Orbital Scythe Prototype Development and Testing

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Final Report

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Acknowledgments

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We would also like to thank Steve Church and his colleagues in the Research Division of the California Air Resources Board for their encouragement and administrative flexibility over the period of the grant. This project was a departure from the ICAT norm in that it was directed to the development of a consumer, rather than an industrial, product. The grant was also made to a start-up entity at an early stage of development, when technical uncertainties are greatest. As it turned out, the project experienced a number of delays, for both technical and non-technical reasons. We are grateful to the Air Resources Board and the ICAT administrative staff for their support and patience throughout the extended course of the project. The grant has been a significant factor in enabling this project to move forward.

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Abstract

The purpose of the project was to test a new type of energy-efficient mulching lawnmower by building ‘near-commercial’ prototypes, and comparing the operation of the prototypes, including their energy consumption characteristics, with comparably-sized commercially available products, as well as using the mowers for sufficient time under typical operating conditions to evaluate the robustness of the design and the potential commercial viability.

Three prototypes were assembled. Two were sent to the Chicago Botanic Garden for use by the lawn maintenance crews. The third was used for comparison testing with electric rotary mowers from established manufacturers.

The in-use testing identified several areas that required modification, but nothing that has motivated a fundamental change in the current design approach. In general, the problems that arose were due to mechanical tolerances not being rigorously observed in the fabrication of the prototypes.

Energy consumption tests showed the new design has a significant advantage over rotary mowers, using about a third less energy than rotary electric mowers per area of grass cut. As a consequence, the prototypes were shown to be capable of cutting significantly larger lawns than established electric designs under identical conditions. The prototype design therefore represents a significant new opportunity to replace gas-powered rotary mowers – which expend several times as much energy as electric rotary mowers to cut an identical area of grass, and which produce disproportionate levels of air pollution – for yards in the range of ½-acre, which is substantially larger than the size of the average American lawn.

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Introduction

This report is the final element of the ICAT grant.

A related presentation is available on the California Air Resources Board website at http://www.arb.ca.gov/research/seminars/witty/witty.pdf. The presentation, which in its native format includes video of the mower cutting head in operation, is also available from craigwitty@sbcglobal.net.

Innovative Technology

With 54 million Americans mowing the lawn weekly, the EPA estimates that the average homeowner spends about 40 hours a season cutting the grass. If the homeowner uses a traditional gas-powered lawnmower, he or she can produce as much pollution in that time as 40 cars traveling 12,000 miles. On average, a gas mower spews around 87 pounds of greenhouse gases (mostly CO_2) and 54 pounds of other pollutants into the air every year.

In addition, more than 17 million gallons of gas are spilled each year refueling lawn and garden equipment – more petroleum than was spilled by the Exxon Valdez – and the majority is tied to the fueling of gasoline powered lawnmowers. When compared to existing battery-powered mowers, gas mowers send more than 1,800 times the hydrocarbons into the atmosphere. According to the EPA, gas mowers are responsible for nearly 5% of our nation's total air pollution.[1]

In addition to the environmental harm, almost 80,000 injuries occur annually due to lawnmower accidents. Given these statistics, for many years there has been growing concern regarding the harmful emissions and safety risks created by rotary gas-powered lawnmowers. Both issues are of such magnitude that new legislation has either been passed, or is in process, to minimize these harmful effects. These factors create a significant product opportunity in a $1.2 billion wholesale market.

Given rotary mower drawbacks, it's also worth asking a more fundamental question: Since grass is relatively fragile stuff – a blade of it can easily be bisected with the pressure of a fingernail – is it really necessary to apply an engine rated at several horsepower to do the job?

From an energy perspective, the heavy steel blade of a rotary mower is a very inefficient grass cutting instrument. Because a shaft of grass has little mass and can be easily deflected, the blade must spin at very high power levels to perform the cutting function with purely inertial force. The energy requirements of mulching mowers are disproportionately greater, since the clippings are re-cut in the air, when they are already in motion. Compared to the basic requirements of the task, a gasoline-powered rotary mower, in particular, uses outlandishly large amounts of energy per blade of grass actually cut. And given the inherently large power requirements, battery-operated rotary mowers have relatively short run times. As a consequence, battery-powered mowers have so far failed to capture a substantial share of the market.

