

Aerial Forest Operations: Mineral Amendment Project

by

Jennie L. Cornell

A PAPER

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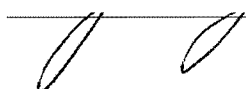
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## AN ABSTRACT OF THE MASTERS PAPER OF

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Abstract approved:



John J. Garland

A helicopter operations problem was studied for a private forest landowner testing an experimental application of minerals on Douglas-fir (*Pseudotsuga menziesii*) in the Coast Range of Oregon to offset growth reductions from Swiss needle cast disease. A planning approach was needed to minimize costs for transportation and aerial application of the minerals.

A transportation network model was developed for a heliport and service landing location facility problem which used mixed-integer linear programming techniques. Cost and production elements were identified along with interactions of significant variables for the operation. An empirical production model estimated application costs. For one type of mineral, five transportation and application options with two types of helicopters, two types of material delivery options and a shared road system were modeled for a simplified field application version (i.e. two application units in the case study). The solution minimized costs for a transportation and aerial application option for a total cost at \$39,060, or \$212 per ton of applied material, reducing costs on a per-ton basis by approximately 9% over estimates for current operations.

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APPROVED:

\_\_\_\_\_  
Major Professor, representing Forest Engineering

\_\_\_\_\_  
Department Head, Forest Engineering

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Finally, I want to dedicate this paper to my husband, Bryan, who is a steady source of inspiration and support in my life. Thank you for your unwavering love and devotion.

## TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION.....	1
1.1 Purpose and Objectives.....	1
1.2 Organization.....	3
2.0 LITERATURE REVIEW.....	4
2.1 Aerial Spray Operations.....	5
2.2 Helicopter Logging Operations.....	7
2.3 Summary.....	9
3.0 CASE STUDY.....	10
3.1 Land Management Objectives.....	10
3.2 The Operation.....	10
3.3 Study Site.....	11
4.0 METHODOLOGY TO EVALUATE OPTIONS.....	12
4.1 Methodology.....	12
4.1.1 Operations Problem.....	12
4.1.2 Goals and Outcomes for a Planning Solution.....	15
4.1.3 Variables of Influence.....	15
4.1.4 Visual Concept Model.....	16
4.1.5 Mathematical Models.....	16
4.1.6 Generalized Solution.....	19
4.1.7 Comparison of Selected Components of Case Study With Mathematical Models.....	19
5.0 DATA COLLECTION.....	21
5.1 Data Collection Techniques.....	21

## TABLE OF CONTENTS (CONTINUED)

	<u>Page</u>
5.2 Objectives for Data Collection.....	21
5.2.1 Shift Level Objective.....	22
5.2.2 Detailed Flight Time Objective.....	22
5.3 Data Description.....	23
5.3.1 Shift Level Data.....	25
5.3.2 Detailed Flight Data.....	25
6.0 PRODUCTION AND COST ESTIMATES.....	26
6.1 Transportation Options.....	26
6.2 Empirical Production Models.....	28
6.2.1 Helicopter Production.....	29
6.2.2 Agricultural Trucks.....	33
6.3 Cost Estimates.....	35
6.3.1 Helicopters.....	36
6.3.2 Agricultural Trucks.....	37
6.3.3 Material and Transportation.....	40
6.3.4 Road and Heliport Improvements, Maintenance, Move-In.....	40
7.0 MATHEMATICAL MODELS FOR OPERATIONS PLANNING.....	43
7.1 Mathematical Models.....	43
7.2 Formulations.....	44
7.2.1 Mixed-Integer Linear Programming Models.....	44
7.2.2 A Heuristic Algorithm Model.....	45
7.3 Fixed and Variable Cost Information.....	46
7.4 Software Capacity.....	47
7.5 Results.....	48
7.6 Model Advantages.....	50

## TABLE OF CONTENTS (CONTINUED)

	<u>Page</u>
7.7 Model Limitations.....	50
8.0 DRAFT ARTICLE: EVALUATION OF AERIAL FOREST OPERATIONS.....	52
8.1 Abstract.....	52
8.2 Introduction.....	53
8.3 Methodology.....	55
8.4 Case Study.....	59
8.5 Study Site.....	59
8.6 Transportation Network Options.....	60
8.7 Variables.....	62
8.8 Production.....	63
8.8.1 Helicopters.....	64
8.8.2 Agricultural Trucks.....	65
8.9 Costs.....	66
8.9.1 Helicopters.....	68
8.9.2 Agricultural Trucks.....	69
8.9.3 Cost-per-Ton Calculations – Application.....	69
8.9.4 Road Improvement and Maintenance, Move-In Costs.....	70
8.9.5 Material and Delivery Costs.....	71
8.10 Mixed-Integer Linear Programming Model.....	71
8.10.1 Concept Diagram.....	71
8.10.2 Formulations of Equations.....	71
8.11 Results.....	73
8.11.1 Production.....	73
8.11.2 Costs.....	75
8.12 Discussion.....	75



## TABLE OF CONTENTS (CONTINUED)

	<u>Page</u>
8.12.1 Variables.....	76
8.13 Applications/Limitations of Model.....	77
8.14 Additional Research Needs.....	78
8.15 Summary.....	80
8.16 Literature Cited.....	80
9.0 FLIGHT DATA ANALYSES.....	82
9.1 Data Management.....	82
9.1.1 Random Sample Selection.....	83
9.1.2 Data Conversion.....	84
9.2 General Helicopter Production.....	84
9.3 Empirical Model Comparison.....	84
9.3.1 Differences in Model and Actual Flight Data.....	88
9.4 Comparison of Heliports.....	89
9.5 Acceleration Effect on Time Estimates.....	90
9.6 Other Considerations.....	94
9.7 Production Estimate Model.....	96
9.7.1 Use of Regression to Describe Cycle Time as a Function of Flight Path Distance.....	96
9.7.1.1 Regression Variables.....	98
9.7.1.2 The Regression Equation.....	98
9.7.2 Limitations of Simple Linear Regression for Estimating Production.....	99
9.7.3 Other Applications.....	100
9.8 Discussion.....	103

## TABLE OF CONTENTS (CONTINUED)

	<u>Page</u>
10.0 CONCLUSIONS, DISCUSSION, AND RECOMMENDATIONS.....	105
10.1 Conclusions.....	105
10.2 Discussion.....	107
10.2.1 Operational Considerations for Relative Comparison.....	108
10.2.1.1 Ferry Distance.....	108
10.2.1.2 Helicopter Performance.....	113
10.2.1.3 Physical Properties of Applied Minerals.....	113
10.2.2 Summary.....	115
10.3 Recommendations.....	115
10.3.1 Research Needs.....	117
LITERATURE CITED.....	119
APPENDICES.....	123
Appendix A Time Study Elements and Variables.....	124
Appendix B Production and Cost Estimate Spreadsheets.....	130
Appendix C Input for Mixed-Integer Linear Programming Models.....	196
Appendix D Input for Network 2000 Model.....	210
Appendix E Output from Mixed-Integer Linear Programming Models.....	214
Appendix F Output from Network 2000 Model.....	231
Appendix G Time Study Forms.....	236
Appendix H Ag-Nav <sup>®</sup> 2 Unit Maps.....	242
Appendix I Flight Data Analyses.....	245

## LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Vicinity map for mineral amendment project.....	11
2. Project flowchart of cost components for transportation and application of minerals.....	13
3. Flowchart to estimate helicopter production and cost.....	14
4. Visual concept diagram of transportation network for five options to transport and apply doloprill to units #4 and #5.....	17
5. Empirical model estimate for helicopter flight pattern in a delay-free cycle.....	24
6. B47G3 helicopter with fiberglass bucket.....	27
7. Empirical helicopter model estimate of average total flight path distance.....	34
8. Vicinity map for mineral amendment project.....	54
9. Project flowchart of cost components for transportation and application of minerals.....	56
10. Visual concept diagram of transportation network for five options to transport and apply doloprill to units #4 and #5.....	57
11. B47G3 helicopter with fiberglass bucket.....	61
12. Comparison of empirical model estimate and flight data from unit 6 for 10 random delay-free cycles.....	86
13. Comparison of empirical model estimate and flight data from unit 5 for 10 random delay-free cycles.....	87
14. Heliport approach and departure flight paths and effects on total cycle time.....	91
15. Influence of heliport approach and departure path on helicopter production.....	92

## LIST OF FIGURES (continued)

<u>Figure</u>	<u>Page</u>
16. Influence of heliport approach and departure path on helicopter cost-per-ton....	93
17. Comparison of fitted lines for influence of acceleration and deceleration on elapsed time estimates for unit 3 .....	95
18. Regression of total cycle time on total flight path distance with 95% prediction band and range of validation data.....	97
19. Projected production estimates for B47G3 based on regression line in Figure 18	101
20. Projected helicopter cost estimates for B47G3 based on production estimates (Figure 19).....	102
21. Relative helicopter production for application based on empirical model estimates over a range of one-way ferry distances.....	110
22. Relative helicopter application costs based on empirical production estimates (Figure 21) and hourly direct operating costs over a range of one-way ferry distances.....	111

## LIST OF TABLES

<u>Table</u>	<u>Page</u>
1. Empirical model production estimates for helicopters for transportation network options (tons/hour).....	30
2. Cost estimates for helicopters for transportation network options (\$/ton).....	38
3. Cost estimates for agricultural trucks, doloprill and transport to transfer site for transportation network options (\$/ton).....	39
4. Cost estimates for road and heliport improvements and maintenance for transportation network options.....	41
5. Summary of cost estimates for transportation network options.....	49
6. Summary of cost estimates for transportation network options.....	67
7. Empirical model production estimates for helicopters for transportation network options (tons/hour).....	74
8. Production summary form shift level data for flight hours and tons applied on mineral amendment project.....	85
9. Summary of cost components by percentage of transportation network option costs.....	116

## LIST OF APPENDIX FIGURES

<u>Figure</u>	<u>Page</u>
23. Cycle time elements.....	128
24. Time study form: Daily operations summary.....	237
25. Time study form: Daily hauling summary.....	238
26. Time study form: Helicopter payload tally.....	239
27. Time study form: Helicopter non-productive time elements .....	240
28. Ag-Nav <sup>®</sup> 2 Flight Path Map for Unit 3.....	243
29. Ag-Nav <sup>®</sup> 2 Flight Path Map for Unit 5.....	244
30. Empirical model estimate and flight data for unit 3.....	247
31. Empirical model estimate and flight data for unit 4.....	248
32. DGPS flight data with acceleration/deceleration components included in elapsed cycle time for unit 3.....	250
33. Box plots of 50-cycle data samples.....	252
34. Matrix of scatterplots for full regression model.....	252
35. Residuals plot for 50-cycle data sample (Group 1).....	253
36. Normal QQ plot for 50-cycle data sample (Group 1) .....	253
37. Cook's distance plot for 50-cycle data sample (Group 1).....	254

