INSECT REPELLENT DESIGN: RESEARCHING ALTERNATIVES TO DEET

Submitted to:
Dr. Miguel Bagajewicz
School of Chemical, Biological, and Materials Engineering

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Erin Ashley
Scott Doman

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EXECUTIVE SUMMARY

This report summarizes the investigation of developing a new insect repellent that would be more effective, safer, and less expensive than the current market leader, a DEET-based repellent. However, after discovering that the relationship between repellent molecules' physical properties and their repelling abilities is poorly understood, another objective was pursued. The new aim was to develop a new product from an existing repellent. It was decided that the new repellent would contain Picaridin, a repellent that is new to the US market that has been shown to be just as effective as DEET, but less toxic and more pleasant for consumers to use.

To develop this new product, a utility function was created to measure the wants and needs of repellent consumers. Six important characteristics of a repellent were chosen: effectiveness, durability, feel, form, scent, and toxicity. Four ingredients were chosen to contribute to these characteristics: Picaridin, ethanol, aloe, and fragrance. A utility level for each of these characteristics was related to a physical property of the repellent formula using simple tests that a consumer could perform. These utilities were then combined in a weighted average, where each characteristic was weight-based to consumer preferences gathered in marketing surveys.

The resulting utility function was used in conjunction with a demand model derived from consumer choice theory that compares any proposed repellent formula's utility with a competing product's utility. Processing costs, shipping costs, raw material costs, and advertising costs were also included in the model for optimization.

When utility was maximized, the model suggested a product that was 98% Picaridin and 2% ethanol. The optimum situation when this product was placed in competition with the specialty repellent 'Deep Woods OFF! for Sportsmen' was shown to produce a net income of $310,000 producing 125,000 pounds per year to be sold at $80 per pound retail. However, this product showed a high likelihood of being unprofitable, so a different approach was investigated.

When the model was set up to find a product that could compete with a broader range of products, the most profitable formula was 43% Picaridin, 55% ethanol, and 1% each of aloe and fragrance. When 5 million pounds per year are sold at $28 per pound retail, the net income would be $2.55 million per year. This product had the potential of making a lot more money than the first product, but it showed even more risk of being unprofitable at this price. Further market research is needed to investigate whether consumers would be willing to buy this product at more than $28 per pound, which is uncertain at this time. If this product could be sold at a higher price, it would definitely be the more profitable option and should be pursued.

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INTRODUCTION

History

Insect repellents have been used for a considerable length of time in recorded history. Ancient man used naturally occurring compounds, such as tar, plant oils or even smoke to dispel or kill bothersome insects. Industrial advances eventually allowed for production of synthetic or engineered repellents, with Indalone® being patented in 1937. For almost twenty years, the US military relied on this and other repellents like Rutgers 612 and dimethyl phthalate for protecting soldiers in the field. After testing more than 20,000 substances as repellents, DEET (N,N-diethyl-*m*-toluamide) was introduced into military usage and quickly spread into the marketplace as an effective, moderately safe insect repellent.[1]

There has been little change in the repellent market since that time. General consumer pressures have led manufacturers to seek more 'earth-friendly' repellents, derived from plant oils and other organic sources. As this study has commenced, researchers have also sought repellents that are safer than DEET.

In limited instances, DEET has been related to encephalopathy and seizures in children, as well as other less serious side effects such as skin irritation.[2] DEET melts plastic and has an unpleasant odor that is hard to cover up.[3] Manufacturers and consumers would readily accept a repellent that has similar repellent abilities as DEET in similar concentrations without the adverse effects.

One such repellent that has been developed is Picaridin, also known as KBR 3023, or Bayrepel. Developed in the 1980's by Bayer AG and introduced in the European market in 1998, Picaridin has been shown to be just as effective as DEET, but with no scent, a light, non-sticky feel and no corrosive properties. It is now one of the best-selling repellents in Europe and Asia and has recently been added to the list of recommended

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[1] Coats and Peterson, "Insect Repellents—Past, Present and Future," 154.
[2] http://pmep.cce.cornell.edu/profiles/extoxnet/carbaryl-dicrotophos/deet-ext.html
[3] http://www.deet.com/astmh99/Barnard%20Slides/Barnards%20Page.htm

repellents by the Center for Disease Control (CDC) and the World Health Organization (WHO).[4]

Objective

Picaridin has been introduced in the U.S. as the active ingredient in one product, Cutter Advanced®, at 7% concentration. Repellents containing DEET as the active ingredient exist at up to a 100% DEET formula. The goal of this research project was to create a new Picaridin-based repellent to satisfy the demands of the market more effectively than Cutter Advanced®. This product was optimized according to specific required properties of a repellent and consumers' tastes. A production process was designed and an economic analysis of this process was performed to maximize profit.

BACKGROUND

This section contains the results of research related to the mechanism of insect repellents and their interaction with insects' sensory systems. This research was originally performed in the hopes that a new repellent molecule could be developed based on this interaction. However, current research suggests that this is not possible with the resources available to us.

The Repellent Function

The Insect Sensory System

Insects respond to stimuli in their environment by way of receptors—tiny hair-like structures covering their bodies. There are many different types of receptors, each responding to specific stimuli. Each is a simpler version of receptors found in vertebrates. Thermoreceptors respond to temperature changes. Mechanoreceptors respond to physical movement and include tactile (touch) and sound structures. Photoreceptors respond to changes in light intensity.[5]

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[4] http://picaridin.com.
[5] http://www.cals.ncsu.edu/course/ent425/tutorial/senses.html.

The receptors most relevant to repellent research are chemoreceptors. These receptors respond to the presence of chemicals in the air. Included in the chemoreceptor category are gustatory, or taste, receptors and olfactory, or smell, receptors. Gustatory chemoreceptors are located on an insect's mouth and feet. Olfactory chemoreceptors are located on the antennae.[6] A magnified photograph of these receptors is shown below.

Figure 1: Olfactory chemoreceptors on an insect's antenna[7]

Several types of olfactory receptor cells have been identified. Broad generalists are those cells that respond to a variety of chemicals, while narrow specialists respond to only one chemical, such as a species-specific sex pheromone. Other cells fall between these extremes and respond to families of chemicals, such as alcohols or the smells of fruits.[8]

The Insect-Human Interaction

The first sign of human presence that an insect detects is motion. An insect's photoreceptors respond to a change in light and send a signal to the insect's brain, causing a change in direction toward the source of the change. As an insect gets closer to the potential meal, its chemoreceptors come into play. Humans give off carbon dioxide

[6] Delcomyn, Fred, "Foundations of Neurobiology," 310-316.
[7] http://insectscience.org/3.2/ref/figure5.html.
[8] Delcomyn, Fred, "Foundations of Neurobiology," 329.

and lactic acid from their breath and skin that serve as attractants to insects. At very close ranges, a human's body heat triggers the insect's thermoreceptors. The insect has then found its meal.[9]

Olfactory Chemoreceptor Mechanism

Because insects, and especially mosquitoes, are such small and delicate animals, it is very difficult to perform research on them. As a result, there are a few theories regarding the mechanism of olfaction, none of which is supported with solid data.[10]

The structure of an insect olfactory receptor is shown in Figure 2 below. The generally accepted theory is that when a molecule of an attractant chemical comes within range of the insect, it enters the pore and contacts a sensillar liquor, an ionic liquid surrounding a cluster of sensory neurons.[11]

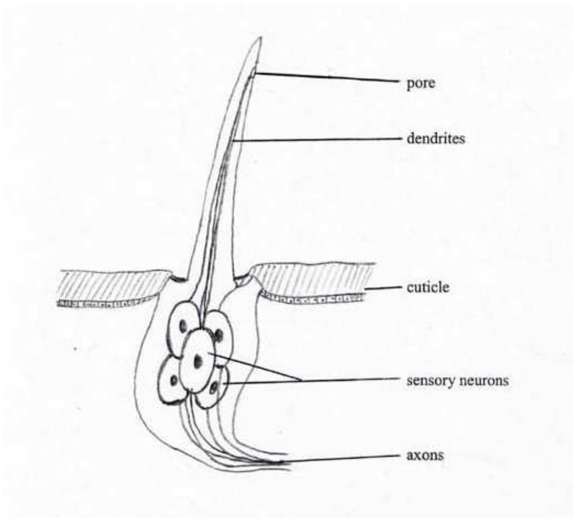

Figure 2: An insect chemoreceptor[12]

This is where the theories diverge. One theory is that the molecule reacts with proteins suspended in the sensillar liquor, which creates an ionic current sending a signal to the insect's brain. Another is that the molecule binds directly with proteins embedded in the neural cell membrane. This binding initiates a reaction that opens sodium channels in the

[9] Fradin, Mark, "Mosquitoes and Mosquito Repellents: A Clinician's Guide," 2-3.
[10] Gaffin, Douglas, Interview.
[11] *Ibid.*
[12] www.bioweb.uncc.edu/BIOL3235/Handouts%20for%20webpage/tarsal%20chemo%20chordonotal.jpg.

membrane, allowing sodium ions to flow into the cell. This causes an ionic current that sends a signal down the cell's axon to the brain.[13] See Figure 3 for a drawing of a neural cell membrane.

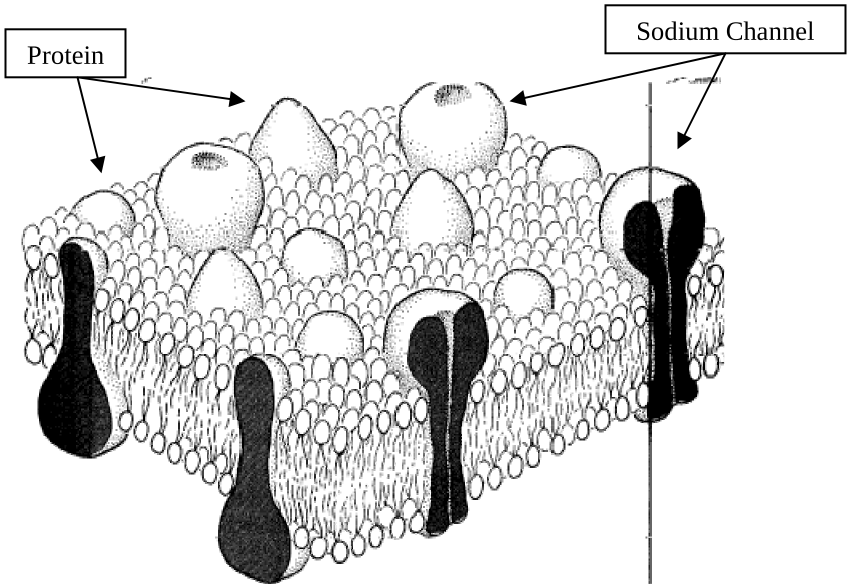

Figure 3: Close-up view of an insect's neural cell membrane.[14]

Chemoreceptor-Repellent Interactions

If a new repellent molecule were to be designed, it would be crucial to know the mechanism of an insect chemoreceptor's reaction to a repellent. This information would be linked to specific properties of a repellent, so a new repellent could be designed with the necessary properties.

Based on the mechanism used by a chemoreceptor when an attractant is nearby, one might think that repellents would work in a similar manner. The molecule would enter the receptor pore, causing some sort of signal to travel to the brain and instruct the insect to move away from the area. Unfortunately, little is known about how repellent molecules specifically interact with the olfactory chemoreceptors in insects.[15]

[13] Gaffin, Douglas, Interview.
[14] http://www.pneuro.com/publications/insidetheneuron/01_part2.html.
[15] http://www.annals.org/cgi/content/full/128/11/931.

DEET, the most common repellent, is thought to block chemoreceptors from receiving carbon dioxide or lactic acid molecules from humans, either physically lodging in the pores of the receptors, or somehow jamming the signals sent from the receptor cells to the brain. Specific receptor mechanisms in the presence of repellents are, however, largely unknown.[16]

The relationships of repellent properties and repellent activity are also largely unknown. According to Dr. Joel Coats of Iowa State University, "Structure-activity relationships of repellents are unclear, and little definitive work has been done…Vapor pressure is the only parameter significantly related to mosquito repellent activity. Partition coefficient, molecular weight, infrared absorption, viscosity, surface tension, molecular polarizability, and Hammett substituent constants have all failed to be correlated to repellent activity."[17]

The Modified Goal

Since the chemoreceptor-repellent interaction is not understood, and repellent activity cannot be linked to any specific repellent physical property, the goal of designing a new repellent was discarded. Instead, an existing repellent molecule was studied, and a new repellent formula was created and optimized with this molecule as the active ingredient.