Another common, and historically significant, grass cutting mechanism is the reel mower. This device has a set of helically twisted flat steel bars fixed in a cylindrical form, and positioned to graze the leading edge of a horizontal bed knife supported at the desired cutting height. As the mower moves forward, the blades of grass are swept against the bed knife and sheared between the knife and the cylindrical reel. Such reel mowers have been powered by both gasoline and

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[1] See http://www.epa.gov/air/community/details/yardequip_addl_info.html#activity2 , second bullet point.

electric motors, but the only common configuration for residential use today is the human-powered "push mower".

Compared to rotary mowers, reel mowers have a great advantage in terms of energy efficiency. The bed knife and reel interact to create a scissors-type action that is not only energy efficient, but which creates a clean cut at the top of the shaft of grass. Lawns that are routinely cut with reel mowers have a groomed appearance that is generally considered superior to lawns cut with rotary mowers. There is also a consequent beneficial effect on the health of the grass.

However, compared to a rotary mower blade, the reel mechanism is complex and expensive to produce. In particular, the need to preserve a precise gap between the reel and the bed knife generally requires that the mechanism be constructed of heavy-gauge, rigid materials that are capable of maintaining proper alignment through long-term use.

In addition to complexity and cost, reel mowers suffer from another disadvantage compared to rotary mowers – the mechanism is inherently incapable of mulching grass (i.e., cutting it up into small pieces that can be left on the lawn). The reel sweeps each blade of grass against the bed knife only once. Unless a lawn is cut frequently, any mowing system that does not mulch grass generally requires that the clippings be removed for aesthetic reasons. This creates an additional task for the operator (either raking the lawn or emptying a clippings catcher), and – more importantly for the health of the grass – deprives the lawn of valuable nutrients. It also creates a burden for the local municipality if the clippings are hauled away to a landfill. If the clippings are packed together, whether in a landfill or a compost pile, they will tend to ferment, which creates methane, a greenhouse gas many times more powerful than CO^2. The practice of disposing of grass clippings, rather than mulching them, is therefore counterproductive in a compound way.

O-Sage Power Equipment LLC has developed and patented a lawnmower cutting head that has the potential to overcome the inherent disadvantages of both rotary and reel mowers. The design incorporates a number of flexible blades fixed to a rotor *inside* a cylindrical reel. The rotor turns in the opposite direction of the reel, and cuts each blade of grass several times, to a progressively lower height, as the mower passes above it, rather than re-cutting clippings suspended in the air.

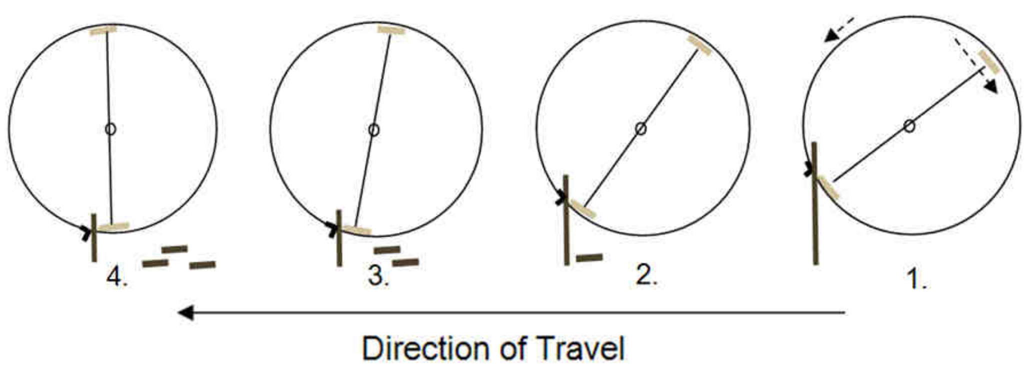

Figure 1

The O-Sage cutting head is similar to a reel mower in that the grass is sheared, scissors-like, between the blades and the reel bars. Unlike a reel mower, however, the mulching action is intrinsic, and requires relatively little additional power. Compared to a rotary mower operating at 3,000+ rpm, the O-Sage® rotor has a speed of around 450 rpm, while the reel turns in the opposite direction at approximately 100 rpm. This minimizes the safety issues associated with rotary mowers (whether gas or electric).