## LIST OF APPENDIX TABLES

<u>Table</u>	<u>Page</u>
10. Estimated improvement and maintenance costs – unit 4, option 1.....	143
11. Estimated costs for transportation and application of materials – unit 4, option 1	145
12. Estimated improvement and maintenance costs – unit 4, option 2.....	152
13. Estimated improvement and maintenance costs – unit 4, option 3.....	153
14. Estimated improvement and maintenance costs – unit 4, option 4.....	154
15. Estimated improvement and maintenance costs – unit 4, option 5.....	155
16. Estimated costs for transportation and application of materials – unit 4, option 2	157
17. Estimated costs for transportation and application of materials – unit 4, option 3	158
18. Estimated costs for transportation and application of materials – unit 4, option 4	159
19. Estimated costs for transportation and application of materials – unit 4, option 5	160
20. Estimated improvement and maintenance costs – unit 5, HP 5A, option 1.....	166
21. Estimate of costs for delivery and application of materials – unit 5, HP 5A, option 1.....	168
22. Estimated improvement and maintenance costs – unit 5, HP 5B, option 1.....	173
23. Estimated costs for transportation and application of materials – unit 5, HP 5B, option 1.....	174
24. Estimated improvement and maintenance costs – unit 5, HP 5A, option 2.....	183
25. Estimated improvement and maintenance costs – unit 5, HP 5A, option 3.....	184
26. Estimated improvement and maintenance costs – unit 5, HP 5B, option 2.....	185
27. Estimated improvement and maintenance costs – unit 5, HP 5B, option 3.....	186

## LIST OF APPENDIX TABLES (CONTINUED)

<u>Table</u>	<u>Page</u>
28. Estimated improvement and maintenance costs – unit 5, option 4.....	187
29. Estimated improvement and maintenance costs – unit 5, option 5.....	188
30. Estimated costs for transportation and application of materials – unit 5, HP 5A, option 2.....	190
31. Estimated costs for transportation and application of materials – unit 5, HP 5A, option 3.....	191
32. Estimated costs for transportation and application of materials – unit 5, HP 5B, option 2.....	192
33. Estimated costs for transportation and application of materials – unit 5, HP 5B, option 3.....	193
34. Estimated costs for transportation and application of materials – unit 5, option 4	194
35. Estimated costs for transportation and application of materials – unit 5, option 5	195



## Aerial Forest Operations: Mineral Amendment Project

### 1.0 INTRODUCTION

Aerial operations play an important role in efficient and cost-effective management of forestlands. Helicopters are used for aerial seeding of harvested or burned areas; application of herbicides, insecticides and fungicides; fertilization; timber harvesting; delivery of water and retardant in fire suppression efforts; transportation of crews, equipment and supplies; slash disposal; emergency medical evacuations; cone collection; insect and disease surveys; and for general reconnaissance.

Planning for aerial operations has traditionally sought the use of the safest and least-cost approach for the helicopter, crew and support personnel. The focus of interest for this case study is the development of a planning approach that considers the economics of several options for the transportation and aerial application of specialized minerals to stands of Douglas-fir (*Pseudotsuga menziesii*) in the Coast Range of Oregon.

#### 1.1 Purpose and Objectives

A forestland manager identified a practical need for an operations planning approach to minimize costs for transportation and aerial application of experimental minerals on private

forestland. Stands of Douglas-fir regeneration in the Coast Range of Oregon have experienced significant growth reductions in recent years due to the effects of the Swiss needle cast pathogen (Filip et al. 2002). Preliminary study results indicate application of specialized minerals have potential to offset growth reductions from Swiss needle cast disease. To facilitate incorporation of the minerals into the soil with natural precipitation the minerals are applied during the winter and spring season (Gourley 2002).

The application of large amounts of minerals during the winter season potentially increases road improvement and maintenance costs for the landowner and thus can increase overall project costs. The landowner is interested in evaluating potential transportation and application scenarios to minimize the total project costs and facilitate future planning on a landscape scale. The purpose of this research paper is to address the planning needs of the landowner for this aerial forest operation.

The objective of this research is to develop a planning approach using mixed-integer linear programming techniques to evaluate a combination of heliports, aircraft, and transportation options to minimize overall project costs under the constraints of operational safety while meeting the forest landowner's objectives. The approach should be suitable for the case study and be applicable to other aerial forest operations involving helicopters as well.

A methodology for evaluation of the case study was outlined based on background references for other forest planning problems and harvesting operations (Davis et al. 2001; Matzka 1997). Development of a conceptual diagram identified important variables and factors of influence in the operation and their relationships. Data collection in the field application phase of the case study supported formulation of production and cost estimates in the planning model. Initially, the production and cost estimates were calculated in spreadsheet format for four

field units in the project. The formulation of the operation for the mixed-integer model used two field units with a shared road system and associated transportation and application options. The spreadsheet calculations were used to verify the mixed-integer model solution. Flight data analysis compared empirical estimates of helicopter cycle times and production to actual flight data. A simple linear regression developed from a sample of recorded flight data predicted an average estimated total cycle time for the helicopter under conditions and limits of the actual field application for one type of mineral. The most significant independent variable was the total flight path distance of the helicopter per cycle. The empirical estimates for helicopter cycle time fall within the 95% prediction band for the simple linear regression.

## 1.2 Organization

This paper includes chapters typically found in most research papers plus a chapter that is a draft journal article. Chapters 1 through 7 introduce the project and operations problem, the methodology used for a planning solution and the results of an engineered planning approach. Chapter 8 is a draft paper to be submitted to a professional forestry, aviation, or engineering journal. This paper focuses on the mixed-integer linear programming model approach for a solution to the heliport facility location problem. There is some repetition of subject matter in Chapter 8. Chapter 9 addresses the flight data analyses and implications for estimates of helicopter production. Finally, Chapter 10 presents conclusions, discussion, recommendations for implementation of research findings and future research needs.

## 2.0 LITERATURE REVIEW

Fixed-wing aircraft have commonly been used to apply materials to target areas in agricultural operations. They have been used to apply materials in forestry operations in New Zealand as well (Gourley 2002). In the Coast Range of Oregon, helicopters are the primary aircraft type utilized for forestry application operations. Helicopters offer more flexibility in forest operations, with minimal requirements for heliport and service landing areas close to the operational units. Helicopters are better suited to uneven terrain and can operate at lower altitudes with greater maneuverability than fixed-wing aircraft.

The search for efficiency in aerial forest operations historically focuses on optimizing helicopter productivity and minimizing aircraft costs for an operation. Other aspects of the operation are usually only considered peripherally. For aerial spray operations, the basis for evaluating an operation traces back to the Baltin-Amsden formula first presented in 1959 (Curbishley et al. 1993). For helicopter logging operations, estimating the average total production time per turn of logs as a function of several cycle time variables has been emphasized (Dykstra 1975). Comments have been made about the importance of other operational factors when evaluating the benefits of using helicopters, such as when the cost of road access is high (Neal and Studier 1993; Farley 1994) or when there are extenuating environmental considerations (Kirk 1992).

Few models or decision support systems exist for evaluating helicopter operations in conjunction with transportation costs and options. An early helicopter logging model considered road and landing costs plus helicopter yarding costs (Egging and Gibson 1974). Recently,

Sessions and Chung (1999) developed a model for the strategic and tactical planning of helicopter logging operations. This model identifies the transportation plan that minimizes the sum of the road, landing and helicopter yarding costs. It also provides a method for planning daily production. The following review highlights selected models used for production and cost evaluation of aerial spray operations and helicopter logging operations.

## 2.1 Aerial Spray Operations

Most modern aerial spray models used to estimate helicopter productivity and efficiency incorporate the efficacy (i.e. chemical effectiveness) of the applied material with the production capacity of the aircraft. None of the models found consider costs of options for road or access networks or address applications of dry materials. Some models incorporate mechanisms to compare the relative cost and efficiency of different aircraft (Ghent 1999; Potter et al. 2002).

The Baltin-Amsden formula was an early measure of effectiveness for an aerial spray operation. Banaugh (1984) modified the formula to account for irregularly-shaped and topographically-varied spray areas and to provide a systematic and orderly calculation procedure for predicting spray productivity and efficiency (Curbishley et al. 1993). Banaugh also presented two measures of the effectiveness of the delivery of an aerial spray: the “spray productivity” and the “spray efficiency” (Ghent 1999). The definition of spray productivity of an operation is the area sprayed divided by the operation time to spray that area. The definition of spray efficiency is the time spent during application divided by the total operation time (Curbishley et al. 1993). A model developed by the USDA Forest Service, CASPR (Computer Assisted Spray

Productivity Routine, 1988), estimates productivity for an individual, rectangular treatment block (Ghent 1999). To predict time and cost elements of an aerial spray operation, CASPR requires specific input data including: application rate, tank capacity, flying speeds, hourly costs, turning times and the number and lengths of spray paths flown (Curbishley et al. 1993).

Since 1995, GypsES (Gypsy Moth Expert System) has demonstrated its use as a technology transfer tool and application program for gypsy moth management. GypsES is a computerized decision support system using a geographic information system framework for creation and analysis of complex map sets and on-screen digitizing with topographic map backdrops or aerial photography (Ghent 1999). Ghent proposed integrating the phenology (i.e. relating climate to plant responses) model BioSIM to improve treatment timing and the CASPR model to estimate production of aircraft on a project. The goal of the integrated program was realistic estimates of various aircraft productivity, total project needs to achieve target productivity levels and to improve chemical efficacy through planned treatment block selection. The basis for productivity was the Baltin-Amsden formula, which requires inputs of calibration, ferry speed, turning time, loading time and fueling time.

Another model, SSM (SpraySafe Manager), is a computer-based aerial application model designed to predict spray deposition and integrate this data with herbicide-plant dose-response curves. Developed by the New Zealand Forest Research Institute Ltd. in collaboration with the USDA Forest Service, SSM is a decision support system for aerial application of herbicides in forestry ([www.forestresearch.co.nz/topic.asp?topic=...](http://www.forestresearch.co.nz/topic.asp?topic=...), 7/29/02). It is a reliable method of calculating plant exposure and a means to mitigate adverse effects on non-target plants and protected resources (Ray et al. 1999).

Heuristic algorithms have been used to improve existing models that predict spray efficacy. AGDISP, an aerial spray simulation model, predicts the deposition of spray material released from an aircraft. The prediction is based on well-defined input parameter values as well as constant data. SAGA (Spray Advisor using Genetic Algorithm) was developed to search heuristically for optimal or near-optimal input parameters needed to achieve a desired spray deposition (Wu et al. 2002).

A model recently developed as an intelligent decision support system is STP (Spray Treatment Planner) and is an extension to the CASPR model. It evaluates productivity and efficiency in an aerial spray treatment project. It also schedules the spraying operation of selected blocks from selected airports using single or multiple aircraft. The scheduling is done to maximize the spray efficacy and productivity while minimizing the total time and distance flown. The model uses heuristics to obtain a near-optimal solution. It can be used to estimate total time required for a treatment operation and to determine an efficient treatment plan (Potter et al., 2002).