The repellent chosen for this new formula is Picaridin. It is widely used in Europe and Asia[18] and has been introduced in the U.S. in the product Cutter® Advanced at 7% concentration.[19] Picaridin has been shown to be as effective as, but safer than DEET at equal concentrations,[20] and it was recently recommended by the Center of Disease Control as an effective and safe repellent.[21]

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[16] Davis, Edward E., "Insect Repellents: Concepts…," 237.
[17] Coats, Joel, *et. al*., "Insect Repellents-Past, Present, and Future," 156.
[18] www.picaridin.com.
[19] http://cutterinsectrepellent.com/ProductCategories/PersonalRepellents/Advanced/.
[20] www.picaridin.com
[21] http://cutterinsectrepellent.com/ProductCategories/PersonalRepellents/Advanced/.

DEMAND MODEL

In evaluating Picaridin as a product, economics, product utility and market conditions needed to be analyzed further. The methods used and a summary of results are detailed below.

Economic Formulas

Consumer choice theory in microeconomics teaches that consumers seek to be happy by purchasing goods. Unfortunately for them, they only have limited resources to obtain this happiness. At the same time, firms want to maximize their profit with the goods they sell. If they charge too much, consumers cannot afford it; if they undercharge, they lose potential profits. Consumers want to be as happy as possible for as little money as possible. This balance between available resources and consumer wants is known as the basic economic problem.

There are equations that can describe this somewhat complex relationship between product pricing, demand, budget constraints and consumer utility (i.e., consumer happiness or satisfaction). The first equation is $P_1D_1 + P_2D_2 \leq Y$ (Equ. 1), where P is price, D is demand, Y is the consumer budget constraint, and 1 and 2 refer to different products. Multiplying price and demand gives the total amount of money spent on any one product. Because the consumer only has a limited amount of money to spend, the sum of all that they spend must be less than or equal to their budget constraint.

In addition to an overall budget constraint, there are also product-specific budget constraints. For example, a person may have $1000 of discretionary income in a month, but they will not spend all of that on video games if there are other products that also bring him or her satisfaction. Thus, there is a video game-specific budget constraint. A similar constraint applies to insect repellents; it can be projected from the size of the total market, which is estimated at $200 million per year.[22]

[22] http://www.bizjournals.com/twincities/stories/2003/05/26/story5.html.

There is another equation that describes the criteria consumers use to evaluate what they will purchase with their limited funds: $\beta P_1 D_1 = \alpha P_2 D_2 D_1^{\alpha} / D_2^{\beta}$ (Equ. 2), where β is the relative consumer utility and α is the relative consumer awareness. If $\beta < 1$, then product 1 is more desirable to the consumer than product 2. If $\alpha < 1$, this means that the consumer knows more about product 2 than product 1. This is important because consumers will not buy products they do not know about. If either of these parameters equals one, then the two products are the same in that respect. Once these parameters and the competition are understood, the resulting demand for any product price can be determined.

The challenge became developing models to establish utility relationships for our product and the consumer. After that, the above equations were used to optimize the price and demand for profit in regards our product.

The Utility Function

A function must be devised that describes how desirable consumers find any particular product. Consumers must maximize this satisfaction, or 'utility,' without exceeding any budget constraints. This utility function can then be used to compare the desirability of products and help to explain consumer purchasing behavior.

In order to create a product that maximizes the happiness available to the consumer, utility levels need to be assigned to various characteristics of our product. This is most easily accomplished by developing relationships between physical properties and the resulting consumer utility.

The consumer is not expected to understand the physical chemistry or mass transfer/diffusive behavior, etc. of our product so intermediate steps are needed to develop the final utility relationships. A simple, qualitative test that can be performed by any consumer without a scientific background is devised to relate the utility associated with the full range of each qualitative product trait.

For the repellent, the following traits were deemed important to the consumer: durability, effectiveness, feel, form, toxicity and scent. For each trait, a consumer test is devised and that data is connected to a related physical property. This results in a single correlation between the physical property and the consumer utility.

The active ingredient was already chosen as Picaridin. It is just as effective as DEET, the most popular repellent on the market, but it does not have any of the adverse properties that DEET possesses: it will not damage synthetic materials[23], and it is odorless.

However, Picaridin is quite expensive, so adding a solvent to the formula would decrease product cost. Picaridin is virtually insoluble in water, so ethanol was chosen as the solvent. Ethanol, or ethyl alcohol, is commonly used as a solvent in other insect repellents.

A repellent's aesthetic properties were also taken into account. It was decided to add fragrance to the formulation to provide a pleasing scent and aloe to improve the texture or feel of the repellent.

The properties of each component contribute to each characteristic in varying degrees. One of the purposes of the utility function is to determine the extent of that contribution to consumer satisfaction.

Effectiveness

The first step in defining the utility of repellent effectiveness was relating utility to some kind of experiment evaluating effectiveness. A common experiment performed on repellents is the "mosquitoes in a box" test. In this test, a known mosquito population is placed inside a long rectangular box. One side of the box is treated with the repellent of interest and the other side of the box is left untreated. At the end of a certain amount of time, the number of mosquitoes on the repellent side of the box is counted. Fifty percent of the mosquito population on the repellent side would prove the repellent was ineffective

[23] www.picaridin.com/advantages.htm.

and would correspond to a utility of zero. Zero mosquitoes on the repellent side would prove the repellent was completely effective and would correspond to a utility of 100. The exponential relationship shown in Figure 4 was the best fit for the behavior of this utility.

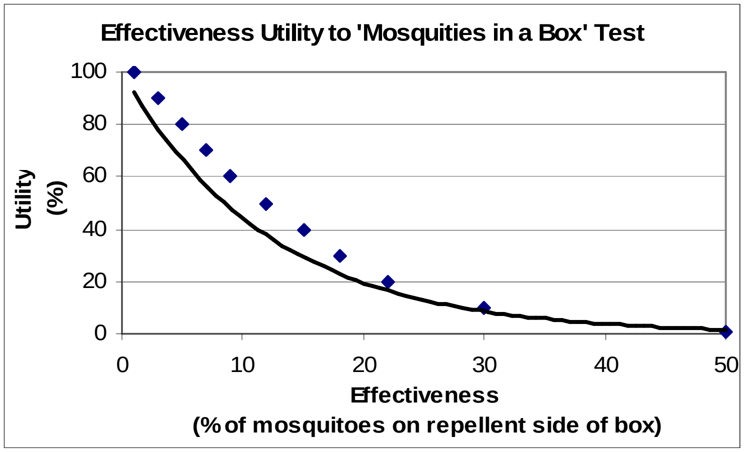


Figure 4: Utility relating to repellent effectiveness test

Next, this repellent effectiveness test needed to be related to a physical property of the repellent formula. Effectiveness was determined to be tied only to the amount of the active ingredient in the formula. This was also best described by an exponential relationship and is shown in Figure 5.

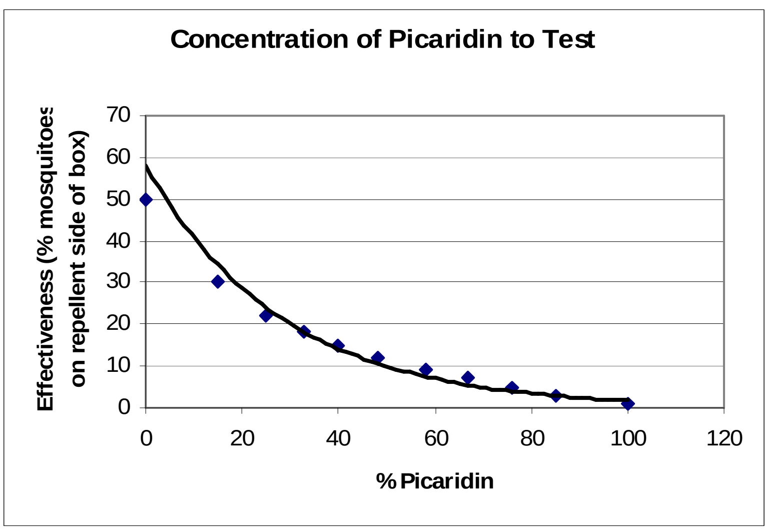


Figure 5: Effectiveness test relating to the volume fraction of Picaridin

The data from these two graphs were combined to find the relationship between utility and the amount of Picaridin in the product. After doing this, the trend is best represented with a linear relationship. This is shown in Figure 6. This relationship was used in the formula optimization.

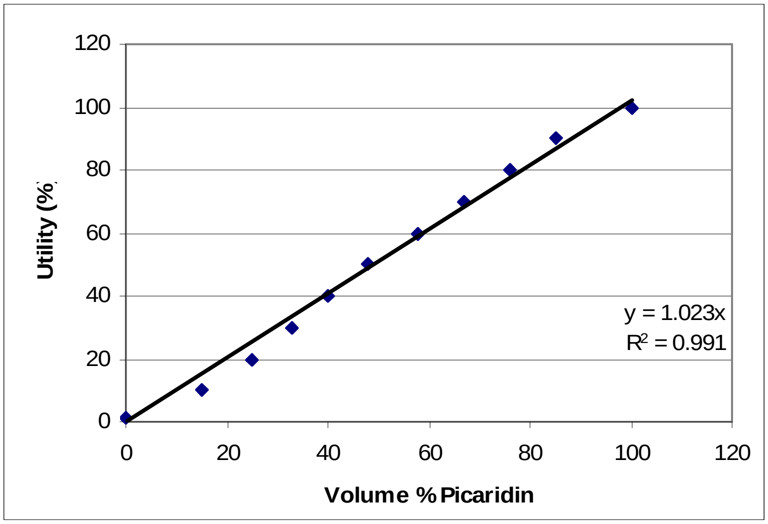


Figure 6: Effectiveness utility related to the volume fraction of Picaridin

Durability

Durability, or the length of time that one dose of repellent remains effective, is obviously a very important aspect of a repellent. Once again, the first step in relating durability's utility to a physical property of the repellent was to relate it to a consumer-measured value. This value was an easy choice: time. It was determined that a great repellent, one that would have a utility of 100%, would last all day, or 12 hours, and would be best explained with a linear relationship. This is shown in Figure 7.

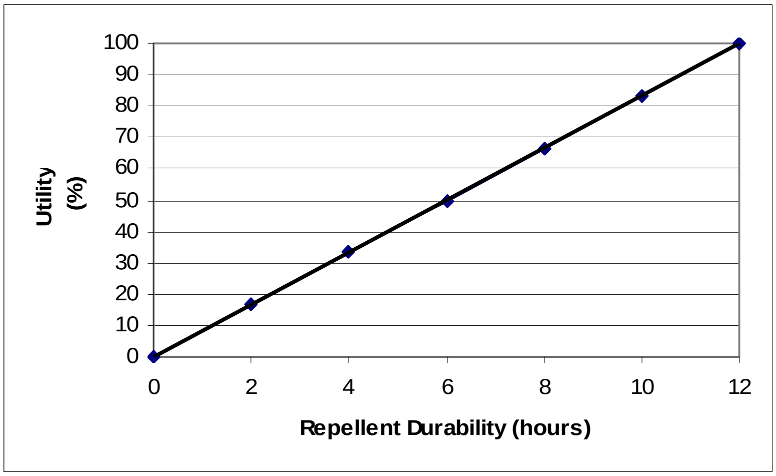


Figure 7: Utility related to repellent durability in hours

Next, repellent durability needed to be related to some physical property of the repellent. The length of time that one dose of repellent would take to evaporate is believed to be controlled by diffusion of the repellent from the boundary layer above the skin into the air. This is represented by Fick's second law of mass transfer[24]:

$$\frac{\partial c_A}{\partial t} = D_{AB} \frac{\partial^2 c_A}{\partial z^2} \qquad \textbf{Equation 3}$$

where c_A = concentration of component A

D_{AB} = diffusion coefficient of component A

t = time

z = distance from skin.

