BEND RADII 6
2) STATIC BAL WITHIN 1.38 G.M.
3) HEAT TREAT JDHT49, RC42-47
4) TOL +/-1MM, 0.5DEG


ϕ402 +0 −1.5
52
ϕ20.25
65
17
100
A
B
C
22 ± 1
65
MIN FLAT
52
R2
20°
SEC A-A
32
SEC B-B
R125
30° EDGE
SEC C-C
5) HEAT TREAT RC 42-47 JDMT 49
4) TOL ±2, ±5°
3) MATL: JDMAO QL-2 MIN AISI 10B38 4 x 63.5
2) STATIC BALANCE WITHIN 1.38 g.m.
1) BEND RADII 15 MAX
PART: CUTTER (CW)


(63.5)
120
56
16°
30 DEG BEND
BEND RADIUS 6
30 DEG CUTTING EDGE
DIA 20.25
DIA 402
PART STACKED CUTTER
1) MATL 4X63.5 STEEL
2) TOL +/- 1MM, 0.5 DEG


(63.5)
19
(4)
397
44
56
DIA 20.25
30 DEG CUTTING EDGE
PART STACKED MULCHER
1) MATL 4X63.5 STEEL
2) TOL +/- 1MM, 0.5 DEG

APPROVED

Frank J. Fronczak, Nov 16, 1995

Associate Professor