## 2.2 Helicopter Logging Operations

Helicopter logging operation computer models for evaluating productivity have primarily focused on selecting an aircraft to deliver a payload from a pickup point to a drop point at the least cost. In helicopter logging, the emphasis has been on methods for estimating cycle time and average payload to calculate the cost-per-unit volume (Hartsough et al. 1986; Malone 1991). Recent models predict a mean load volume and cycle time to determine average helicopter

yarding costs for a harvest unit (Lyons et al. 1999; Heinimann 1996). Additional research has also estimated helicopter logging productivity and costs in partial cutting operations (Kockx et al. 1993; Krag and Clark 1995; Lyons et al. 1999).

The HELIPACE program (Aerial Forest Management Foundation, first released 1990) is designed to assist harvest planners and timber appraisers (Malone 1991). The program considers variables that affect helicopter logging production and cost-per-unit of logs yarded (Giles and Marsh 1994). By comparing choices for yarding distance and landing location scenarios using various aircraft, the program estimates round trip flight times and associated yarding costs to evaluate the economic feasibility of unit layout and aircraft options (O'Brien and Brooks 1996).

The helicopter logging cost and productivity model introduced by Egging and Gibson (1974) included costs for transportation options. Road and landing construction costs plus helicopter yarding costs were summed to identify landings that minimized the total yarding, road, landing and hauling costs. The program calculated the shortest straight-line flight path around obstacles using an average flight speed. The capacity of the model was limited to eight field units, twenty road segments and one obstacle per harvest unit.

A spatial computer model introduced by Sessions and Chung (1999) assists in the strategic and tactical planning of helicopter logging operations. The strategic planning approach identifies a transportation plan that minimizes the summation of road, landing and helicopter yarding costs. The tactical planning approach provides a method for planning daily production.

Harvesting costs generally increase with yarding distance (Dykstra 1975; Heinimann 1996), but yarding distance and costs can be reduced by increasing landing availability. The strategic component of the Sessions and Chung model consists of two phases: first a search of option paths between log pickup points and landings to identify the shortest flight time from each



pickup point to each landing; a second phase searches for the combination of roads and landings to minimize total construction plus yarding costs. The tactical component of the model uses information from the strategic model solution to determine the sequence of yarding during a day to maximize yarding productivity (Sessions and Chung 1999).

### 2.3 Summary

Only two models were identified that considered transportation costs and helicopter costs together for an operation. Both of those models were for helicopter logging applications. The Egging and Gibson model introduced in 1974 has a limited capacity for options and operational conditions. The Sessions and Chung model introduced in 1999 has the possibility for evaluating a much larger combination of helicopter and transportation options to minimize total operational costs. While conceptually useful, neither model is directly suitable for modeling the mineral amendment case study.

### 3.0 CASE STUDY

#### 3.1 Land Management Objectives

The forest operations problem was identified through contact with a private forest landowner. The landowner is testing applications of minerals on stands of Douglas-fir in the Coast Range of Oregon to offset stand growth reductions from Swiss needle cast disease. The landowner desires to minimize transportation and application costs for the mineral amendment project, and when needed, plan future projects on a landscape scale. The goal is to provide an acceptable distribution of minerals on targeted units for the least total project cost.

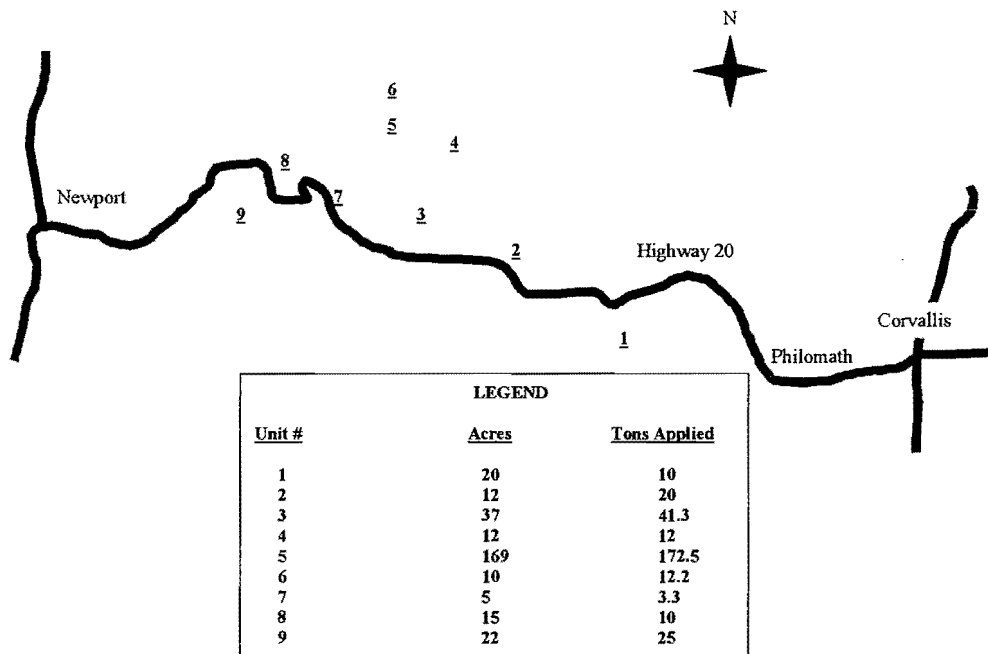
#### 3.2 The Operation

The operation involved various applications of minerals at different times. Dry material is applied in the winter and may include up to five different minerals. Then, a two-stage liquid sulfur application follows in late spring. The total 2002 acreage for the case study (dry material) application was 302 acres, with a combined amount of applied minerals of 306 tons. The mineral selected for production and cost estimates and the flight data analyses was doloprill. This mineral is a pelletized dolomitic lime with a molasses binder and consists primarily of calcium with a 9% magnesium content. The application rate ranged from 1000 – 2273 lbs/acre.

### 3.3 Study Site

The project covered nine application units in the central Coast Range of Oregon on private forestlands. The units varied from 5 acres to 169 acres, with tree ages from 2 to 30 years. The minerals were applied from January 16, 2002 to February 1, 2002. Four of the nine units in the project were chosen to formulate cost and production estimates for a transportation network (units 3, 4, 5, and 6 in Figure 1). Two of the units (4 and 5) were used in the simplified mixed-integer formulation and share a common road transportation system. Unit 5 has two heliports.

Figure 1: Vicinity map for mineral amendment project



Scale: 1 inch  $\approx$  8 miles

## 4.0 METHODOLOGY TO EVALUATE OPTIONS

### 4.1 Methodology

The solution for the heliport facility location problem began with a flowchart of important cost components for the project (Figure 2) and the helicopter costs (Figure 3). From the flowchart framework, a methodology was developed to solve questions of interest for production and costs. The mixed-integer linear programming model solution for a simplified (two field unit) version of the project was part of this approach. The subsections that follow describe steps in the methodology.

#### 4.1.1 *Operations Problem*

The first step was to describe the operations problem and a timeline for a needed solution. The operations problem of interest is to evaluate options for transportation and aerial application of minerals on Douglas-fir stands in the Coast Range of Oregon. The approach considers transportation and aerial application costs for the operation to minimize project costs. The timeline for a solution to the problem is prior to commencement of the next operation season.

Figure 2: Project flowchart of cost components for transportation and application of minerals