Given the design concept of the O-Sage mower, it was anticipated that a practical version would use a small fraction of the energy consumed by a standard gas-powered mower, and therefore a battery-powered version could be produced that would be a viable option for yards as large as, or larger than, the average American lawn. This was the concept that the ICAT grant was intended to demonstrate in practice. Although initial tests had validated the energy-saving potential, rigorous comparison testing with regard to energy consumption had not yet been performed. And although a number of prototypes had been built and tested before the ICAT grant application was submitted, several operational drawbacks in these early prototypes were underappreciated at the time.

ICAT Project

The specific, concrete goals outlined in the ICAT grant application included: testing five prototype machines for at least 100 hours each in order to validate the mechanical design as being appropriate for a commercial product; evaluating the quality of the cut produced by the prototypes compared to rotary and reel mower alternatives; and rigorously examining the energy savings possible with the O-Sage cutting head in practice, compared to rotary mowers.

Fairly soon after grant approval, however, it became clear that a key mechanical design issue needed further refinement before a 'near commercial' prototype could be produced.

The cut quality of the early prototypes was remarkably good, and the first 20-inch-wide versions produced adequate performance under typical conditions with 250W and 350W, 24v motors. This gave a strong indication that the basic cutting head concept could deliver the expected energy efficiency. (A comparably-sized [19"] electric rotary mower uses a 1000W, 24v motor, and cutting performance is still challenged when mulching a heavy growth of grass.)

The mechanical issue that presented the main obstacle was related to the angle of the blades. In the pre-grant prototypes, this was a very shallow angle (relative to the tangent of the reel cylinder), so that the grass was cut with a pinching, scissors-like action between the blade and an edge machined into the inner surface of each reel bar.

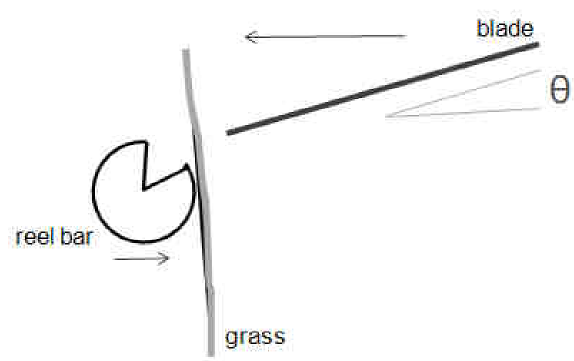

Figure 2

The difficulty was that, at such a low blade angle, a foreign object such as a large twig could deflect the blade edge downward into the reel bar, and the cutting head would become jammed. This was in spite of several design features that were implemented (and eventually patented) to minimize the tendency. Ultimately, it was decided that such fixes could not reliably overcome the problem, and a more radical response was needed.

A second series of prototypes was built and tested that put the blades at about 90 degrees to the tangent of reel cylinder.

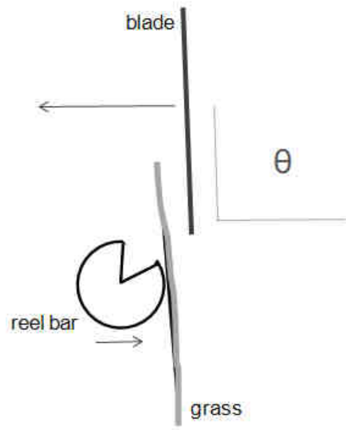

Figure 3

None of these prototypes ever jammed. However, the near-perpendicular angle caused the blades to flex to a much greater extent than they had at a shallow angle, and as a result there was an unacceptable degree of blade failure due to stress cracking. Here again, efforts were made to counteract the problem with various tweaks to the basic design, but none proved satisfactory.

As a result, a third series of prototypes was built around a modification in which the blade angle was increased further, so that the grass was cut between the trailing edge of the blade and the reel bar in a 'wiping' action.