When this differential equation is solved, it yields the solution

$$c_A = c_{As} - (c_{As} - c_{Ao}) erf\left(\frac{z}{2\sqrt{D_{AB}t}}\right) \qquad \textbf{Equation 4}$$

When an approximation of the error function is substituted, the following equation is formed:

[24] Welty, et. al., "Fundamentals of Momentum, Heat, and Mass Transfer," 513.

$$c_A = c_{As} - (c_{As} - c_{Ao})\left(1 - \frac{1}{\sqrt{\pi}} e^{-\left(\frac{z}{2\sqrt{D_{AB}t}}\right)^2}\right)$$ **Equation 5**

Taking the second derivative of this equation with respect to z, the following expression is found:

$$\frac{\partial^2 c_A}{\partial z^2} = \frac{c_{As} \cdot e^{\frac{-z}{2\sqrt{D_{AB}t}}}}{4D_{AB}t\sqrt{\pi}}$$ **Equation 6**

Plugging this equation into Equation 3, the concentration with respect to time can be determined and solved numerically:

$$\frac{\partial c_A}{\partial t} = \frac{c_{As} \cdot e^{\frac{-z}{2\sqrt{D_{AB}t}}}}{4t\sqrt{\pi}}$$ **Equation 7**

C_{As}, or the surface concentration of the component, is calculated using Raoult's Law[25]:

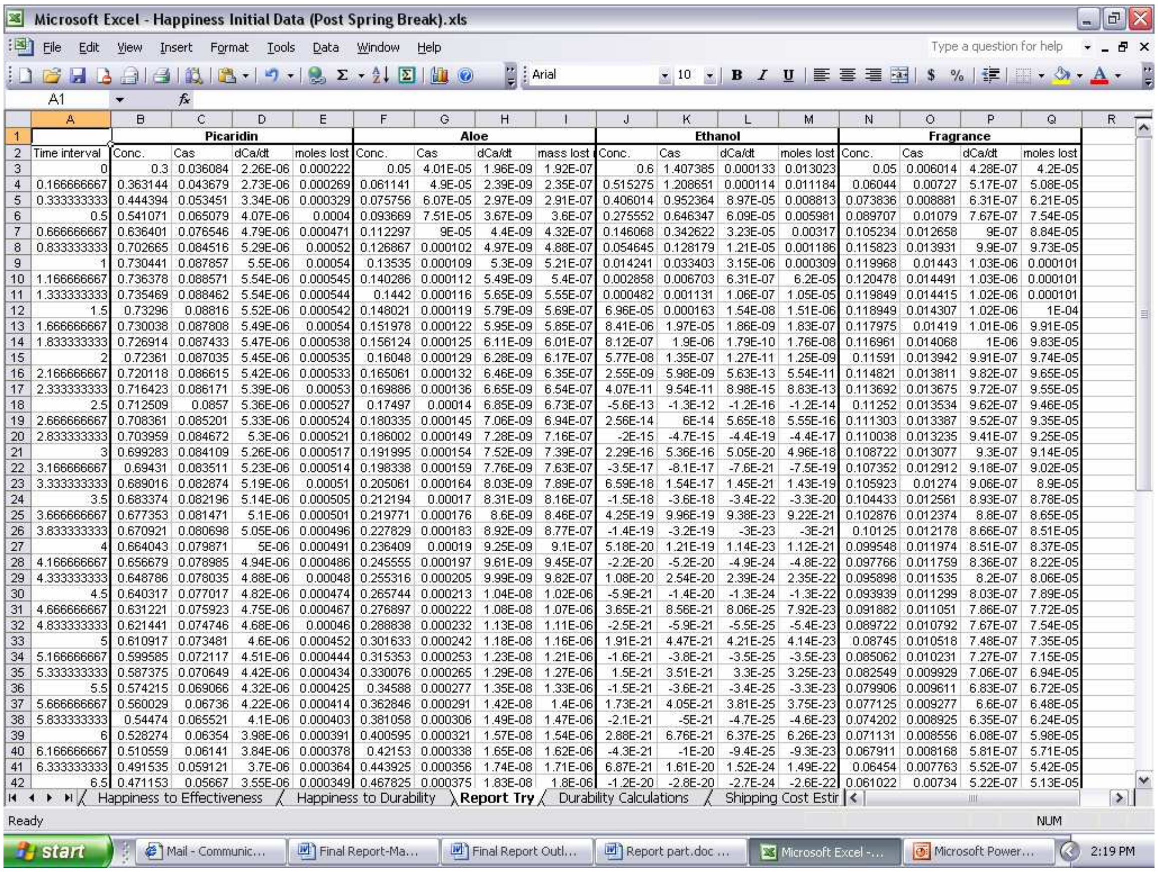
$$C_{As} = \frac{p_A}{RT} = \frac{x_A(VP)}{RT}$$ **Equation 8**

Raoult's Law is more accurate for liquid mole fractions close to one, while the mole fractions of these components are most likely smaller. Henry's Law, which is more accurate for small mole fractions, would be a better approximation, but, unfortunately, Henry's Law constants could not be found for all ingredients.

The iterative procedure begins by setting the time interval at 10 minutes, the distance of interest at 0.3 meters and setting the initial liquid concentrations of each component. The surface concentrations are then calculated, and the concentrations at 0.3 m are calculated using the differential equation for the first time interval. From these concentrations, the amount of moles of each component lost from the skin can be determined, and new surface concentrations can be calculated. The differential equation is then used again for

[25] Welty, et. al., "Fundamentals of Momentum, Heat, and Mass Transfer," 631.

the next time interval with the new surface concentrations, and the process repeats itself. Once the concentration of Picaridin at 0.3 m fell below a threshold of 0.05 mol/m^3, the calculations were stopped and the total time recorded. The entire procedure was then repeated for differing initial concentrations. The Excel spreadsheet used to do these calculations is shown in Figure 8.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1		Picaridin				Aloe				Ethanol				Fragrance			
2	Time interval	Conc.	Cas	dCa/dt	moles lost	Conc.	Cas	dCa/dt	mass lost	Conc.	Cas	dCa/dt	moles lost	Conc.	Cas	dCa/dt	moles lost
3	0	0.3	0.036084	2.26E-06	0.000222	0.05	4.01E-05	1.96E-09	1.92E-07	0.6	1.407385	0.000133	0.013023	0.05	0.006014	4.28E-07	4.2E-05
4	0.166666667	0.363144	0.043679	2.73E-06	0.000269	0.061141	4.9E-05	2.39E-09	2.35E-07	0.515275	1.208651	0.000114	0.011184	0.06044	0.00727	5.17E-07	5.08E-05
5	0.333333333	0.444394	0.053451	3.34E-06	0.000329	0.075756	6.07E-05	2.97E-09	2.91E-07	0.406014	0.952364	8.97E-05	0.008813	0.073836	0.008881	6.31E-07	6.21E-05
6	0.5	0.541071	0.065079	4.07E-06	0.0004	0.093669	7.51E-05	3.67E-09	3.6E-07	0.275552	0.646347	6.09E-05	0.005981	0.089707	0.01079	7.67E-07	7.54E-05
7	0.666666667	0.636401	0.076546	4.79E-06	0.000471	0.112297	9E-05	4.4E-09	4.32E-07	0.146068	0.342622	3.23E-05	0.00317	0.105234	0.012658	9E-07	8.84E-05
8	0.833333333	0.702665	0.084516	5.29E-06	0.00052	0.126867	0.000102	4.97E-09	4.88E-07	0.054645	0.128179	1.21E-05	0.001186	0.115823	0.013931	9.9E-07	9.73E-05
9	1	0.730441	0.087857	5.5E-06	0.00054	0.13535	0.000109	5.3E-09	5.21E-07	0.014241	0.033403	3.15E-06	0.000309	0.119968	0.01443	1.03E-06	0.000101
10	1.166666667	0.736378	0.088571	5.54E-06	0.000545	0.140286	0.000112	5.49E-09	5.4E-07	0.002858	0.006703	6.31E-07	6.2E-05	0.120478	0.014491	1.03E-06	0.000101
11	1.333333333	0.735469	0.088462	5.54E-06	0.000544	0.1442	0.000116	5.65E-09	5.55E-07	0.000482	0.001131	1.06E-07	1.05E-05	0.119849	0.014415	1.02E-06	0.000101
12	1.5	0.73296	0.08816	5.52E-06	0.000542	0.148021	0.000119	5.79E-09	5.69E-07	6.96E-05	0.000163	1.54E-08	1.51E-06	0.118949	0.014307	1.02E-06	1E-04
13	1.666666667	0.730038	0.087808	5.49E-06	0.00054	0.151978	0.000122	5.95E-09	5.85E-07	8.41E-06	1.97E-05	1.86E-09	1.83E-07	0.117975	0.01419	1.01E-06	9.91E-05
14	1.833333333	0.726914	0.087433	5.47E-06	0.000538	0.156124	0.000125	6.11E-09	6.01E-07	8.12E-07	1.9E-06	1.79E-10	1.76E-08	0.116961	0.014068	1E-06	9.83E-05
15	2	0.72361	0.087035	5.45E-06	0.000535	0.16048	0.000129	6.28E-09	6.17E-07	5.77E-08	1.35E-07	1.27E-11	1.25E-09	0.11591	0.013942	9.91E-07	9.74E-05
16	2.166666667	0.720118	0.086615	5.42E-06	0.000533	0.165061	0.000132	6.46E-09	6.35E-07	2.55E-09	5.98E-09	5.63E-13	5.54E-11	0.114821	0.013811	9.82E-07	9.65E-05
17	2.333333333	0.716423	0.086171	5.39E-06	0.00053	0.169886	0.000136	6.65E-09	6.54E-07	4.07E-11	9.54E-11	8.98E-15	8.83E-13	0.113692	0.013675	9.72E-07	9.55E-05
18	2.5	0.712509	0.0857	5.36E-06	0.000527	0.17497	0.00014	6.85E-09	6.73E-07	-5.6E-13	-1.3E-12	-1.2E-16	-1.2E-14	0.11252	0.013534	9.62E-07	9.46E-05
19	2.666666667	0.708361	0.085201	5.33E-06	0.000524	0.180335	0.000145	7.06E-09	6.94E-07	2.56E-14	6E-14	5.65E-18	5.55E-16	0.111303	0.013387	9.52E-07	9.35E-05
20	2.833333333	0.703959	0.084672	5.3E-06	0.000521	0.186002	0.000149	7.28E-09	7.16E-07	-2E-15	-4.7E-15	-4.4E-19	-4.4E-17	0.110038	0.013235	9.41E-07	9.25E-05
21	3	0.699283	0.084109	5.26E-06	0.000517	0.191995	0.000154	7.52E-09	7.39E-07	2.29E-16	5.36E-16	5.05E-20	4.96E-18	0.108722	0.013077	9.3E-07	9.14E-05
22	3.166666667	0.69431	0.083511	5.23E-06	0.000514	0.198338	0.000159	7.76E-09	7.63E-07	-3.5E-17	-8.1E-17	-7.6E-21	-7.5E-19	0.107352	0.012912	9.18E-07	9.02E-05
23	3.333333333	0.689016	0.082874	5.19E-06	0.00051	0.205061	0.000164	8.03E-09	7.89E-07	6.59E-18	1.54E-17	1.45E-21	1.43E-19	0.105923	0.01274	9.06E-07	8.9E-05
24	3.5	0.683374	0.082196	5.14E-06	0.000505	0.212194	0.00017	8.31E-09	8.16E-07	-1.5E-18	-3.6E-18	-3.4E-22	-3.3E-20	0.104433	0.012561	8.93E-07	8.78E-05
25	3.666666667	0.677353	0.081471	5.1E-06	0.000501	0.219771	0.000176	8.6E-09	8.46E-07	4.25E-19	9.96E-19	9.38E-23	9.22E-21	0.102876	0.012374	8.8E-07	8.65E-05
26	3.833333333	0.670921	0.080698	5.05E-06	0.000496	0.227829	0.000183	8.92E-09	8.77E-07	-1.4E-19	-3.2E-19	-3E-23	-3E-21	0.10125	0.012178	8.66E-07	8.51E-05
27	4	0.664043	0.079871	5E-06	0.000491	0.236409	0.00019	9.25E-09	9.1E-07	5.18E-20	1.21E-19	1.14E-23	1.12E-21	0.099548	0.011974	8.51E-07	8.37E-05
28	4.166666667	0.656679	0.078985	4.94E-06	0.000486	0.245555	0.000197	9.61E-09	9.45E-07	-2.2E-20	-5.2E-20	-4.9E-24	-4.8E-22	0.097766	0.011759	8.36E-07	8.22E-05
29	4.333333333	0.648786	0.078035	4.88E-06	0.00048	0.255316	0.000205	9.99E-09	9.82E-07	1.08E-20	2.54E-20	2.39E-24	2.35E-22	0.095898	0.011535	8.2E-07	8.06E-05
30	4.5	0.640317	0.077017	4.82E-06	0.000474	0.265744	0.000213	1.04E-08	1.02E-06	-5.9E-21	-1.4E-20	-1.3E-24	-1.3E-22	0.093939	0.011299	8.03E-07	7.89E-05
31	4.666666667	0.631221	0.075923	4.75E-06	0.000467	0.276897	0.000222	1.08E-08	1.07E-06	3.65E-21	8.56E-21	8.06E-25	7.92E-23	0.091882	0.011051	7.86E-07	7.72E-05
32	4.833333333	0.621441	0.074746	4.68E-06	0.00046	0.288838	0.000232	1.13E-08	1.11E-06	-2.5E-21	-5.9E-21	-5.5E-25	-5.4E-23	0.089722	0.010792	7.67E-07	7.54E-05
33	5	0.610917	0.073481	4.6E-06	0.000452	0.301633	0.000242	1.18E-08	1.16E-06	1.91E-21	4.47E-21	4.21E-25	4.14E-23	0.08745	0.010518	7.48E-07	7.35E-05
34	5.166666667	0.599585	0.072117	4.51E-06	0.000444	0.315353	0.000253	1.23E-08	1.21E-06	-1.6E-21	-3.8E-21	-3.5E-25	-3.5E-23	0.085062	0.010231	7.27E-07	7.15E-05
35	5.333333333	0.587375	0.070649	4.42E-06	0.000434	0.330076	0.000265	1.29E-08	1.27E-06	1.5E-21	3.51E-21	3.3E-25	3.25E-23	0.082549	0.009929	7.06E-07	6.94E-05
36	5.5	0.574215	0.069066	4.32E-06	0.000425	0.34588	0.000277	1.35E-08	1.33E-06	-1.5E-21	-3.6E-21	-3.4E-25	-3.3E-23	0.079906	0.009611	6.83E-07	6.72E-05
37	5.666666667	0.560029	0.06736	4.22E-06	0.000414	0.362846	0.000291	1.42E-08	1.4E-06	1.73E-21	4.05E-21	3.81E-25	3.75E-23	0.077125	0.009277	6.6E-07	6.48E-05
38	5.833333333	0.54474	0.065521	4.1E-06	0.000403	0.381058	0.000306	1.49E-08	1.47E-06	-2.1E-21	-5E-21	-4.7E-25	-4.6E-23	0.074202	0.008925	6.35E-07	6.24E-05
39	6	0.528274	0.06354	3.98E-06	0.000391	0.400595	0.000321	1.57E-08	1.54E-06	2.88E-21	6.76E-21	6.37E-25	6.26E-23	0.071131	0.008556	6.08E-07	5.98E-05
40	6.166666667	0.510559	0.06141	3.84E-06	0.000378	0.42153	0.000338	1.65E-08	1.62E-06	-4.3E-21	-1E-20	-9.4E-25	-9.3E-23	0.067911	0.008168	5.81E-07	5.71E-05
41	6.333333333	0.491535	0.059121	3.7E-06	0.000364	0.443925	0.000356	1.74E-08	1.71E-06	6.87E-21	1.61E-20	1.52E-24	1.49E-22	0.06454	0.007763	5.52E-07	5.42E-05
42	6.5	0.471153	0.05667	3.55E-06	0.000349	0.467825	0.000375	1.83E-08	1.8E-06	-1.2E-20	-2.8E-20	-2.7E-24	-2.6E-22	0.061022	0.00734	5.22E-07	5.13E-05