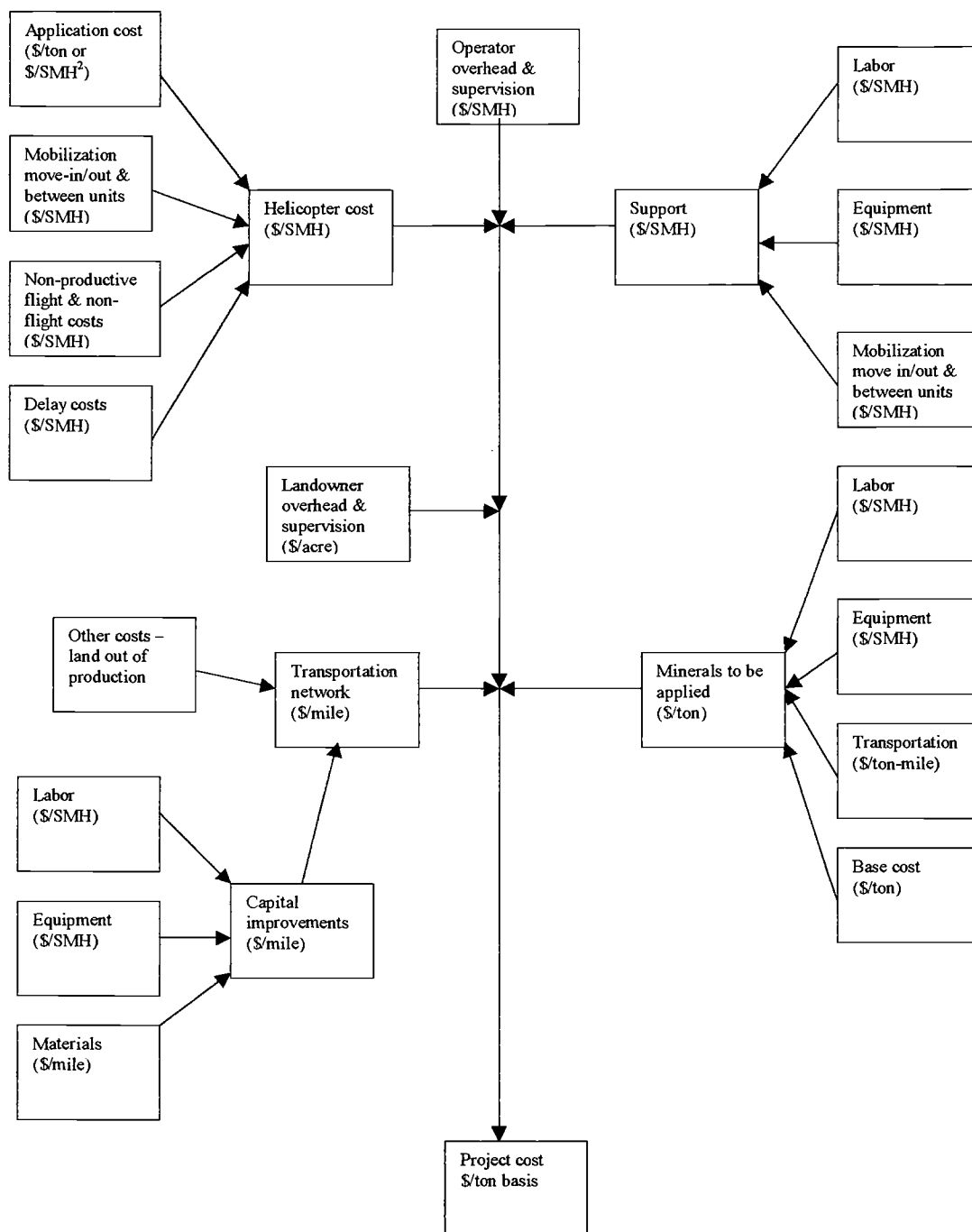
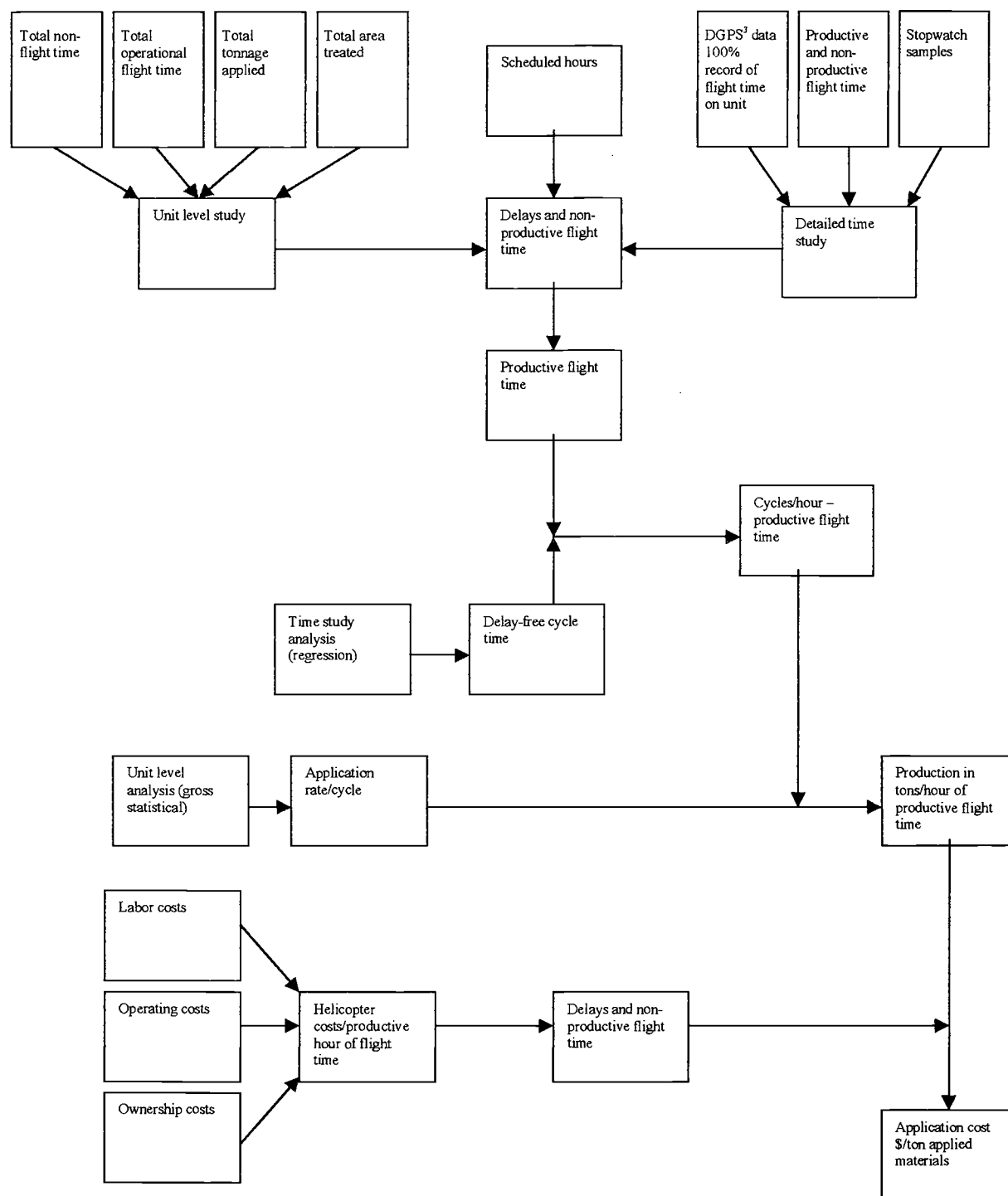
<sup>2</sup>SMH = Scheduled Machine Hour

Figure 3: Flowchart to estimate helicopter production and cost

<sup>3</sup>DGPS = Differential Global Positioning Satellite system

#### 4.1.2 *Goals and Outcomes for a Planning Solution*

The second step was to identify goals and outcomes with acceptable bounds. The goal for the planning solution is to minimize overall project costs for operations. The desired outcome is an approach to find a least-cost combination of heliports, aircraft, crew, equipment and road networks to safely meet landowner management objectives. The distribution of the minerals on the field units should be fairly uniform and applied at the target application rate, cover the entire unit, stay within unit boundaries and avoid direct application to open water.

#### 4.1.3 *Variables of Influence*

The third step was to identify significant variables of influence for the evaluation of the operation and formulation of a solution. Variables include fixed and variable costs for transportation and application of minerals. Fixed costs are lump sum costs incurred as a result of road improvement or other activities. Variable costs are expressed as dollars-per-unit of material applied (\$/ton basis). Such costs include helicopter direct operating costs, move-in costs (to heliports), helicopter costs for application and ferrying, cost of the agricultural trucks (based on estimated helicopter production per hour of flight time and number of trucks), primary transportation costs to deliver minerals to the transfer site, cost of raw minerals, cost of heliport and road improvements and cost of road maintenance. Additional variables include: quantity of minerals hauled over a road segment; ferry distance and airspeed of the helicopter from the heliport or service landing to the unit; calibrated application rate; acceleration and deceleration

of the helicopter; heliport configuration and approach and departure paths; and helicopter payload.

#### 4.1.4 *Visual Concept Model*

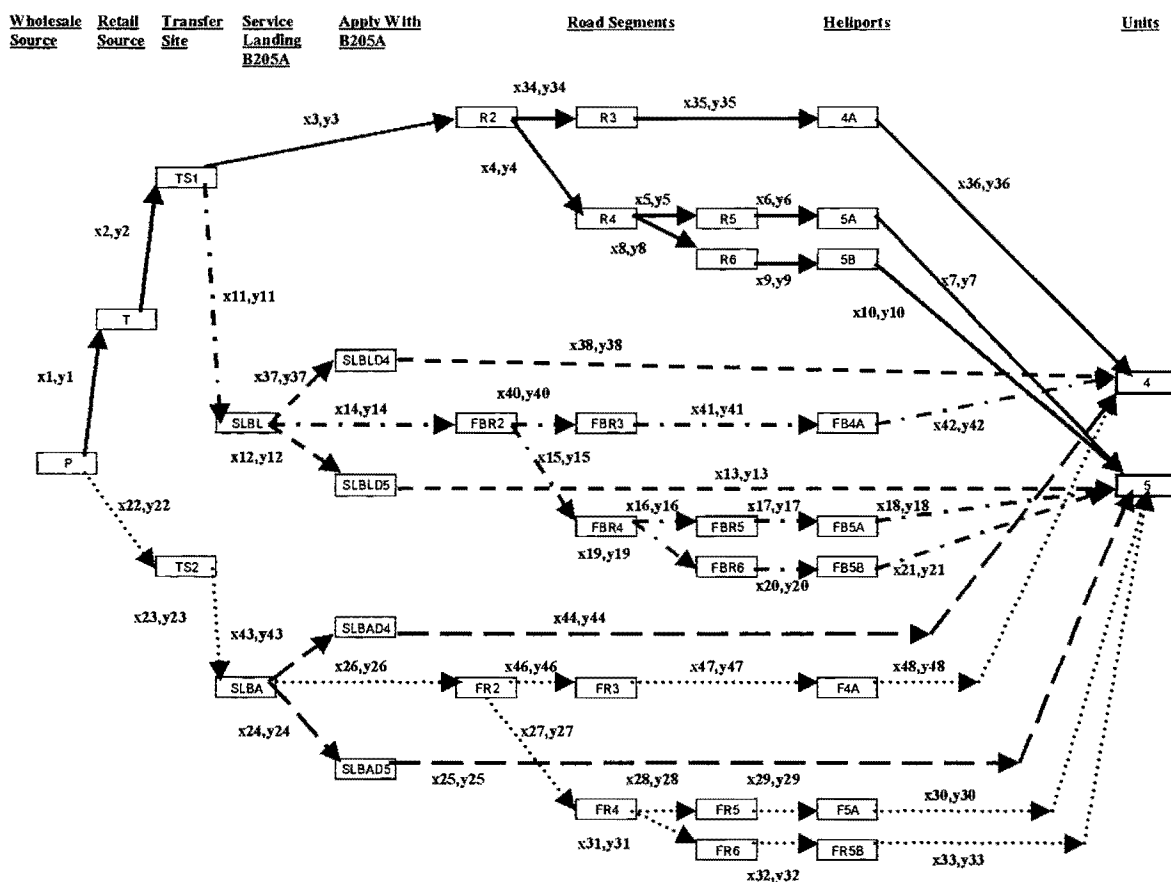
The fourth step visualized the problem in terms of a transportation network to address influences from significant and interacting variables. Figure 4 represents the visual concept of five options for transportation “routes” for two application units in the case study. The options include one main factory source of minerals, two choices for delivery of minerals to the transfer site (bulk or bag) and three choices for delivery of minerals to each unit.

#### 4.1.5 *Mathematical Models*

The fifth step used existing software programs to solve a mathematical algorithm representing the operations problem. A mixed-integer linear programming model was derived from the concept model as a heliport facility location problem. Equations for the mixed-integer model include fixed and variable cost links represented in Figure 4. The objective function includes both continuous and integer variables and cost coefficients for the variables. The goal is to identify a combination of transportation and application options to minimize total fixed and variable costs for the two-unit scenario.