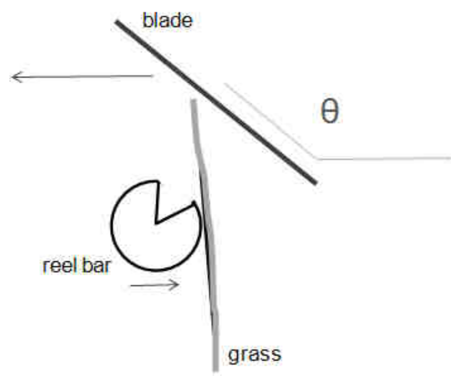

Figure 4

The prototypes built using this configuration experience much less blade flex, and significantly reduced blade breakage. This is the version that was tested under the ICAT grant. (All three general blade configurations are covered by patents.)

An additional complication that arose during prototype fabrication deserves mention. To maintain a sharp cutting edge, the reel bars must be hardened. Because the reel bars have a small diameter, relatively long length, and an asymmetric cross-section, it proved very difficult to heat treat the bars without inducing an unacceptable degree of warpage. The solution to this problem involved the development of a more controlled quenching system. This requirement added additional time to the overall prototype production schedule.

Due to these delays, in-use testing of two O-Sage mowers by lawn maintenance crews at the Chicago Botanic Garden had not completed by the end of the grant period. However, sufficient testing was done to indicate that the general design approach appears sound. The problems that have occurred to date generally appear to be related to a failure to maintain the required tolerances in the fabrication process, rather than as a result of a basic design flaw. The specific failure events that have occurred so far are shown in Diagram 1.

Diagram 1

The energy consumption testing has been more definitive. Three separate tests were done in which an O-Sage mower was compared to a similarly-sized rotary electric mower.

In the first very preliminary test, the O-Sage mower was tested against a pre-owned Ryobi 18" rotary electric mower set at the same cutting height of 1½ inches. In this test, the energy consumption of each mower was recorded after four laps across a 95' lawn. The results indicated the O-Sage mower consumed about 32% less energy than the Ryobi mower.

The second and third tests were performed using a new Black & Decker 19" rotary electric mower (model CMM1200). Both the O-Sage and B&D mowers were powered by 24v motors. The B&D mower had a new, sharp blade, and both mowers were fitted with identical power consumption meters. The lead acid batteries in each mower were new, and were charged with identical high-capacity chargers. The battery capacity of the B&D mower was 17 Ahr. (two 12v, 17 Ahr batteries connected in series), while the battery capacity of the O-Sage mower was 19 Ahr. (two sets of 12v 12 Ahr. and 7 Ahr. batteries connected in parallel, and then in series with each other). Since the cutting width of the rotary mower was 19", and the cutting width of the O-Sage mower was 21.5", the ratio of the battery capacity to the cutting width was thus nearly identical for both mowers. That is, the ratio of the capacity of the O-Sage mower's batteries to the capacity of the B&D mower's batteries was 1.12, while the ratio of the O-Sage cutting width to the B&D cutting width was 1.13. As a consequence, we compensated for the slightly wider cutting capacity of the O-Sage mower by providing that mower with a comparably increased battery capacity, so that the battery capacity per inch a cutting width was essentially identical for each mower.

For the second test, the cutting height of each mower was set at 1 3/8" for a relatively heavy cut, and each mower made six complete laps across a lawn with an average length of 88 feet, with each lap of the O-Sage mower interleaved with a lap of the B&D mower, for a total distance traveled of approximately 1,050 feet per mower. At the end of the test, the O-Sage mower had consumed 1.392 Ahr., and the B&D had consumed 2.234 Ahr. The difference of 0.842 Ahr. represents 38% less power consumed on the part of the O-Sage mower.

The third test was performed on an area the size of a football field, with grass varying in height from moderate to tall. The cutting height of both mowers was set at 2 inches. The operators pushed the mowers side-by-side across the length of the field (350') and back, starting and stopping the mowers at the same time at the end of each lap.

The third test consisted of 12 laps up and back across the field. Energy consumption (in Ahr.) was measured at the end of each 700' round-trip. Each mower always traversed only uncut grass – there was no overlap between mower paths. The total distance traveled by each mower was 8,400 feet.