Figure 8: Concentration calculation spreadsheet

After correlating the recorded times with several physical properties, initial vapor pressure of the mixture showed the strongest relationship that could be described with a trendline. This relationship is shown in Figure 9.

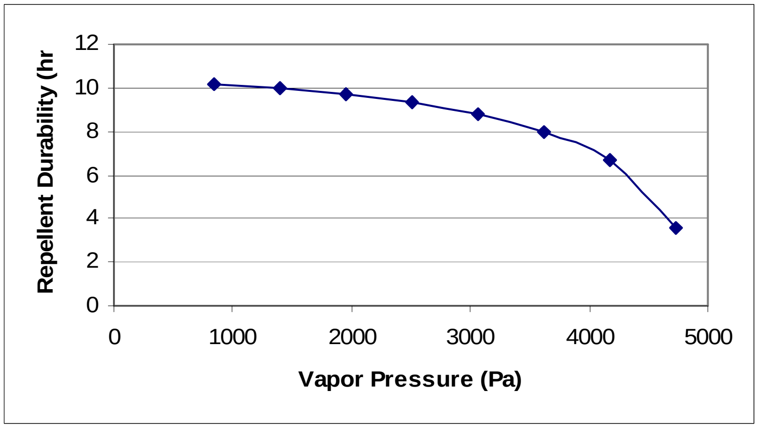


Figure 9: Repellent durability correlated to mixture vapor pressure

This data was then combined with the utility-durability relationship to find an equation relating utility to vapor pressure to be used in the optimization. This graph and equation are shown in Figure 10.

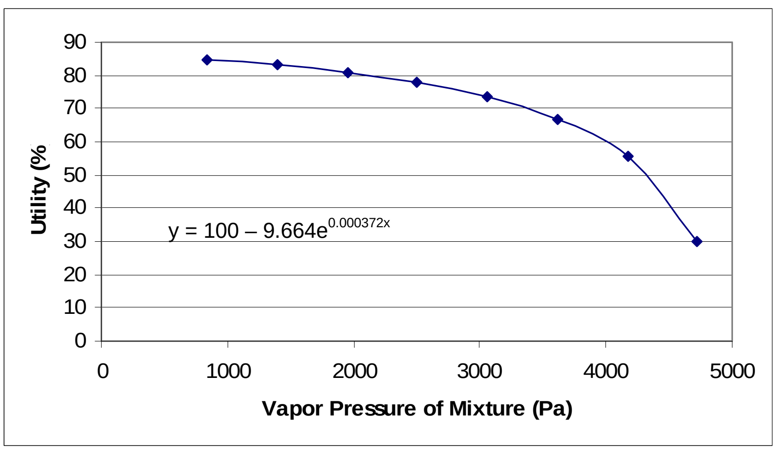


Figure 10: Durability utility correlated to mixture vapor pressure

Feel

The first step in relating utility to feel, or stickiness, was assigning qualitative descriptions to levels of utility. This is shown in Figure 11.

Figure 11: Utility related to descriptions of feel

These qualitative descriptions then needed to be related to some sort of consumer test. For this reason, the "Paper Test" was developed. To perform this test, a person applies repellent of a specific formulation to the underside of his arm. He then places a two-inch-by-two-inch piece of paper on the applied area. The thickest piece of paper that sticks to the applied area and does not fall off determines the stickiness of the repellent. Thickness of paper, or basis weight, is measured by the weight of 500 sheets of that type of paper. For example, a full sheet of 50-pound paper would weigh 1/500 of 50 pounds, or one tenth of a pound. The relationship between paper basis weights and stickiness levels are shown in Figure 12.

Figure 12: Consumer tests results for feel

The next step is to relate this consumer test to a physical property of the repellent formula, in this case, to the amount of ingredient in the repellent formula. Ethanol does not have a sticky feel or leave any residue, and Picaridin is reported to be non-sticky[26], so only aloe and fragrance were related to the feel consumer test. The relationship of the test to fragrance is shown in Figure 13, and the test to aloe in Figure 14.

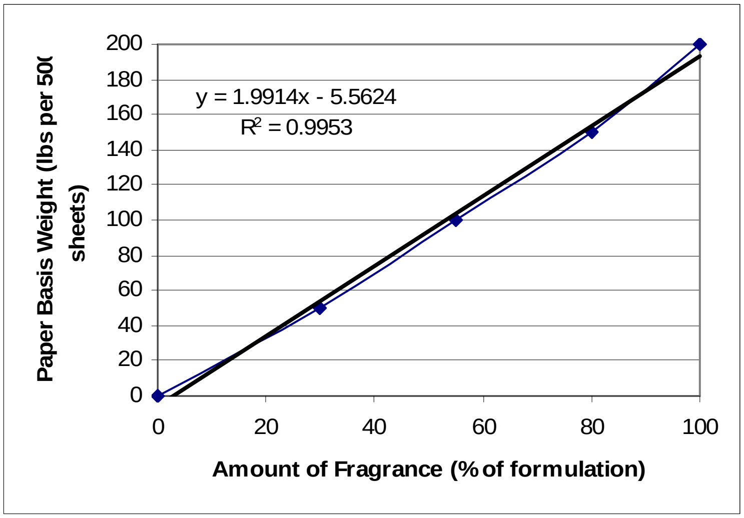


Figure 13: Consumer test related to volume fraction of fragrance

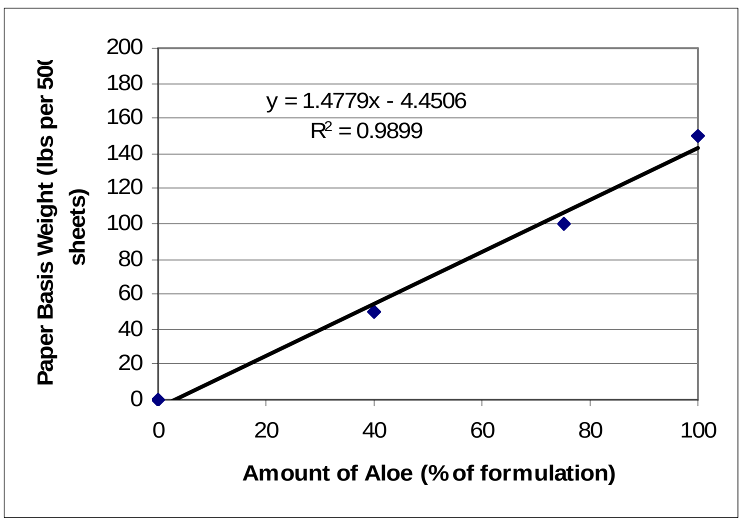


Figure 14: Consumer test related to volume fraction of aloe

[26] www.picaridin.com/advantages.htm.

The physical properties of the formula, i.e., the amounts of each ingredient, were then related directly to the utility levels determined previously. These relationships will be used in the product formula optimization and are shown in Figures 15 and 16.