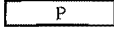
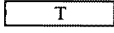
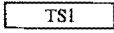
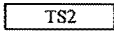

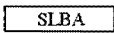

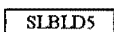
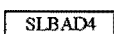

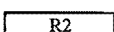
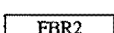
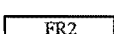
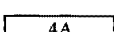
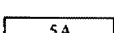
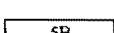
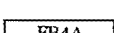
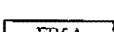
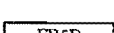
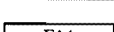

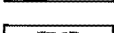




Figure 4: Visual concept diagram of transportation network for five options to transport and apply doloprill to units #4 and #5








### Key for visual concept diagram (Figure 4)

#### Network Nodes:

	Wholesale source of materials applied
	Retail source of materials applied
	Transfer site for bulk material
	Transfer site for bagged material
	Service landing for B205A bulk material
	Service landing for B205A bagged material
	Dummy node for direct apply with B205A of bulk material to Unit 4
	Dummy node for direct apply with B205A of bulk material to Unit 5
	Dummy node for direct apply with B205A of bagged material to Unit 4
	Dummy node for direct apply with B205A of bagged material to Unit 5
	Road segment/node for conventional application with B47G3 and bulk material
	Road segment/node for ferry with B205A, apply with B47G3 and bulk material
	Road segment/node for ferry with B205A, apply with B47G3 and bagged material
	Heliport for Unit 4, apply with B47G3 bulk material
	Heliport for Unit 5, apply with B47G3 bulk material
	Heliport for Unit 5, apply with B47G3 bulk material
	Heliport for Unit 4, ferry with B205A, apply with B47G3 bulk material
	Heliport for Unit 5, ferry with B205A, apply with B47G3 bulk material
	Heliport for Unit 5, ferry with B205A, apply with B47G3 bulk material
	Heliport for Unit 4, ferry with B205A, apply with B47G3 bagged material
	Heliport for Unit 5, ferry with B205A, apply with B47G3 bagged material
	Heliport for Unit 5, ferry with B205A, apply with B47G3 bagged material
	Unit 4
	Unit 5

#### Network Links:

$x_{24}, y_{24}$	Variables for link: variable and fixed costs; {0,1} variables
	Transportation route for bulk material; apply with B47G3
	Transportation route for bulk material; ferry with B205A; apply with B47G3
	Transportation route for bulk material; direct apply with B205A
	Transportation route for bagged material; ferry with B205A; apply with B47G3
	Transportation route for bagged material; direct apply with B205A

The concept model was further used to formulate another mathematical model that applies a heuristic algorithm (Network 2000, Chung and Sessions 2000) to search for feasible solutions to the heliport facility location problem. This model may not find the optimum, but it searches for a “good” solution that can be close to the optimum.

#### 4.1.6 *Generalized Solution*

The sixth step used data and information from the case study to solve the mathematical formulations developed in step 5. Linear equations were formulated for two units in the case study that have a shared road transportation system. One of the units had two heliports. The mixed-integer model was solved using commercial linear programming software that allowed the use of  $\{0,1\}$  integer variables for the transportation and application option that minimized total cost. The heuristic model (Network 2000, Chung and Sessions 2000) was used to solve for the least-cost network solution.

#### 4.1.7 *Comparison of Selected Components of Case Study With Mathematical Models*

The seventh and final step compared the results of the mathematical models with selected components of the case study. The empirical formulations for important cost and production variables were developed in spreadsheet format. The estimated costs in the spreadsheet

summaries were used to verify the solutions for the mixed-integer model and the heuristic algorithm model.

The flight data from the case study was compared to empirical estimates for helicopter production. A simple linear regression was developed from the helicopter flight data to estimate average total delay-free cycle time. The empirical estimates for cycle time fell within the 95% prediction band limits for the regression. A second randomly selected data set indicated the regression consistently predicts average total delay-free cycle time within specified operational conditions and limits of the case study.

## **5.0 DATA COLLECTION**

### **5.1 Data Collection Techniques**

Previous experience with collecting production data in logging operations has shown it to be challenging due to variability of the operating environment (Olsen and Kellogg 1983). The same is true for aerial forest operations because the activity is outdoors and performed under varying weather conditions and changing geographic locations.

Production study methods are used to calculate productive time and non-productive time, allocate productive time into cycle elements, and quantify interactions between equipment, personnel and operational attributes. The methods used for the case study include collection of shift level production data and detailed flight time data. Diagrams developed to identify time study elements and variables are in Appendix A. The forms used to collect production data are in Appendix G.

### **5.2 Objectives for Data Collection**

The overall objective for data collection was to obtain production information for the B47G3 helicopter applying an experimental mineral and use that information to estimate production for future projects.

### 5.2.1 *Shift Level Objective*

The objective for collecting shift level data was to determine the general production rate of the B47G3 for the application of a selected mineral in the case study.

### 5.2.2 *Detailed Flight Time Objective*

The objective for collection of detailed flight time data was for three purposes: to evaluate the empirical production models; to evaluate operational aspects of the project (e.g. restricted heliport approach and departure flight path) and the effect on production and costs; and to develop a regression to estimate helicopter cycle time.

Random samples of delay-free cycle data were used to complete the analyses. Ten cycles from units 3, 4, 5, and 6 were plotted and compared to the empirical model estimates for total cycle time. Twenty-five cycles from units 3 and 5 were used to evaluate the relative effect of restricted approach and departure flight paths for a heliport on total cycle time and to evaluate the influence of acceleration and deceleration on elapsed time. Two independent samples of fifty cycles each from the entire project were used to develop and validate a simple linear regression to predict an average total cycle time.

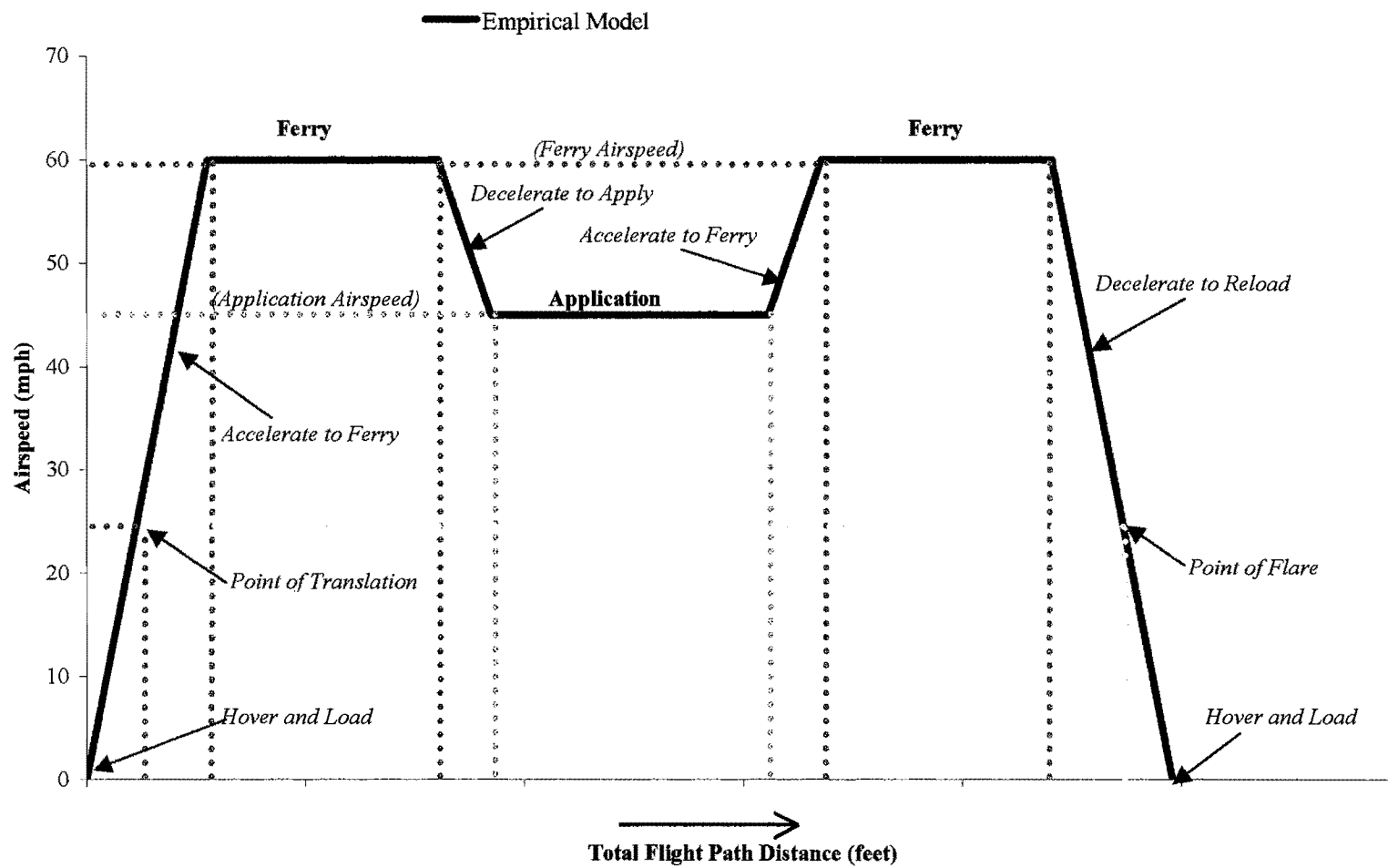
### 5.3 Data Description

To control variation in the case study, the same pilot, helicopter, support crew and agricultural trucks were used for the entire project. The pilot was highly skilled with a total of 6000 flight hours, of which 2500 hours were in aerial application operations and included 2.5 years of experience with aerial GPS navigation systems.

The cycle elements (Figure 5) for the empirical model are the same for flight data collection for a delay-free cycle and include:

- Hover and reload: the time it takes to reload the helicopter with the desired payload
- Lift and accelerate: the time from when loading is completed to the point of translation (airspeed above 25 mph) of the aircraft
- Outhaul: the time the helicopter travels from point of translation to application unit
  - Accelerate to ferry velocity
  - Ferry distance
  - Decelerate to application velocity
- Application on operations unit
- Inhaul: the time it takes the helicopter to travel from the application unit to point of flare (airspeed below 25 mph) of the aircraft
  - Accelerate to ferry velocity
  - Ferry distance
  - Decelerate to flare
- Hover and reload: the time from when the helicopter flares to when it comes to a hover for reloading

Figure 5: Empirical model estimate for helicopter flight pattern in a delay-free cycle





### 5.3.1 *Shift Level Data*

According to Olsen and Kellogg (1983), shift level summaries are hourly production averages based on an observer's (worker) records of pieces handled and hours worked. For this project, the shift level data summary was based on an observer's record of the tons of material applied, productive flight time and non-productive flight time.

### 5.3.2 *Detailed Flight Data*

The detailed time study is a direct observation technique to determine the time required for a qualified, well-trained person working at a normal pace to perform a defined task (Keyserling 2000). Data collection for detailed flight time used the Ag-Nav<sup>®</sup>2 differential global positioning system (DGPS) installed on a Bell 47G3 (B47G3) helicopter. The latitude, longitude and elevation of the helicopter were recorded every 0.6 of a second and have an accuracy of one meter or less under ideal conditions (Reynolds 1999). The Ag-Nav<sup>®</sup>2 system also recorded a unit map with flight lines and application swaths flown by the helicopter. Examples of unit maps with flight lines and application swaths are in Appendix H. The flight and application data were cross-referenced with non-productive flight times and activities recorded with the shift level information to identify delay-free cycles.

## 6.0 PRODUCTION AND COST ESTIMATES

### 6.1 Transportation Options

The operation modeled includes five operational scenarios for applying one type of mineral to each one of the two field units. Assumptions for formulation of the options include: one main factory source of mineral, two primary transportation choices for mineral delivery to the transfer site (bag or bulk) and three choices for aerial delivery of the mineral to each unit.