At the start of the test, the voltage of the rotary mower's batteries measured 26.52, and the voltage of the O-Sage mower was 26.35. The test was concluded when the voltage of the rotary mower reached 23.68. At that time, the mowers had both traveled a total distance of 8,400 feet. The cumulative energy consumption at the end of each full lap is shown in the following table:

Lap #	O-Sage Ahrs.	B & D Ahrs.	O-Sage V	B & D V
0	0	0	26.35	26.52
1	0.681	1.097	25.9	25.92
2	1.303	2.014	25.72	25.66
3	1.969	2.922	25.61	25.49
4	2.62	3.795	25.38	25.17
5	3.253	4.593	25.17	24.96
6	3.905	5.413	24.98	24.78
7	4.52	6.184	24.87	24.64
8	5.128	6.937	24.8	24.43
9	5.759	7.709	24.71	24.25
10	6.383	8.462	24.62	24.1
11	6.999	9.196	24.52	23.88
12	7.633	9.954	24.45	23.68

Table 1

In chart form, this data clearly shows that the O-Sage mower had a significant energy consumption advantage compared to the rotary mower throughout the test. After the first lap, the O-Sage mower had used 37.9% less energy than the rotary mower. By the end of the test, the relative advantage was 23.3% (due, we believe, to the faster drop in the voltage of the rotary mower's batteries), while the absolute difference continued to increase.

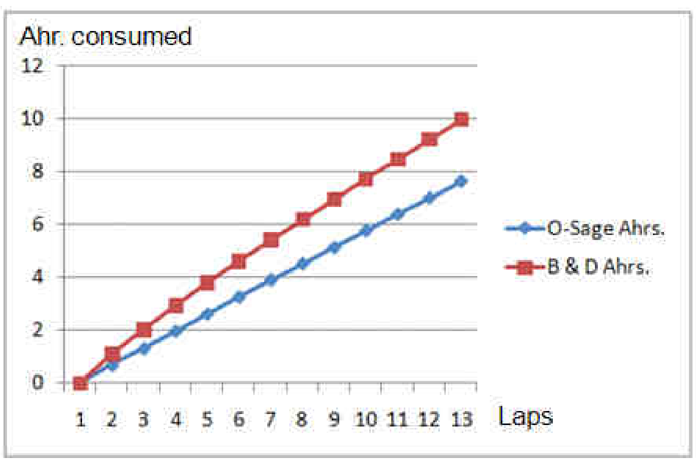

Chart 1

Based on this energy consumption advantage, it is clear that an O-Sage mower with an equivalent battery capacity is capable of cutting a substantially greater area than the rotary mower. By using the rule of thumb that cutting should stop when the voltage of the mower reaches 23.5 volts, Chart 2 shows the approximate additional number of laps that would be possible before the O-Sage mower reached that point. In-use tests at the Chicago Botanic Garden have shown that the O-Sage mower will, in fact, operate for almost 2 hours under similar cutting conditions.

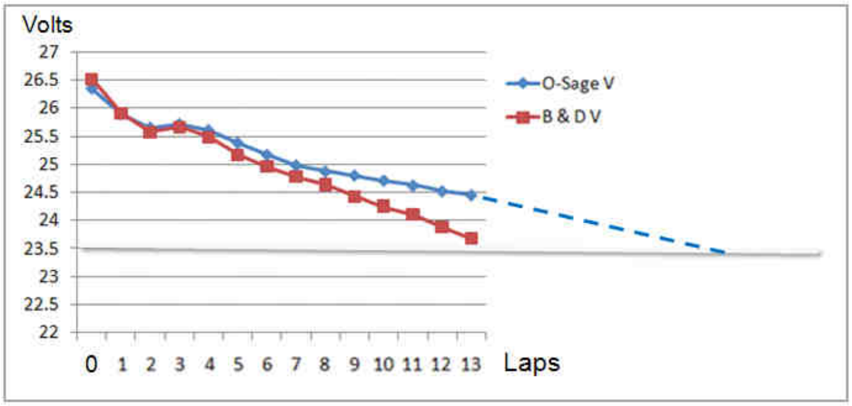

Chart 2

The main *strategic* intention behind the ICAT grant was to demonstrate the potential for the O-Sage design to reduce air pollution. Because the O-Sage prototypes have so far all been powered by electric motors, direct comparison to gas-powered rotary mowers has not yet been practical. A realistic calculation, however, can be based on the fact that 1hp is commonly understood to be the equivalent of 746 Watts.