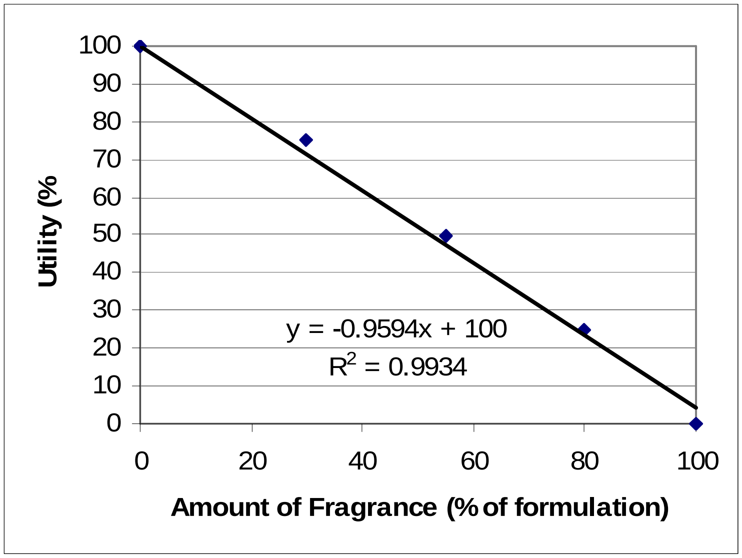


Figure 15: Feel utility related to the volume fraction of fragrance

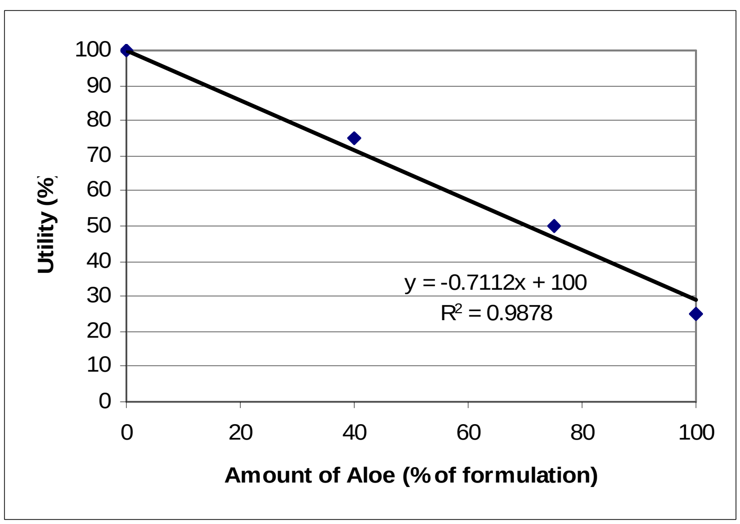


Figure 16: Feel utility related to the volume fraction of aloe

Scent

To construct the scent utility function, the consumer determines how satisfying each fragrance scent strength would be to them. The happiest point is where the repellent has only a trace scent, and it decreases for any change in strength, as illustrated in Figure 17.

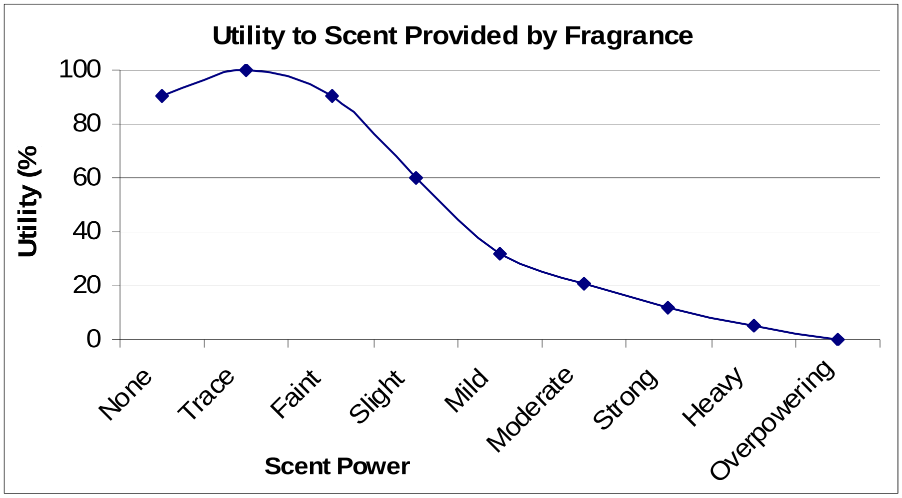


Figure 17: Utility vs. Scent Strength

Next, the concentration of fragrance is determined for each scent strength. The resulting data is coupled with the data for happiness versus scent strength to show the relationship between fragrance concentration and happiness. The relationship is then fit with a trendline, and the trendline equation describes the happiness resulting from any pleasant scents.

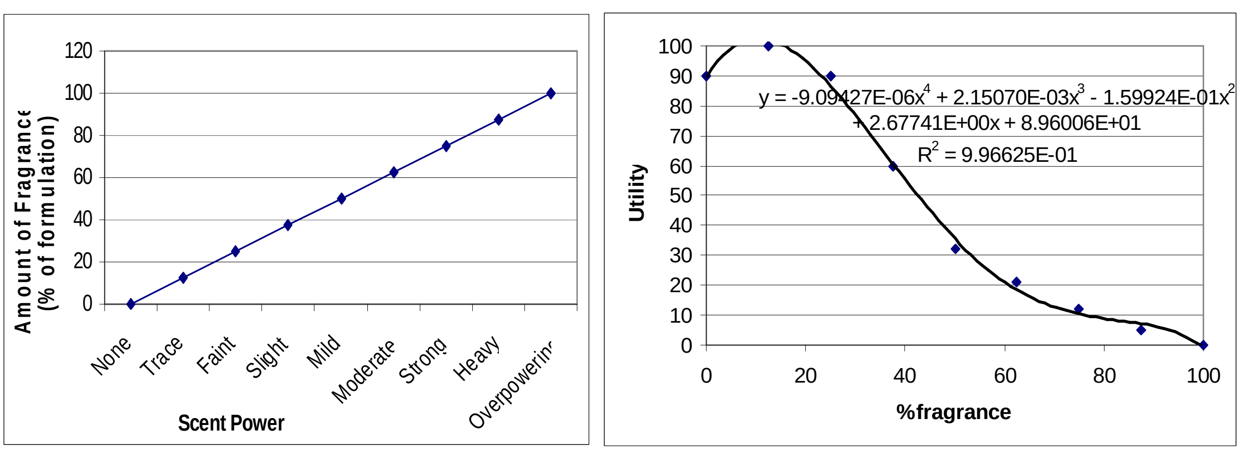


Figure 18: Relationships between % fragrance and scent power, utility

Ethanol contributes an unpleasant scent to the product, so the happiness provided by the scent of ethanol is continually decreasing as the strength of the scent increases. Next, the concentration of ethanol is determined for each scent strength. The resulting data is coupled with the data for happiness vs. scent strength to show the relationship between ethanol concentration and happiness.

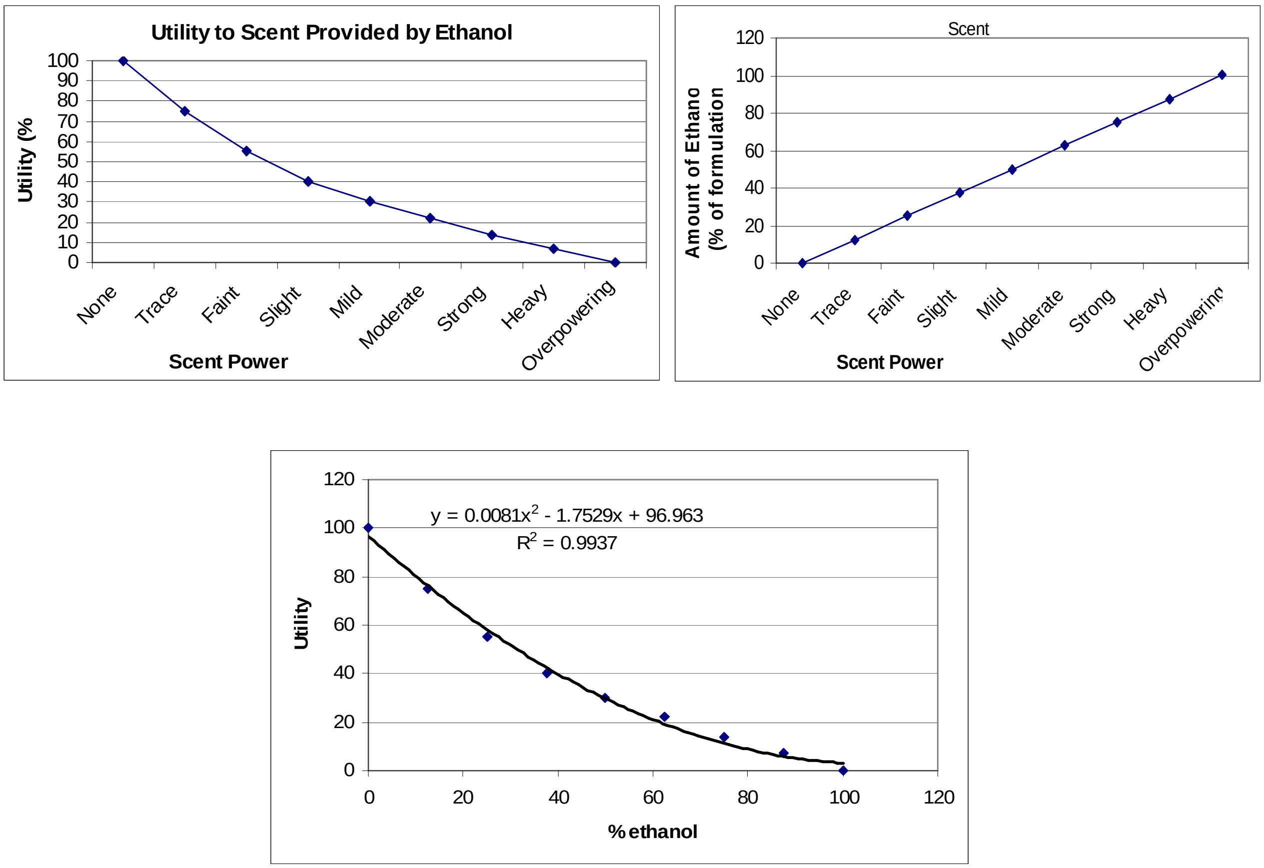


Figure 19: Relationships between % ethanol, scent power and utility

There is a challenge in devising a single equation relating positive and negative scent contributions. For any composition of repellent, the total scent happiness can be found with a weighted average of two utility equations. The first equation describes the happiness from pleasant scents and the second describes the happiness from unwanted scents. By taking a weighted average of the resulting happiness for each segment, the total happiness derived from scent can be determined as follows, with x as a volume percentage of composition:

$$U_{scent} = \frac{U_{ethanol} x_{ethanol} + U_{fragrance} x_{fragrance}}{x_{ethanol} + x_{fragrance}}$$ **Equation 9**

This model assumes that Picaridin and aloe have a negligible contribution to the scent of the product.

Form

There are two forms of repellent available to consumers—lotion or spray. The most important physical property to ascertain this form is the mixture viscosity. Surface tension would address droplet size and related topics, but viscosity determines if the product will be free flowing enough to be a spray. If it is too thick, it will be a gel or lotion. Consumer happiness is derived from this property.

Liquids with a kinematic viscosity over 75 centistokes will be too thick to be sprayed[27] by a finger pump, a typical packaging for insect repellent. The values for dynamic viscosity are known or estimated for each of the materials. For any mixture, the resulting dynamic mixture viscosity is calculated with the Grunberg and Nissan method[28] and converted to kinematic viscosity.

The utility of each repellent form is derived from consumer preferences. For example, if 83% of consumers prefer spray repellent over the lotion form, a repellent in spray form would give '100% utility' to 83% of consumers, but less happiness to the other 17%. This lesser value is approximated at 50% utility. Thus, a spray repellent would have an overall consumer utility of 83% + 0.5*(17%) = 91.5%.

Finally, the relationship between viscosity and utility can be expressed with an 'If… then….' statement giving the utility for any mixture viscosity, i.e. 'If kinematic viscosity is less than 75 centistokes, utility is 91.5%; if kinematic viscosity is more than 75 centistokes, utility is 58.5%.' This relationship is then easily integrated into the product optimization. The viscosity/utility relationship is summarized in Figure 20.

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[27] http://www.jamestowndistributors.com/decoder_epifanestopcoats.jsp; http://www.byk-gardner.com/images/applications/sub/viscosity_abb7.jpg.
[28] Reid, *et. al.*, "The Properties of Gases and Liquids," 474-5.