The first option evaluated was the method by which the project was conducted. This includes:

- Ground transportation of the bulk material from the factory source to a retailer
- Ground transportation from a retailer to a transfer site
- Transfer from the retailer trucks to 13-ton agricultural trucks
- Ground transportation on forest roads with the 13-ton trucks to the heliports
- Transfer to a B47G3 helicopter for aerial delivery of the material to the unit with a fiberglass bucket application system (Figure 6)

The second and third options involved the use of a Bell 205A1 (B205A1) helicopter to ferry the materials (bulk or bag) from the transfer site to the heliports, transferring materials to agricultural trucks and then transferring materials to the B47G3 helicopter for aerial delivery to the unit. The only difference between these two options is the form of the mineral (bag or bulk).

Figure 6: B47G3 helicopter with fiberglass bucket



The fourth and fifth options used the B205A1 helicopter to load the mineral (bulk or bag) at a transfer site in an application bucket, ferry to the application unit and then apply the mineral directly to the unit with no further transfers. The only difference between these two options is the form of the mineral (bulk or bag).

Assumptions for operational choices included no delays for delivery of material to the transfer site or to the heliports. In the aerial ferry with the B205A1 to support the B47G3 application, production rates were assumed balanced for any given operation period. The production basis for the agricultural truck coincided with the lowest production rate for the application helicopter, and finally the bagged material was assumed to be in specially packaged 1000-pound bags. The costs for the 1000-pound bags were hypothetical and do not include any additional packaging, transportation or handling costs that may be associated with the mineral in this form. The landowner assumed the bagged form of the mineral, if made available, may lower overall handling costs and limit the amount of fines in the material by reducing the number of times it had to be transferred. It would also be less exposed to the effects of weather (Gourley 2002).

## 6.2 Empirical Production Models

Production estimates for the helicopters were calculated from the author's empirical production model (Figure 5 in Chapter 5). The model estimates a total cycle time for each helicopter based on an average forward acceleration/deceleration airspeed, a maximum ferry

speed, a total ferry distance, a maximum payload and a calibrated application rate (where appropriate). Calculations for the model are in spreadsheet format in Appendix B.

The production rate for the helicopter was assumed to be the controlling factor for overall production on the operation. Production rates for the agricultural trucks were based on the lowest estimated production rate for a helicopter for a given heliport.

### 6.2.1 *Helicopter Production*

Production estimates for the helicopters were based on a maximum external HOGE (hover out-of-ground-effect) payload of 1000 pounds for the B47G3 and 3200 pounds for the B205A1 (Conklin and deDecker Associates, Inc 2001). The estimated maximum payloads are for relative comparison purposes only and do not necessarily represent the actual operating payloads for a given operation. Estimated payloads were reduced for some heliport and loading configurations because of terrain limitations and to adjust for potential safety hazards.

The estimated production rate (tons-per-hour of flight time) for application was calculated using the maximum payload, a maximum ferry velocity (adjusted for maximum payload), an average application velocity, bucket dispensing rate, swath width, total flight path ferry distance and reload time for each option, unit and heliport (Table 1). The total estimated cycle time for an application was a function of the calculated application time for a payload (based on target application velocity, bucket rate and swath width), reload time, and travel time to and from the application unit. (Due to the form and density of the mineral, the maximum swath width was 50 feet). The travel time to and from the unit was calculated as a function of

Table 1: Empirical model production estimates for helicopters for transportation network options (tons/hour)

Option Unit Heliport	Option 1 <sup>1</sup>			Option 2 <sup>2</sup>			Option 3 <sup>3</sup>			Option 4 <sup>4</sup>		Option 5 <sup>5</sup>	
	5	5	4	5	5	4	5	5	4	5	4	5	4
	5A	5B	4A	5A	5B	4A	5A	5B	4A	n/a	n/a	n/a	n/a
B47G3 (apply)	9.7	14.8	20.0	9.7	14.8	20.0	9.7	14.8	20.0	-	-	-	-
B205A1 (apply)	-	-	-	-	-	-	-	-	-	15.4	24.0	15.4	24.0
B205A1 (ferry)	-	-	-	18.3	16.9	30.0	18.3	16.9	30.0	-	-	-	-

Footnotes:

- 1 Bulk application with B47G3; ground transportation
- 2 Bulk application with B47G3; aerial ferry B205A1 from transfer site
- 3 Bag application with B47G3; aerial ferry B205A1 from transfer site
- 4 Bulk application with B205A1, ferry from transfer site
- 5 Bag application with B205A1, ferry from transfer site

the total flight path distance to the center of the unit, an average estimated acceleration and deceleration rate and a maximum ferry velocity. The acceleration rate was used for acceleration to ferry velocity from a heliport, transfer site or to application velocity. A deceleration rate was used to decelerate from ferry velocity to application velocity and to decelerate to the heliport or transfer site. When the total flight path ferry distance was less than the sum of the distances required to accelerate to maximum ferry velocity and decelerate to application velocity, the model calculated the time to accelerate to the application velocity instead of the maximum ferry velocity. The production model calculations are in Appendix B.

Equations used to estimate production are as follows:

$$T_c = [2*(T_a + T_d + T_f)] + T_p + T_l$$

$$P_r = (P_l / T_c) * f_l$$

$$T_a = [ \text{if } (S_a + S_d) < S_{tf}, \text{ then } T_a = v_f / a ] \text{ or } [ \text{if } (S_a + S_d) \geq S_{tf}, \text{ then } T_a = \{(2 * S_{tf})/a\}^{1/2} ]$$

$$T_d = (v_f - v_p) / a$$

$$T_f = S_f / v_f$$

$$T_p = P_l / (A_p * B_r)$$

$$A_p = s_w * V_p * f_2$$

$$S_f = S_{tf} - (S_a + S_d)$$

$$S_a = (1/2)(a)(T_a)^2$$

$$S_d = (v_f)(T_d) - (1/2)(a)(T_d)^2$$

$$S_p = v_p * T_p$$

$$S_c = (2 * S_{tf}) + S_p$$

where:

$T_c$  = total cycle time (seconds)

$T_a$  = time to accelerate to ferry or apply (seconds)

$T_d$  = time to decelerate to apply or reload (seconds)

$T_f$  = time to ferry (seconds)

$T_p$  = time to apply (seconds)

$T_l$  = time to reload (seconds)

$P_r$  = production (tons/flight hour)

$P_l$  = maximum payload for helicopter (pounds)

$f_l = 1.8$  = unit conversion factor = (1 ton/2000 lbs)\*(3600 secs/1 hour)

$a$  = maximum average acceleration/deceleration rate (feet/second<sup>2</sup>)

$v_f$  = maximum ferry velocity (feet/second)

$v_p$  = target application velocity (feet/second)

$B_r$  = bucket dispensing rate (pounds/acre)

$A_p$  = application potential (acres/minute)

$s_w$  = target application swath width (feet)

$V_p$  = application velocity (miles per hour)

$f_2 = 0.002$  = unit conversion factor = (5280 ft/mile)\*(1 acre/43,560 ft<sup>2</sup>)\*

(1 hour/60 minutes)

$S_{tf}$  = one-way total flight path ferry distance (feet)

$S_f$  = one-way ferry distance excluding distance to accelerate and decelerate (feet)

$S_a$  = one-way distance to accelerate to ferry velocity or application velocity (feet)

$S_d$  = one-way distance to decelerate to application velocity or reload (feet)

$S_p$  = distance to apply (feet)

$S_c$  = total flight path distance (feet)



A graphical representation of model variables is illustrated in Figure 7.

The production rate estimates for the B205A1 aerial ferry used an average cycle time based on the maximum payload, a maximum ferry velocity, a total flight path ferry distance and a hook/unhook time. The travel time to and from the unit was calculated as a function of the flight path distance to a heliport from the transfer site, an average estimated acceleration and deceleration rate and a maximum ferry velocity. No other adjustments to the cycle time were made for delays, breakdowns, reconnaissance, or other non-productive flight time elements.

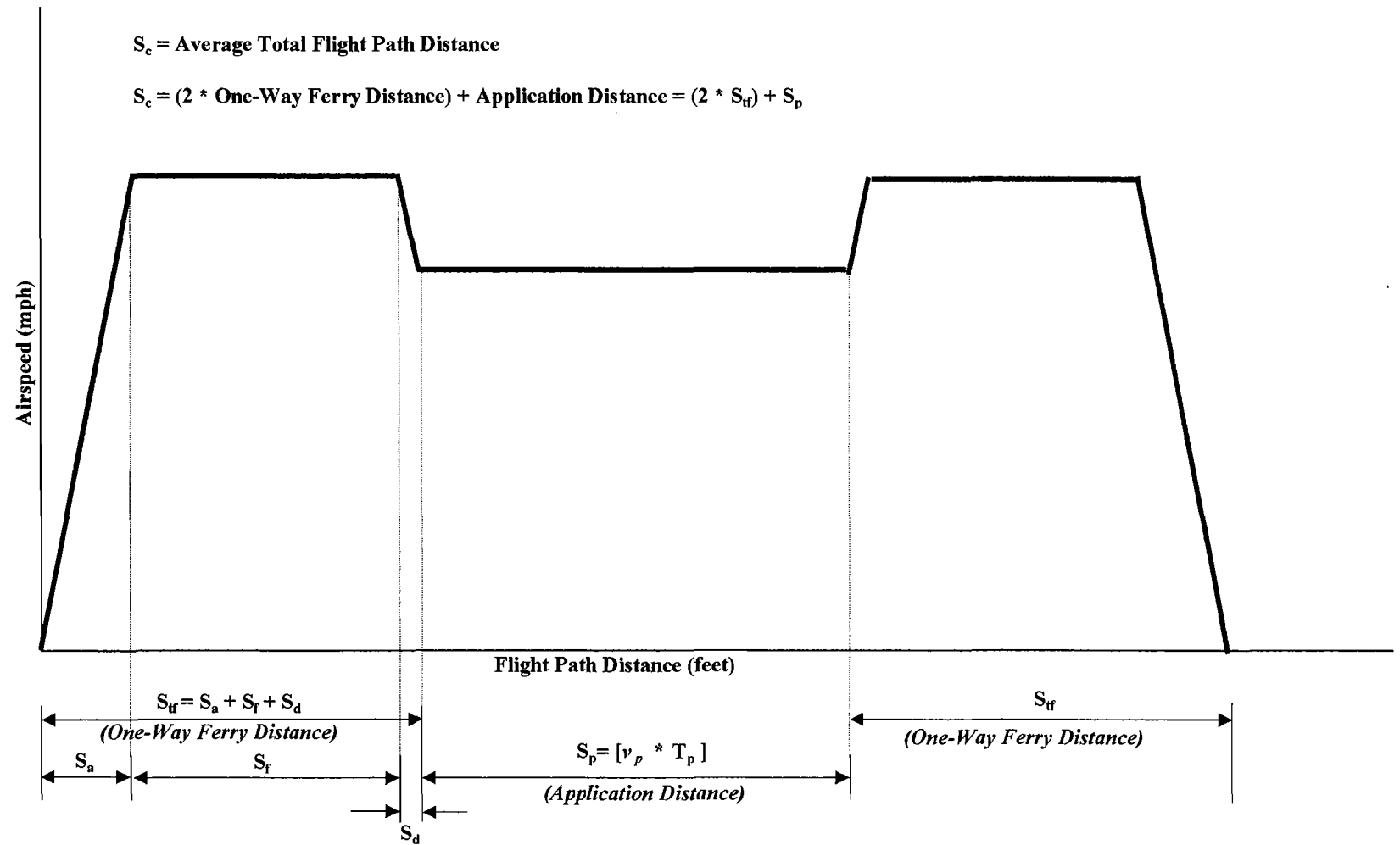
Pilot estimates of a forward acceleration rate range from 2 ft/sec<sup>2</sup> for the B47G3 (Mateski 2002) up to 8 ft/sec<sup>2</sup> for the B205A1 (Cline 2002) with full payloads. A conservative figure of 3.5 ft/sec<sup>2</sup> (Sessions 2002) was used as a maximum for both helicopters. The deceleration rate was assumed equal to the acceleration rate.