In the side-by-side test described above, the instantaneous power consumption of the O-Sage mower varied between about 250W and 500W, depending on the height and thickness of the grass in any given spot. The instantaneous power consumption of the rotary mower varied between about 350W and 700W. A 3hp gas engine, by comparison, generates something like 2,100 Watts on a more-or-less continuous basis, and a 6.5hp engine generates about 4,500 Watts. Thus, the O-Sage mower would presumably consume, on average, about one-tenth the energy of a 6.5hp rotary gas mower to cut and mulch the same area of lawn.

Thus, the O-Sage design could play a significant role in reducing the overall amount of air pollution created by rotary mowers, as described at the beginning of this report. By improving the efficiency of the grass-cutting mechanism, O-Sage technology would qualify as an *emission-prevention technology* relative to *any* power mowers currently available (gas or electric).

Furthermore, by preferentially encouraging the use of electric mowers, O-Sage technology could increase the scope of emission-prevention relative to locally produced HC, NOx, and particulate emissions from gas mower engines. [The emission benefits of substituting an electric mower for a gas-powered mower have been thoroughly presented in the California ARB's *Report to the Board on the Potential Electrification Programs for Small Off-Road Engines* (4/2/04).]

There is another context in which the O-Sage mower can play a role in reducing air pollution. By providing a practical alternative to the collection of grass clippings as yard waste, O-Sage technology would contribute to the prevention of methane generation by the anaerobic fermentation of clippings in landfills and compost piles. Data regarding the proportion of methane produced in landfills due to the fermentation of yard wastes, and estimates of the methane produced by residential compost piles, is hard to find. It is worth noting, however, that landfills are by far the largest source of organic gas emissions in the state of California.[2]

[2] California ARB *Top 25 Emissions Report*, annual average 2004/2005.

The aggregate benefit achievable in actual practice in each of these three categories is, of course, dependant not only on the inherent efficiency advantages of the O-Sage technology, but on the likelihood that consumers and commercial users will embrace it. This question generally boils down to a cost / benefit analysis by the end-user.

There are no apparent intrinsic disadvantages to the O-Sage approach on the cost side of such an analysis. The construction of the cutting head is relatively straightforward. Mechanical tolerances are less critical than in conventional reel mowers. (The prototypes have so far been 'garage-built', and lacked the advantages, in terms of dimensional tolerance, of even standard manufacturing processes.) No exotic materials are required to make the device. Our retail price targets are on a par with currently available electric rotary mowers, and competitive with equivalently-featured gas-powered mowers.

The consumer benefits to be derived from a switch from rotary to O-Sage technology, even ignoring the potential emissions reductions, are substantial. These include; (1) a better safety profile, (2) a healthier, better-looking lawn, (3) lower operating costs, (4) easier blade maintenance, (5) better maneuverability, and (6) more compact storage.

Potential for Air Emissions Reduction in California

Assuming, then, that the product will be acceptable to the consumer from the overall cost/benefit perspective, estimates of the potential *aggregate air emission reductions* that would result from a switch from rotary mowers to O-Sage mowers *in the state of California* were made based on the referenced sources of information.

According to the ARB's *Report to the Board on the Potential Electrification Programs for Small Off-Road Engines*, *4/2/04*[3] there were approximately 4.8 million walk-behind residential lawn mowers in California as of the year 2000 (Figure 5, page 9). Of these, about 15% were electric mowers.

The US EPA currently hosts a website which calculates the net reduction of pollutants as a result of the substitution of electric mowers for gas mowers[4]. Using the number of gas mowers in use in California as estimated in the *Potential Electrification* report cited above (i.e., 4.8 million – 15% = 4.08 million gas mowers), and assuming that all such mowers were produced after 2000 and have 4-cycle, rather than 2-cycle engines (best case), and assuming each residential mower is used for approximately 50 hours per year (as was concluded by a survey performed for the Air Resources Board by the Eastern Research Group, Inc. in 2009[5]), the net reduction in air pollutants (exclusive of CO_2) predicted for the substitution of electric mowers for each *one percent* of the current installed base of gas mowers (i.e. per 40,800 mowers) is:

Potential Daily Emission Reductions from Removal of Gas-Powered Lawn Mowers from Service (tons/day)				
	HC	CO	NO_x	PM
2-stroke engines	0.000	0.000	0.000	0.000
4-stroke engines	0.015	0.554	0.005	0.005

Table 2 *HC = Hydrocarbons

[3] http://74.125.95.132/custom?q=cache:nHl5zNnvTjUJ:www.arb.ca.gov/msprog/offroad/sore/staff-report-electrification programs.doc+potential+electrification+program&cd=2&hl=en&ct=clnk&gl=us&client=google-coop-np
[4] http://www.epa.gov/air/community/mowerexchange_calculator.html
[5] http://www.arb.ca.gov/research/seminars/baker/baker.pdf See slide 28.

If 100% of gas rotary mowers were to be replaced by electric mowers over the course of time, the reduction in non-greenhouse gas emissions (from the calculated 2000 baseline) would therefore be:

Average Daily Emissions from Existing Lawn Mower Population (tons/day)				
	HC*	CO	NO_x	PM
2-stroke engines	0.000	0.000	0.000	0.000
4-stroke engines	1.482	55.411	0.470	0.452

Table 3

Thus, the total reduction of pollutants due to the replacement of 100% of gas-powered mowers in California with electric mowers would amount to approximately 21,000 tons per year.

The US EPA calculator does not include greenhouse gas emission calculations, and available data is very limited with regard to the generation of CO_2 by lawnmowers. However, studies in Australia indicate the ratio of CO emissions to CO_2 emissions is 1:1.82.[6] This is consistent with a rule of thumb that an average lawnmower generates approximately 54 pounds of hydrocarbon and carbon monoxide pollutants and 87 pounds of CO_2 every year. Based on this ratio, an installed base of 4.08 million gas mowers in California generates approximately 38,000 tons of CO_2 per year.

It is beyond the scope of this paper to attempt to determine the exact reduction of CO_2 levels achievable by 100% of electric mowers for gas-powered mowers, since it would also need to take into account estimates of electric power plant and transmission line efficiencies. However, based purely on power level comparisons *at the mower* (i.e., 250 to 500 Watts compared to 2,100 Watts), it does not seem unreasonable to suspect that greenhouse gas emissions related to lawn mowing could potentially be reduced by up to two-thirds by such a switch.

Nationwide, the scope for reducing air emissions by switching to energy-efficient electric lawnmowers is disproportionately large, since California already leads the country in the use of rotary electric mowers. Almost 6 million new lawnmowers are sold in the US every year.

The follow-on question, of course, is how quickly such a transition would be accomplished.

Estimates of the average life of a residential lawnmower are in the range of six to twelve years.[7] Our product development philosophy has always been that the O-Sage mower must be competitive in every important characteristic with the current technology, and in addition must deliver an environmental benefit. That is, we believe the majority of consumers will not make significant sacrifices in terms of convenience, cut quality, or economy-of-use in order to purchase a product with a superior environmental profile.

It's also very clear, however, that consumers have become much more concerned about environmental issues in general, and climate change in particular, in the five years since this project began. So while we still do not believe the majority of consumers will switch to a new product unless it delivers comparable convenience, cut quality, or economy, we feel that as long as the O-Sage mower is at least as good a the incumbents in these areas, the environmental benefits, including a significant reduction in the operator's exposure to air pollutants, have become an increasingly positive purchasing motive. As it happens, in fact, we feel the current O-Sage design delivers distinct advantages in the areas of convenience (compared to gas-powered

[6] *Emissions from in-use lawn-mowers in Australia*, Priest, M.W.; Williams, D.J.; Bridgman, H.A., *Atmospheric Environment* v34 n4 2000 Elsevier Science Ltd Exeter Engl p 657-664 1352-2310[7]

mowers), cut quality (compared to rotary mowers in terms of damage to the grass, and to reel mowers in terms of mulching), economy of use (compared especially to rotary gas mowers, but also to rotary electrics), and safety.

Status of Technology

Reliability testing will be completed by the Chicago Botanic Garden in the spring of 2010.

The O-Sage mower business plan is being updated to include the results of the tests performed under the ICAT grant. We plan to circulate the business plan to potential partners and investors in the next several months.

Given a favorable response to the business plan, we would anticipate being able to introduce a commercial product within two years.