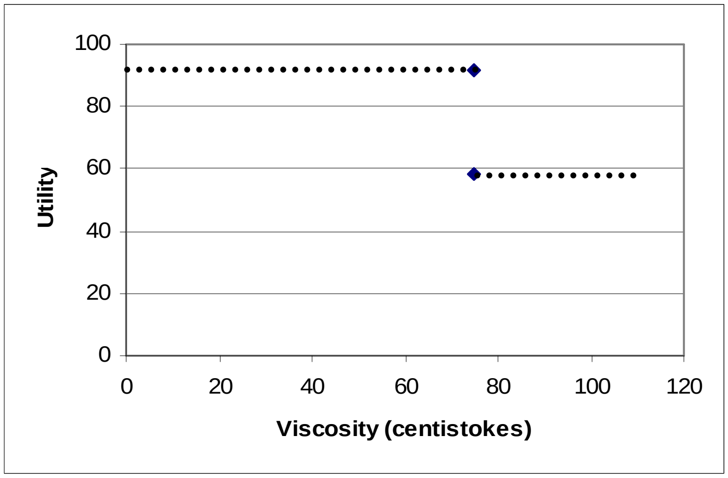

Figure 20: Relationship between mixture viscosity and utility

Note: The weighted average of 'Form' was estimated from the weighted average of 'Cost' from the marketing survey results. After the results had been gathered, it was determined that it would have been more useful to inquire about the 'Form' rather than the 'Cost.' There was insufficient time to gather new data, so 'Form' was substituted in place of 'Cost' and assumed that weighted average for the final calculations and optimizations.

Toxicity

The major benefit of a Picaridin-based repellent is the decreased health risk compared to DEET-based repellents. Consumer utility will be based on the danger to health that is associated with each component. As the risk increases, consumer happiness will decrease; this is modeled as a linear relationship.

The risk associated with each component is derived from the National Fire Protection Association (NFPA) Health Hazard rating, often found on Material Safety Data Sheets (MSDS). The NFPA ratings are as follows for each material: DEET—2; Picaridin—1; ethanol—1. A linear relationship is used to describe the toxicity as the concentration of each component increases to 100% composition, where it reaches its NFPA rating.

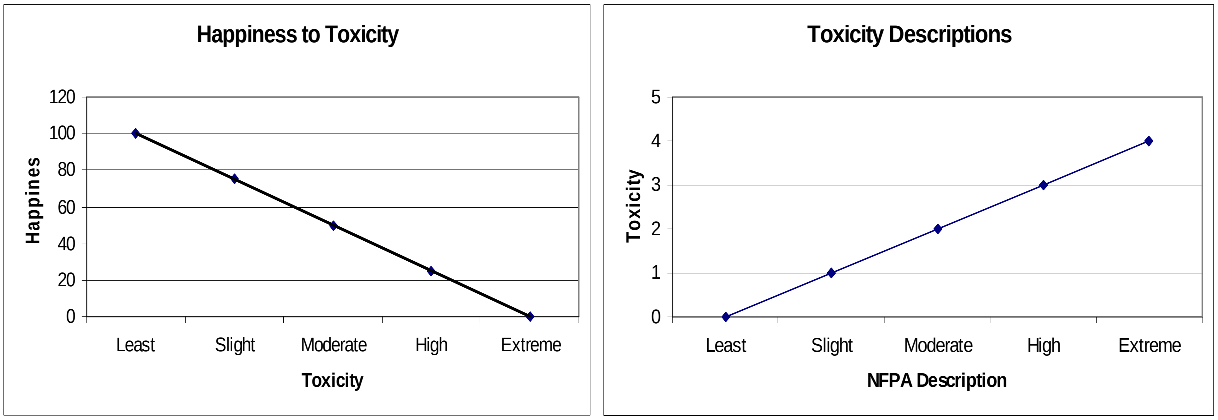

Figure 21: Toxicity and utility relationships

By combining these two relationships, the total consumer happiness related to health risk can be constructed. Because each component contributes unequally to the resulting mixture toxicity, a weighted average is used to determine the overall health risk. The corresponding utility for any combination of the ingredients is calculated with:

$$U_{toxicity} = 100 - 25*(x_{ethanol} + x_{Picaridin}) - 50*(x_{DEET}) . \qquad \textbf{Equation 10}$$

Market Research

In order to create a product that will have the broadest appeal to consumers, the thoughts and preferences of customers needed to be determined. A short marketing survey was devised, distributed and analyzed to elicit this information.

The survey was a three-section document asking questions required to build the complete happiness function and develop an understanding of consumer budgetary constraints. Another section was included to find out the consumers' usage patterns in an attempt to understand better what consumer demographic would use repellents and for what activities.

Weighted Averages

The first portion of the survey was organized to obtain weighted averages for product attributes. After considerable deliberation, the following attributes were believed to be important in consumer behavior: effectiveness, durability, feel, scent, form and toxicity.

Weighted averages could then be calculated for each attribute and incorporated into the happiness function.

The survey-taker was asked to rank the aforementioned attributes in relation to each other, with '1' being the most important consideration in choosing an insect repellent and '6' being the least important of the options. The results of the rankings were collected and a mean ranking was calculated for each attribute.

The resulting weights were determined by the number of attributes analyzed—in this case, six. Thus, the most important attribute would be assigned a value of six, the next most important would have a five, and so on. The numbers were then normalized so the sum would be equal to one. This meant the most important attribute had a weight of 6/21, the second most important had weighted average of 5/21, down to the least important at 1/21. This is the 'x_i' component of the happiness function. This allows construction of a happiness function that gives greater emphasis to what consumers consider most important in an insect repellent. The survey results are summarized in Table 1.

Table 1: Repellent attributes and corresponding weights for the happiness function

Attribute	Weighted Average
Effectiveness	0.2857
Durability	0.2381
Feel	0.1905
Cost	0.1429
Toxicity	0.0952
Scent	0.0476

Demographic Information

The second section of the marketing survey asked about the various activities for which consumers usually use insect repellent. This was included to get an idea of the potential target market for advertising purposes.

Survey respondents were asked to mark each activity for which they commonly use insect repellent. The list included hiking, camping, hunting, fishing, sports, just being outside and going for a walk. There was also a blank space left for those who felt another activity should be included in the list. A space to include the respondents' age and gender was also included on the form; if it was discovered that there were significantly different answers based on gender or age, separate products aimed at each demographic could be pursued.

Most of the respondents indicated that they use repellent for hiking and camping, suggesting that ads placed in related publications or trade shows might be most successful in spreading information about the final product. There was no noticeable divergence based on age or gender from the data collected, so it can be assumed that there is one large demographic to pursue, rather than fractured, smaller groups with distinct tastes in insect repellent. The results of the demographic information are tabulated below, indicating what percentage of respondents use repellent for the specified activity.

Table 2: Survey respondents' repellent usage habits

Activity	Participation
Hiking	92%
Camping	92%
Hunting	0%
Fishing	31%
Just Being Outside	62%
Going for a Walk	31%
Sports	38%
Other (Gardening)	15%

Budget Constraint

The final portion of the marketing survey asked respondents to indicate how much more they would be willing to pay for a repellent that was clearly superior in a certain category (e.g., lasts twice as long, is twice as effective) than their current repellent choice, with all else being equal. The average consumer budget constraint specific to insect repellent could then be calculated and incorporated into the final optimization model.

The survey asked respondents about a repellent that lasted twice as long, was twice as effective, felt better (oiliness, stickiness), smelled better or was considerably safer than their current repellent choice. Options were provided to give an approximate idea of how much more they would be willing to pay for the specified improvement. There were five options for how much more they would pay: $0.00, $0.01 - $0.75, $0.76 - $1.50, $1.51 - $2.25 or more than $2.25. The mean response for each question was tabulated and related to a specific amount by statistical methods designed for assigning values from a range. The sum of the mean values of each question would give the additional amount that consumers are willing to pay for a better repellent.

Table 3 shows the results for each trait and the final budget constraint. (Note: the budget constraint is in relation to the retail price of a 6 oz. repellent container to obtain the final budget constraint value. Not all of these values were needed for the final analysis.)

Table 3: Consumer budget constraints for repellent

Attribute	Budget Constraint
Doubled Durability	$1.32
Doubled Effectiveness	$1.44
Better Feel	$0.82
More Pleasing Scent	$0.44
Considerably Safer	$0.76

OPTIMIZATION

Procedure

Using the economic description and utility model developed previously, profit was analyzed for two scenarios. The first approach was to analyze the profitability of the product providing the greatest consumer utility. The second optimization was aimed at finding a product that would provide the greatest profit.

The economic model contains six variables and the budget constraint introduces one more variable. This leaves five degrees of freedom, but P_2 and α are also fixed, so there are three variables remaining for optimization: β, P_1, D_1. For each P_1, a D_1 was input and the resulting β was computed. The required capital costs, production costs and expected revenues were calculated and recorded. The optimization algorithm is shown below. The highest profit situations were than analyzed for feasibility, associated risk and environmental impact.

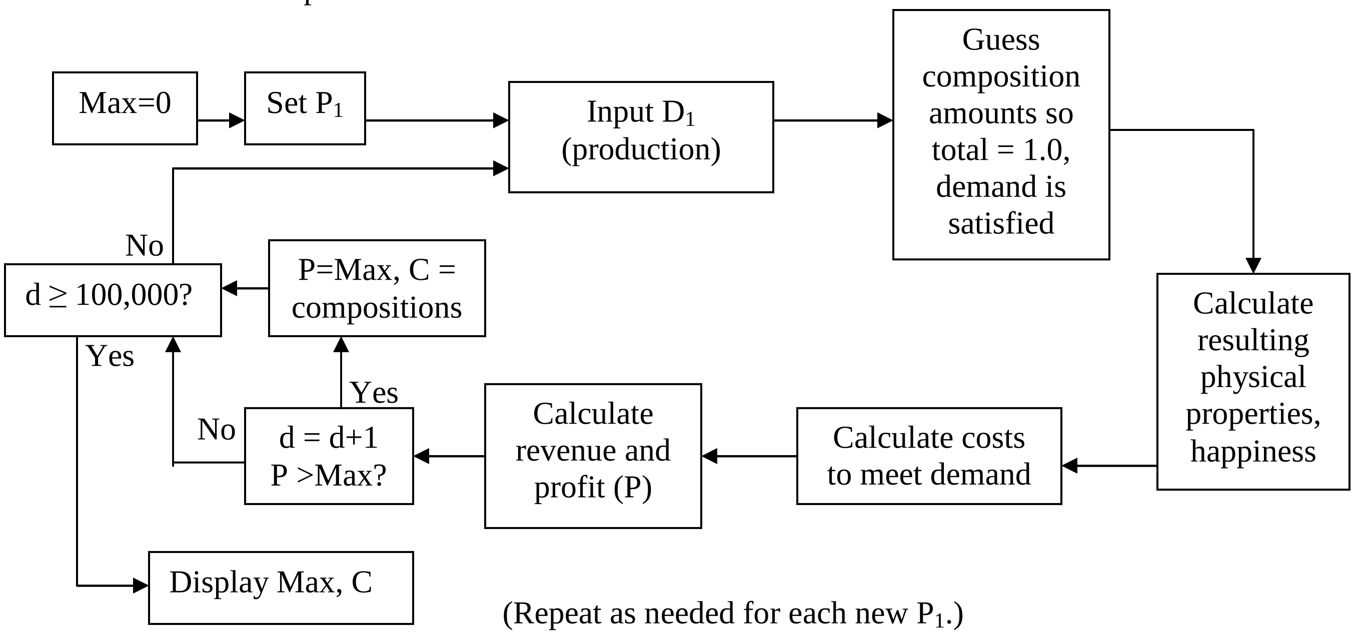

Figure 22: Optimization algorithm

Costs

Various costs involved in producing the repellent were included in the utility optimization. This was necessary to maximize either the profit or the return on investment of the proposed product. The cost information used and the methods of obtaining them are listed below.

Raw Materials

There is widely varying confidence in the raw material costs used in cost calculations. The prices used for this report are shown in the following table.

Table 4: Raw material costs

Ingredient	Raw Material Cost ($/lb)
Picaridin	60
Aloe	11
Ethanol	0.342
Fragrance	10

The cost of Picaridin was estimated from the composition and selling price of the Picaridin-based product Cutter® Advanced.[29] The cost of aloe was estimated from the selling price of pure aloe.[30] Ethanol's cost is the most certain, with the price supplied by a quote from chemical distributor ICIS-LOR.[31] The cost of fragrance was based on costs for vanilla, the fragrance of choice.[32] During the course of the optimization, it was discovered that the raw material costs wee the most significant contributor to the cost of goods sold.