The maximum acceleration rate assumed an ambient air temperature below 50°F, no wind, elevations below 1200 feet above mean sea level and unrestricted approach and departure flight paths with less than a 25% gradient. Maximum payload estimates and acceleration rate need to be adjusted for individual aircraft, steeper approach and departure angles and density altitude effects (higher ambient air temperatures, and/or a higher elevation).

### 6.2.2 *Agricultural Trucks*

Production estimates for the agricultural trucks were calculated from the potential production of the application helicopter for a given heliport. Helicopter production was based on

Figure 7: Empirical helicopter model estimate of average total flight path distance



5 hours of productive flight time per day (100% utilization) and the estimated production rate for a selected aircraft and heliport or transfer site. When the daily total quantity exceeded 13 tons on a unit for application with the B47G3, a minimum of two agricultural trucks were required.

When turnaround time for transfer and travel to a heliport was over 1.5 hours, three trucks were required. When material was ferried by the B205A1 and applied with the B47G3, the same assumptions applied for minimum number of trucks required. With direct application by the B205A1, no trucks were required.

### 6.3 Cost Estimates

Costs included: application and ferry with a helicopter, agricultural trucks, raw material, primary ground transportation, road and heliport improvements and road maintenance. Project costs were a combination of fixed and variable costs to deliver the mineral to a target unit. Fixed costs were assumed to be lump sum costs incurred as a result of move-in, road improvement or other activities. They were independent of the quantity of material applied. Variable costs were expressed as dollars-per-unit of material applied (\$/ton basis). The dollar-per-ton costs in the case study were assumed to be constant and did not vary with the quantity of mineral applied. The helicopter and agricultural truck costs were derived from constructed, direct operating costs-per-hour of productive flight time for the helicopter and estimated helicopter production. The cost for the bagged form of doloprill were hypothetical and currently lack an actual cost estimate basis. For each option, the total costs were reduced to a \$/ton figure and include transportation and application costs. Details of cost estimates are in Appendix B.

The costs for the helicopter, agricultural trucks, minerals and road improvements did not include profit or risk for the landowner or operator or opportunity costs or returns on investments for stand improvement. Other costs not included:

- Management overhead costs for the operator (project supervisor, planning work and preparation)
- Support equipment cost (fuel truck, transport vehicles for crew, service truck)
- Project move-in and set up costs
- Management overhead and equipment costs for the landowner (project supervisor, transport vehicle, office support, planning work and preparation)
- Costs for delays, breakdowns and non-productive time (such as moving between units, weather delays, reconnaissance)

### 6.3.1 *Helicopters*

The method of helicopter cost calculation used provides a common basis for estimating costs of different helicopters to facilitate a comparison of options. The cost estimates may not reflect current market conditions and are not intended to represent the actual costs for a particular operator. These constructed costs are likely to be low and should not be used to assess the economic viability of a project. Model users should use actual helicopter costs for their prospective project based on individual circumstances.

Direct operating cost estimates for the helicopters were derived from information supplied by an independent aviation consulting firm (Conklin and deDecker Associates, Inc.

2001). The estimated direct operating cost for the B47G3 was \$426 per flight hour. The estimated direct operating cost for the B205A1 was \$1134 per flight hour. The basis for the B47G3 and the B205A1 was a 400-flight hour operating season (12-month year) and assumed 100% utilization for the project. Details of direct operating cost calculations are in Appendix B.

The estimated cost-per-ton of applied or ferried material for a helicopter was the operating cost-per-hour of flight time divided by the estimated production rate in tons-per-hour of productive flight time by option, unit and heliport (Table 2). Helicopter costs for the B47G3 were \$28.74/ton on heliport 5B and \$43.93/ton on heliport 5A for unit 5 and were \$21.26/ton on unit 4. The ferry costs for the B205A1 were \$61.85/ton to heliport 5A and \$66.89/ton to heliport 5B on unit 5 and were \$37.73/ton on unit 4. Direct application costs for the B205A1 were \$73.67/ton on unit 5 and \$47.25/ton on unit 4.

### 6.3.2 *Agricultural Trucks*

Costs for the agricultural trucks were based on estimates for: purchase price, annual maintenance costs and lifespan. The lifetime basis for the truck was 18,000 scheduled machine hours (SMH), with a five-month operating season and 1200 SMH per year. The driver was included in the truck cost. The estimated cost for truck and driver was \$362 per day.

The cost-per-ton of applied material for the agricultural truck was the total cost-per-day for each truck divided by the estimated minimum production rate in tons-per-day of the application helicopter by unit, option and heliport (Table 3). The agricultural truck costs were

Table 2: Cost estimates for helicopters for transportation network options (\$/ton)

Option Unit Heliport	Option 1 <sup>1</sup>			Option 2 <sup>2</sup>			Option 3 <sup>3</sup>			Option 4 <sup>4</sup>			Option 5 <sup>5</sup>		
	5 5A	5 5B	4 4A	5 5A	5 5B	4 4A	5 5A	5 5B	4 4A	5 5A	5 5B	4 4A	5 5A	5 5B	4 4A
B47G3 (apply)	43.93	28.74	21.26	43.93	28.74	21.26	43.93	28.74	21.26	-	-	-	-	-	-
B205A1 (apply)	-	-	-	-	-	-	-	-	-	73.67	73.67	47.25	73.67	73.67	47.25
B205A1 (ferry)	-	-	-	61.85	66.89	37.73	61.85	66.89	37.73	-	-	-	-	-	-

Footnotes:

- 1 Bulk application with B47G3; ground transportation
- 2 Bulk application with B47G3; aerial ferry B205A1 from transfer site
- 3 Bag application with B47G3; aerial ferry B205A1 from transfer site
- 4 Bulk application with B205A1, ferry from transfer site
- 5 Bag application with B205A1, ferry from transfer site

Table 3: Cost estimates for agricultural trucks, doloprill, and transport to transfer site for transportation network options (\$/ton)

Option	Option 1 <sup>1</sup>			Option 2 <sup>2</sup>			Option 3 <sup>3</sup>			Option 4 <sup>4</sup>			Option 5 <sup>5</sup>		
Unit	5	5	4	5	5	4	5	5	4	5	5	4	5	5	4
Heliport	5A	5B	4A	5A	5B	4A	5A	5B	4A	5A	5B	4A	5A	5B	4A
<u>Agricultural Truck</u>															
B47G3 (apply)	22.42	14.67	3.62	-	-	-	-	-	-	-	-	-	-	-	-
B205A1 (apply)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B205A1 (ferry)	-	-	-	14.95	9.78	3.62	14.95	9.78	3.62	-	-	-	-	-	-
<u>Doloprill</u>															
Bulk	140.00	140.00	140.00	140.00	140.00	140.00	-	-	-	140.00	140.00	140.00	-	-	-
Bag	-	-	-	-	-	-	130.00	130.00	130.00	-	-	-	130.00	130.00	130.00
<u>Delivery to Transfer Site</u>															
Bulk	2.75	2.75	2.75	2.75	2.75	2.75	-	-	-	2.75	2.75	2.75	-	-	-
Bag	-	-	-	-	-	-	1.61	1.61	1.61	-	-	-	1.61	1.61	1.61

Footnotes:

- 1 Bulk application with B47G3; ground transportation
- 2 Bulk application with B47G3; aerial ferry B205A1 from transfer site
- 3 Bag application with B47G3; aerial ferry B205A1 from transfer site
- 4 Bulk application with B205A1, ferry from transfer site
- 5 Bag application with B205A1, ferry from transfer site

\$14.67/ton to heliport 5B and \$22.42/ton to heliport 5A on unit 5 and were \$3.62/ton on unit 4 with the B47G3 direct application. The truck costs were \$9.78/ton to heliport 5B and \$14.95/ton to heliport 5A on unit 5 and were \$3.62/ton on unit 4 when used with the B205A1 aerial ferry option. There were no agricultural truck costs for the B205A1 direct application option.

### 6.3.3 *Material and Transportation*

The material and primary delivery costs for the bulk form of the mineral were estimated at \$142.75/ton delivered to the transfer site from historic records. The cost for the bagged form of the mineral was estimated at \$131.62/ton delivered to the transfer site (Gourley 2002; Krohn 2002) (Table 3).

### 6.3.4 *Road and Heliport Improvements, Maintenance, Move-In*

Road improvement (fixed) and maintenance (variable) costs were estimated from values provided by the landowner and included costs for grading, rock and repairs prior to and after the operation (Mortenson 2002). Additional costs were included for grading and rock wear (Table 4).

Improvement costs for roads, heliports and move-in to the heliports, ranged from \$1510 to \$10,629 for fixed costs with the B47G3 direct application. Variable costs ranged from



Table 4: Cost estimates for road and heliport improvements and maintenance for transportation network options

Option Unit Heliport	Option 1 <sup>1</sup>			Option 2 <sup>2</sup>			Option 3 <sup>3</sup>			Option 4 <sup>4</sup>			Option 5 <sup>5</sup>		
	5	5	4	5	5	4	5	5	4	5	5	4	5	5	4
	5A	5B	4A	5A	5B	4A	5A	5B	4A	5A	5B	4A	5A	5B	4A
Fixed (\$)	4574.00	10629.00	1510.00	2250.00	4250.00	1750.00	2250.00	4250.00	1750.00	1500.00	1500.00	1500.00	1500.00	1500.00	1500.00
Variable (\$/ton)	0.50	0.57	0.25	-	-	-	-	-	-	-	-	-	-	-	-

Footnotes:

- 1 Bulk application with B47G3; ground transportation
- 2 Bulk application with B47G3; aerial ferry B205A1 from transfer site
- 3 Bag application with B47G3; aerial ferry B205A1 from transfer site
- 4 Bulk application with B205A1, ferry from transfer site
- 5 Bag application with B205A1, ferry from transfer site

\$0.25/ton to \$0.57/ton for this option. For the aerial ferry with the B205A1, the fixed costs ranged from \$1500 to \$4250 and there were no associated variable costs for road maintenance. The direct application with the B205A1 had a fixed cost of \$1500 and no variable costs for road maintenance (Table 4).