Processing Costs

The second most significant expense associated with bringing the product to market is the processing cost. As a simple mixing process, the only equipment needed is storage tanks, a mixer, pumps and a packaging facility. The annual operating costs were estimated by the "Percentage of Delivered Equipment Cost" method.[33]

After determining the process would not involve any reactors or other labor or control-intensive equipment, the necessary equipment was decided. Each ingredient—Picaridin, ethanol, fragrance and aloe—would require an individual storage tank to hold one week's worth of material. A mixer and matching tank capable of holding half of a day's production would be needed. Additionally, a storage tank for two days worth of the mixed product would need to be on site. Six pumps with motors would be required to move material through this manufacturing set-up, which is described in further detail later in this report. Packaging facilities were assumed to be included in the operating expenses resulting from the "Percentage of Delivered Equipment" method used to estimate the total annual costs associated with processing.

[29] http://www.lowes.com/lowes/lkn?action=productDetail&productId=40073-316-40073.
[30] http://www.herbal-medicine.biz/nutritional_products/aloe_pure.shtml.
[31] Allbritten, Yoshiko, Email.
[32] http://www.wholesalefragrance.com/womens.htm.
[33] Peters, *et. al*., 250.

To price the equipment, costing charts for storage tanks were consulted and converted into current-day values. The same was done for the mixing tank.[34] The mixer was sized using the equation

$$P = \Phi N_r^3 D_a^5 \rho \qquad \textbf{Equation 11}$$

Where P = power required in kW

Φ = parameter dependent on the Reynolds number of the system

N_r = impeller speed (rotations per second)

D_a = impeller diameter in meters

ρ = density of the fluid in kg/m^3.

Once the required power was calculated, the price could be obtained from a costing chart.[35] Pumps and motors were also priced using the available correlations.[36]

Once the total cost of the equipment was determined, the "Percentage of Delivered Equipment" method was used to estimate operating costs. For a fluid processing facility, the fixed capital investment is approximately five times the cost of the delivered equipment. Capital costs can be determined based on an 11-year life for the plant; utilities, operating and other labor, overhead and administrative costs can also be estimated from this method. The sum of these costs becomes the total annualized cost associated with production.

The process of creating this repellent is simple. None of the ingredients will be synthesized; instead, all will be purchased. As a result, all that is needed is a simple mixing process. The flow sheet is shown below.

[34] Peters, *et. al.*, 557.
[35] Peters, *et. al.*, 541-2, 546.
[36] Peters, *et. al.*, 516-17, 520.

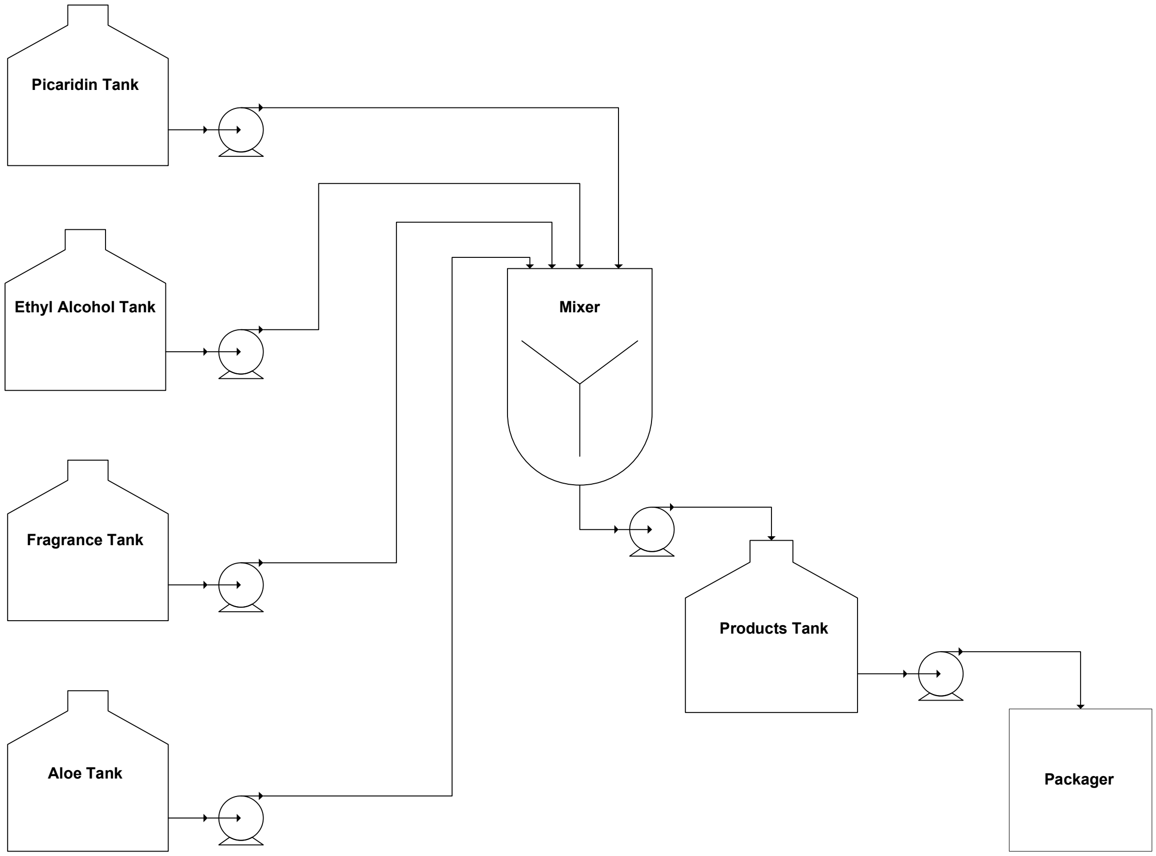

Figure 23: Repellent production flow sheet

Shipping Costs

Another component of product costs that needed to be addressed was associated with the distribution of the final product. Distribution centers and relative amounts to ship to each center were analyzed and optimized using a program in GAMS.

Distribution centers were chosen to be able to supply each region of the country without placing undue delivery burdens on any single distributor. The population surrounding each center and the corresponding insect population of each area were taken into consideration. For example, southern California has a very large population, but not a significant insect problem. Cities in the Upper Midwest are smaller, but there is a much larger insect population. Thus, these two areas would be expected to have similar demand and the following summary was constructed to reflect these considerations.

Geography was also taken into account, especially in regards to the Rocky Mountains. For example, even though Utah and Colorado share a border, Denver would not supply Salt Lake City with repellent because of the prohibitive cost of transporting material over the Rockies. Care was used to ensure that no distributor would have unnecessary burdens in supplying end-users with our product. The final distribution center locations are shown on the map.

Figure 24: Distribution center locations[37]

It was assumed that the infrastructure needed to move our product to the distribution centers is already existent. The final distribution centers and the percentage of production received are summarized in the following table.

[37] http://www.lib.utexas.edu/maps/united_states/united_states_wall_2002_us.jpg.

Table 5: Distribution centers and production to be received

Distribution Center	Percent of Production Received
Eugene, OR	5
Salt Lake City, UT	5
Denver, CO	5
Lubbock, TX	6
Kansas City, MO	7
Indianapolis, IN	7
Jacksonville, FL	7
Albany, NY	7
Sacramento, CA	7
Phoenix, AZ	6
Billings, MT	6
Baton Rouge, LA	7
St Paul, MN	6
Memphis, TN	7
Charlotte, NC	7
Pittsburgh, PA	5

After the shipping destinations had been decided, it was necessary to determine the optimal plant location. Analysis of relative productivity and labor wage rates showed that the region around the Gulf Coast would provide the highest productivity for each dollar invested.[38] The following cities were chosen to assess optimization: Birmingham, AL; Jackson, MS; Lafayette, LA; Little Rock, AR; Shreveport, LA; Oklahoma City, OK.

The distance from each city to each distribution center was calculated based on nearby zip codes.[39] A correlation was developed to relate distance and cost to ship per ton. By receiving quotes for shipping one ton a certain distance, the relationship Cost = 26.791 * Distance$^{0.341}$ was developed, with cost in dollars and distance in miles. This relationship was used to calculate the total cost of shipping 100 tons of production and satisfying the demand at each of our distribution centers. This resulted in the following total shipping costs for 100 tons of central production.

[38] Peters, et. al., 256.
[39] http://www.thepalmbeachtimes.com/TravelNavigator/SunshineMileage.html

Table 6: Potential plant locations and resulting shipping costs (per 100 tons of production)

Location	Shipping Costs
Oklahoma City, OK	$25,680
Lafayette, LA	$26,611
Shreveport, LA	$26,067
Jackson, MS	$25,919
Birmingham, AL	$26,006
Little Rock, AR	$25,243

For each increase in production, the costs would increase proportionally for each potential site. Based on the above results, Little Rock was chosen as the most economical site for the production of repellent.

This model makes several simplifying, but valid, assumptions. The first is that consumer utility is the same in each market. Market research showed that our target consumer uses repellent for mostly camping and hiking. The needs of these consumers would not change from region to region—the repellent needs to be effective and durable. Thus, assuming the consumer utility is constant regardless of location means the percent of production shipped to each distribution center is independent of the product composition and can be optimized separately.

The second simplifying assumption is that the price of our product is constant in relation to the price of the competition's product. The cost of a consumer good varies by region, meaning that the appeal to the consumer varies, too. By assuming P_1/P_2 remains essentially constant, the economic status of our product is static and shipping optimization can be assessed separately from the production or composition optimization.

This also relates to the final assumption that the price of our product stays a constant percentage of the local consumers' disposable income. The cost of living can vary greatly from location to location. However, if the cost of our product is found to be constant in relation to the consumers' overall budget constraint, the consumer will evaluate our product in the same light in each region. This allows the price and demand optimization to be evaluated apart from shipping considerations.

Advertising Costs

In order to increase consumer awareness of any product, significant resources must be invested in advertising. The major expenses for this product were known to be associated with raw materials and processing costs. Therefore, significant effort was not put into determining advertising costs and it was simply estimated to be $1 million annually.

Obviously, launching a new product will take considerable effort in respects to advertising, but generalizations were made to simplify the model. In the utility function optimization, α was set to 0.9, suggesting that the consumer already has an awareness of our product. This is not valid in the initial stages of the product launch, but is reasonable after a few years when the average consumer has achieved knowledge of our product. After this stage, a yearly budget of $1 million was deemed sufficient to maintain that consumer awareness.

Maximized Utility

After the cost analysis had been completed, it was possible to begin the product optimization. First, the optimization model was used to maximize utility with no consideration for product price. This resulted in a product made from 98% Picaridin and 2% ethanol. Since Picaridin concentration directly affects effectiveness and durability, and these characteristics carry the most weight, a formula with mostly Picaridin naturally increases the utility. However, a product with 100% Picaridin would have a kinematic viscosity higher than 75 centistokes and cause the utility of form to drop significantly, but adding only 2% ethanol keeps the viscosity within the spray limit. Even though the addition of fragrance and aloe would increase the utilities of scent and feel, because of the relative weights of these traits they would actually cause an overall decrease in the utility.

One potential drawback to this product is its cost. Since the raw material cost of Picaridin is about $60 a pound, this product would have to be sold at more than $60 a pound for this venture to be profitable. Most common repellents, or those with an active ingredient concentration from 5% to 30%, sell for around $16.00 a pound, so our product would be too expensive to be in competition with these. However, a specialty product such as Deep Woods OFF! for Sportsmen, which is 100% DEET, can sell for as much as $96.00 a pound ($6 per oz.). Therefore, it was decided to use the optimization model to maximize profit of the maximum utility product using Deep Woods OFF! for Sportsmen as the competitor. The market for this product is estimated to be 10% of the overall repellent market, giving a market budget constraint of $25 million per year.

The most profitable scenario for this product was found for a demand of 125,000 pounds per year at a price of $80 per pound, or $5 per one-ounce bottle. This scenario would have a net income of about $310,000 per year. However, raw materials costs are by far the largest cost of the venture, so any deviations in these could have a potentially large effect on the profit. For this reason, a risk analysis was performed assuming a 20% standard deviation in the raw materials costs. Results are shown in Table 7 and Figure 25.

Table 7: Summary of optimized product and economics

Component	Amount
Picaridin	98%
Aloe	0%
Ethanol	2%
Fragrance	0%
Durability	10.5 hrs
Form	Spray
Consumer Utility	93.6
Retail Price (1 oz)	$5.00
Annual Demand	125,000 lbs
Annual Profit	$310,000

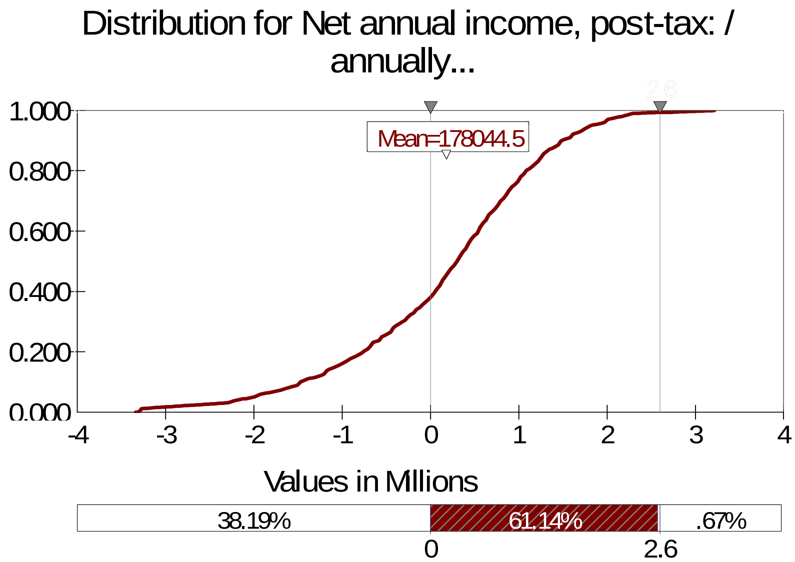

Figure 25: Risk Analysis for maximized utility product

This figure shows that there is only a 60% chance of this product being profitable, which is quite risky, and that the mean income is only $178,000, much less than the anticipated $310,000. Because of this, it was decided to use the optimization model to investigate other possible formulas.

Maximized Profit

After determining that the high-concentration repellent was not likely to be profitable, it was decided to pursue a product with a larger consumer appeal. This would allow larger production capacity, which leads to lower per-unit costs than smaller production facilities. Thus, less sales revenue would go towards covering expenses and profit would theoretically increase.

By developing a product that appeals to the average consumer, rather than just the deep woods camping and hiking enthusiast, the market budget constraint increases. As related previously, the total market budget constraint is an estimated $250 million per year, compared with the $25 million annual constraint associated with the more limited product.

The optimization algorithm did not change, but lower prices were used to begin the optimization iterations. For each price, the optimized demand and profit are shown in the following table.

Table 8: Demand and maximum profit summary for each price

Price ($/lb)	Demand (lb/yr)	Annual Profit
12	958	($2,140,000)
15	10,000	($2,190,000)
18	847	($2,140,000)
21	999	($2,130,000)
23	1,000,000	($3,370,000)
24	100,000	($2,080,000)
26	1,000,000	($1,030,000)
27	3,500,000	$522,000
28	5,000,000	$2,550,000

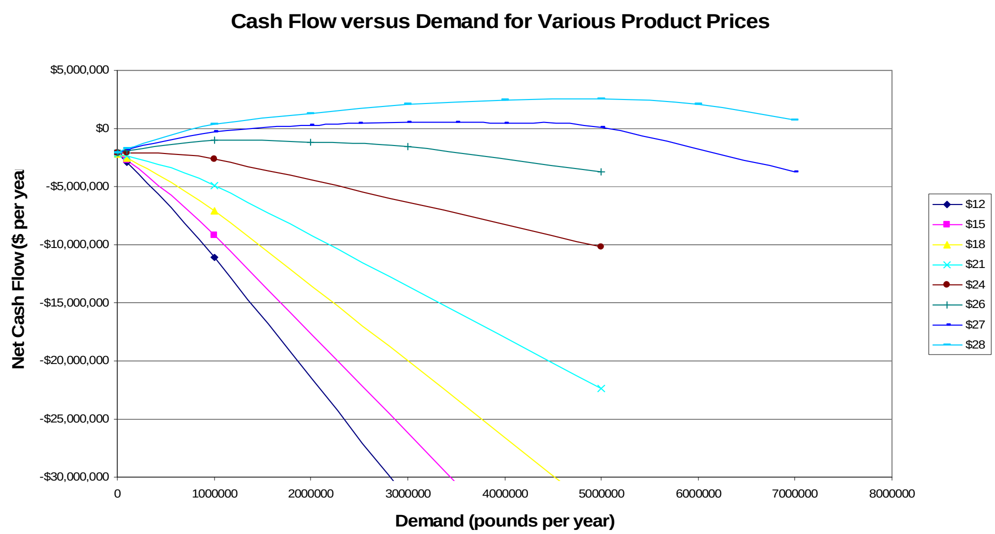

Figure 26: Cash flow versus demand for various product prices

The model showed that a profit was possible charging consumers $28 per pound ($9.75 per 6 oz.). The resulting product was 43% Picaridin, 1% aloe, 55% ethanol and 1% fragrance. The raw material costs were the greatest expense in this situation. These costs are subject to market fluctuations, so a risk analysis was run with a standard deviation of 20% for each component price. This analysis showed that this situation has a 45% chance of losing money in any year because of changes in raw material costs. Because of the high likelihood of losing money, this price is not strongly recommended at this time.

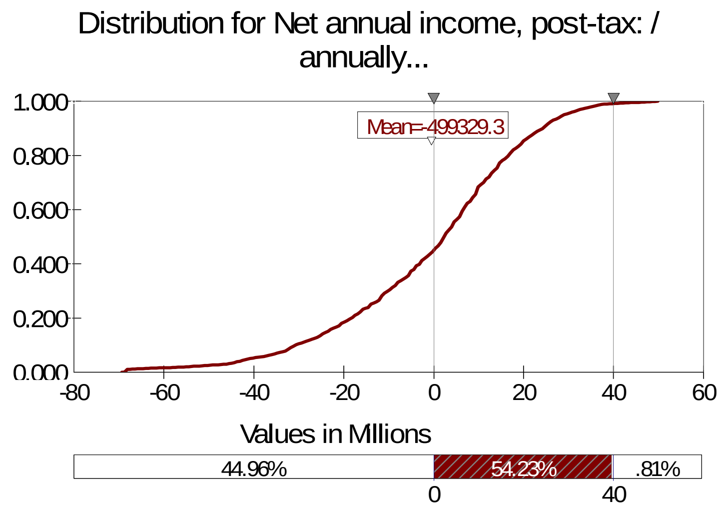

Figure 27: Risk analysis of $28 per pound, 5 million pounds per year

The trend shown in Table 8 suggests that merely increasing the price will increase the profit. However, there is question as to whether the $28 price falls within the consumer budget constraint. The following graph shows two things. The line represents the expected trend for the consumer budget constraint based on responses to consumer surveys. This is accurate for lower effectiveness rates, but can only be projected for higher-concentration repellents at this time. This projection shows obvious error towards the end, because consumers are willing to pay $96 per pound ($6/oz) for 100% repellent products, a trend not represented by the line. The $28 price for our product is close to the line in the range of uncertainty.

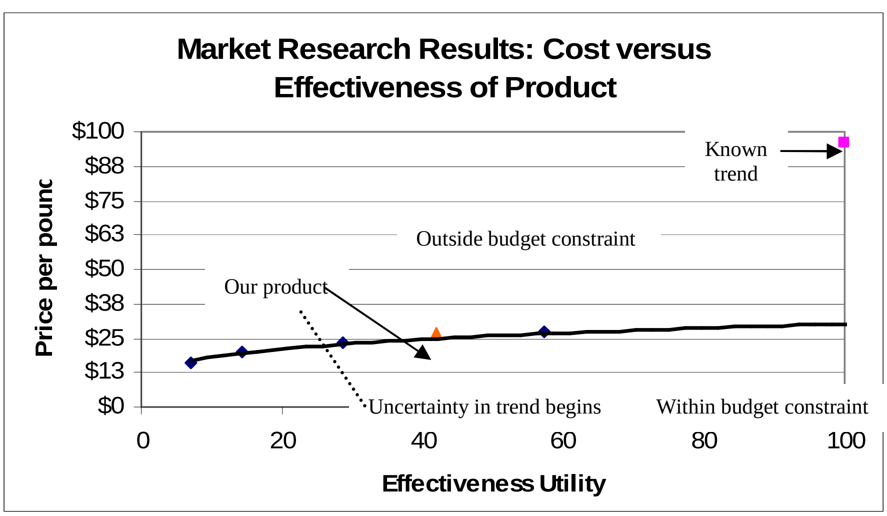

Figure 28: Uncertainty of consumer budget constraint

There is considerably less risk involved in marketing the concentrated repellent, but any success with marketing the $28 formula has a significantly larger possible payoff. Further consumer sampling will clarify whether or not the latter product is within consumer budget constraints and will help improve the risk analysis. If there is, in fact, less risk associated with the project than currently projected, it may be worth pursuing. Table 8 summarizes the proposed product.

Table 9: Summary of optimized product and economics

Component	**Amount**
Picaridin	43%
Aloe	1%
Ethanol	55%
Fragrance	1%
Durability	7.5 hrs
Form	Spray
Consumer Utility	69.0
Retail Price (6 oz)	$9.75
Annual Demand	5,000,000 lbs
Annual Profit	$2,550,000

Environmental Impact

Since this process only involves mixing, it has relatively little environmental impact. There is no possibility of gas releases into the air, and no harmful byproducts will be produced. All ingredients are non-toxic, so any leaks that may form will pose no environmental concerns. The largest environmental impact of this process will be due to shipping and emissions from trucks.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

After extensive optimization efforts, it was still unclear if it was possible to produce a profitable product without violating the consumer budget constraints. The optimized product would be an effective repellent and an improvement over available options, but cannot be done profitably without further investigation of consumer spending behavior.

If the proposed product is, in fact, within the budget constraint, there is a significant chance of profit. However, there is also considerable risk associated with this product at $28 per pound. A higher retail price would likely protect against these risks and have a higher expected profit.

Recommendations

Throughout the optimization process, assumptions were made to simplify relationships and describe behavior. These could be addressed in an effort to increase the accuracy of the proposed models. Additionally, the following areas are topics that could be investigated further, either to develop a more accurate model or to cut costs and eventually achieve a more profitable product.

Survey Sample Size

The sample polled was somewhat small, amounting to only 13 respondents. The larger and more diverse the sample size surveyed, the more accurate the budget constraint and the weighted averages for the happiness function can be developed.

Market Research: Form

One important attribute that was not included in the original market research survey was a place to rank the importance of the form of the repellent (lotion or spray). Based on responses to other questions, this is an important enough attribute that it warrants inclusion in future research. In addition, ‘cost’ was an unnecessary attribute ranked on the original survey.

Synthesis of Picaridin

Purchasing Picaridin was a tremendous raw material expense and is probably the main reason the product was not profitable. Finding a way to produce the molecule in massive quantities from more basic constituents would probably lead to a lower cost than buying it in bulk. This is a key to making this product a less risky investment.

Repellent Mechanisms

There appears to be a very limited understanding, even among entomologists, of how repellents actually repel insects. Understanding how they work would allow pursuit of an original repellent molecule that could possibly be constructed inexpensively. This could yield a very profitable product if more information was available in this field.

Microeconomic Theory

Certain simplifications were made regarding consumer awareness and demand in relation to the repellent market. In reality, consumer knowledge of any product takes time and can be modeled by replacing α with an equation modeling the spread of this awareness, i.e., α would increase with time. These start-up implications were not considered in our model. In addition, the demand for any commodity does not remain constant and generally increases with time. An equation representing this growth could be taken into account if an understanding of the behavior is attainable.

Accurate Numbers

There was tremendous difficulty in obtaining accurate costs for the ingredients without actually purchasing them. Thus, rough approximations were used to develop raw material costs. Since these costs proved to be the major obstacle to producing a profitable repellent, research in this area will go a long way towards assessing risk and potential profitability. In addition, physical property data was hard to come by and some approximations were made. Refining these numbers would help greatly in forming a more accurate model.

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