Overall move-in costs to the project area were not included for this single operation. A cost of \$250 was included for the move-in of the B47G3 to each heliport. The use of the B205A1 included a cost of \$1500 for move-in and improvements to a central service landing.

## 7.0 MATHEMATICAL MODELS FOR OPERATIONS PLANNING

### 7.1 Mathematical Models

Three mathematical models were formulated to provide a solution for a simplified version of the transportation network problem. Two formulations used mixed-integer linear programming techniques and the third used a program with a heuristic algorithm. The models were evaluated for ease of formulation, length of solution time, applicability and quality of solution outputs. The empirical production models and cost estimates from spreadsheet calculations were used to verify the results of the mathematical models. The spreadsheet summaries are in Appendix B.

The solution for the operations questions began with the model conceptualization to identify significant components of the transportation problem. Figure 4 in Chapter 4 illustrates the concept model of the transportation network options for units 4 and 5. The mathematical formulations were derived from this visual model. The mixed-integer models provided an optimal solution to the simplified version of the case study problem minimizing total transportation and application costs. The heuristic algorithm model typically provides a near-optimal solution for combined fixed and variable costs in the transportation network.

## 7.2 Formulations

### 7.2.1 *Mixed-Integer Linear Programming Models*

The equations for the mixed-integer model software included formulations for fixed and variable costs for links in the visual model. The formulation of the heliport facility location problem for units 4 and 5 included an objective function, 92 variables (46 were designated as (0,1) integers) and 82 constraint equations. The input details are in Appendix C. The objective function is:

$$\text{Minimize: (Fixed Costs) + (Variable Costs) = } \sum f^k y^k + \sum c^k x^k$$

Subject to the following constraints:

Road triggers:

$$M^k y^k \geq x^k \quad \text{for } k = 1 \text{ to } n$$

Conservation of flow:

$$\sum_{h \in H_i} x_{hi} = \sum_{j \in J_i} x_{ij} \quad \text{for } i = 1 \text{ to } m$$

Integers:

$$y^k = \{0,1\} \quad \text{for } k = 1 \text{ to } n$$

where:

$n$  = number of links in network

$m$  = number of nodes in network

$k$  = link designator

$f^k$  = fixed cost coefficient for  $y^k$  variable for link  $k$

$y^k = 0,1$  variable indicating whether or not link  $k$  is used

$c^k$  = variable cost coefficient for  $x^k$  variable for link  $k$

$x^k$  = volume transported over link  $k$

$M$  = a large number greater than the maximum potential quantity of material to be hauled over that transportation link

$i$  = node designator

$h$  = designator for link entering a node

$j$  = designator for link leaving a node

$H_i$  = set of links entering node  $i$

$J_i$  = set of links leaving node  $i$

The fixed cost coefficients,  $f^k$ , are the cost coefficients for the  $y_k$  variables shown in Figure 4. The variable cost coefficients,  $c^k$ , are the cost coefficients for the  $x_k$  variables shown in Figure 4.

The model was solved using Hyper LINDO® 6.1 and What'sBest!® mixed-integer linear programming software.

### 7.2.2 A Heuristic Algorithm Model

Chung and Sessions (2000) developed a program for analyzing large fixed and variable cost transportation problems. The Network 2000 program has been used to solve scheduling and transportation problems for timber harvesting. The software program uses three different heuristic algorithms with intelligent neighborhood search rules.

The three heuristic algorithms used include: a shortest path algorithm and two probabilistic algorithms, simulated annealing and great deluge. Complete details for the algorithms used in the software program are in Chung and Sessions (2000).

The shortest path algorithm calculates a minimum cost for the operations problem based on the following equation (Chung and Sessions 2000), where the fixed costs are converted to an equivalent variable cost by the known volume that passes over a link:

$$VC_i = VC_{INTi} + \frac{FC_i}{\sum Vol_i} \quad \text{for } i = 1 \text{ to } n$$

where,

$n$  = Number of links in network

$VC_i$  = Variable cost for link  $i$

$VC_{INTi}$  = Initial variable cost for link  $i$

$FC_i$  = Fixed cost for link  $i$

$Vol_i$  = Volume transported over link  $i$

In the formulation for units 4 and 5, there were 2 source and destination links and 48 network links with associated fixed and variable costs. Details of the link information are in Appendix E.

### 7.3 Fixed and Variable Cost Information

Estimating fixed and variable costs for transporting and applying the experimental mineral was essential for use in the mathematical models. Road and heliport improvement costs

were from the landowner. The service landing cost and heliport move-in costs were constructed costs. Costs for the aerial application of the mineral were constructed from production rates for the selected helicopters. Production rates were based on empirical estimates of an average total cycle time for a unit. Total cycle time was comprised of a calibrated application time, travel time to and from the unit or heliport (including time to accelerate and decelerate) and a load or hook/unhook time. Potential nonlinear production relationships were not included in the mathematical models. Fixed estimates based on assumed static parameters were used. For example, the average flight path distance for each application scenario was from a given heliport or transfer site to the geographic center of a unit.

#### 7.4 Software Capacity

The capacity for the Hyper LINDO®6.1 version is 4,000 constraints, 8,000 variables and 800 integers. This package cannot incorporate nonlinear variables. Using the simplified version of the case study as an indicator, this software program could be used to plan a project roughly 10,000 acres in size.

The capacity for the What'sBest!® Professional version is 4,000 constraints, 8,000 variables, 800 integers and 800 nonlinear variables. Using the simplified version of the case study as an indicator, this software program could be used to plan a project roughly 10,000 acres in size. What'sBest!® Extended has an unlimited capacity for constraints, variables and integers.

The professional version of Network 2000 has a capacity of 20,000 links, 20,000 nodes and 5,000 sales. A sale is equivalent to an application unit for the case study. Using the

simplified version of the case study as an indicator, this software program could be used to plan a project roughly 150,000 acres in size.

The actual maximum size of a planned project for each mathematical model will also depend on the formulations of the network links and variables.

## 7.5 Results

The mathematical models used to solve the heliport facility location problem were suitable for this type of application. The solution of the mixed-integer programming formulations was a cost minimization of the simplified two-unit version of the case study. The solution contained a transportation and application option that minimized the total cost of applying a mineral to a combination of units with shared transportation routes. The lowest cost route for the two units favored the direct application of “bagged” material with the B205A1 (Table 5, Option 5). A relative comparison of routes indicates Option 5 resulted in an estimated cost reduction of 9% from the current application approach (Option 1). The total estimated cost for Option 5 for the two units was \$39,060 for 184.5 tons of applied material, a network cost of \$212/ton. The current method of application with the B47G3 helicopter (Option 1) had a total estimated cost of \$42,991 for 184.5 tons of applied material, a network cost of \$233/ton for the two units. Output for the Hyper LINDO® 6.1 and What’sBest!® software is in Appendix E.

The heuristic algorithm model provided the same optimum as the mixed-integer models and was a cost minimization solution. Output for the Network 2000 software is in Appendix F.



Table 5: Summary of cost estimates for transportation network options

Option Unit Heliport	Option 1 <sup>1</sup>			Option 2 <sup>2</sup>			Option 3 <sup>3</sup>			Option 4 <sup>4</sup>		Option 5 <sup>5</sup>	
	5 5A	5 5B	4 4A	5 5A	5 5B	4 4A	5 5A	5 5B	4 4A	5 n/a	4 n/a	5 n/a	4 n/a
Variable Cost (\$/ton)	209.60	186.73	167.88	263.48	248.16	205.36	252.34	237.02	194.22	216.42	190.00	205.28	178.86
Fixed Cost (\$)	4574.00	10629.00	1510.00	2250.00	4250.00	1750.00	2250.00	4250.00	1750.00	1500.00	1500.00	1500.00	1500.00
Total \$/Ton	236.12	248.35	293.71	276.52	272.80	351.19	265.38	261.66	340.05	225.12	315.00	213.98	303.86
Shared Network \$/Ton	236.12	248.35	188.53	276.52	272.80	226.19	265.38	261.66	215.05	225.12	190.00	213.98	178.86
Combined \$/Ton		233.00										212.00	

Footnotes:

- 1 Bulk application with B47G3; ground transportation
- 2 Bulk application with B47G3; aerial ferry B205A1 from transfer site
- 3 Bag application with B47G3; aerial ferry B205A1 from transfer site
- 4 Bulk application with B205A1, ferry from transfer site
- 5 Bag application with B205A1, ferry from transfer site

## 7.6 Model Advantages

The mixed-integer models provide a discrete, optimal solution for the simplified version of the case study. The solution was a cost minimization for a combination of fixed and variable transportation and application costs for one of five scenarios. The models can be formulated to optimize for partial volumes of several minerals delivered to various units over several transportation and application routes through multiple time periods. Options may be formulated (weighted) to allow for consideration of tradeoffs with other activities and costs as explained in Davis et al. (2001). Although not a part of this research project, with appropriate formulations and/or software, nonlinear variables may be incorporated into the models.

The heuristic algorithm model (Network 2000) has several advantages for formulating and solving transportation network problems. The model is easy to understand and can be learned quickly. It requires minimum data input, has an interactive capability with a user interface and network display functions and has the ability to manage link capacity constraints (Chung and Sessions 2000). The model can evaluate several options over multiple time periods with discounted costs. It is suitable for finding a feasible, near-optimal solution to large complex problems in a reasonable amount of time.

## 7.7 Model Limitations

Mixed-integer models require detailed formulation of all the links in a transportation network problem. As the number of integer variables increases, the time and cost to find a

single, optimal solution for a large-scale problem also increases. The formulations can become quite complex and be a deterrent for using mixed-integer linear programming to solve large, complex problems (Sessions 1987).

The mixed-integer model solution report contains dual prices and reduced costs because a linear programming subroutine is used in the mixed-integer solution process. Unlike a linear programming solution, the interpretation and meaning of these prices is complex and dependent upon the solution process used and are not a by-product of the computations. Thus, the dual prices and reduced cost figures in the mixed-integer output report should not be used to interpret the solution (Schrage 1984).

The heuristic algorithm model quickly searches for a feasible solution to the problem, but it may not be the optimum. The model can only evaluate one parameter per link as an equivalent variable cost. The model does not simultaneously consider tradeoffs between other activities unless they can be formulated as fixed and variable costs in the transportation network problem (Chung and Sessions 2000).

The solution to the mathematical models is only as valid as the input values for costs and variables. Most of the costs in the formulation for the case study are estimated costs and may not reflect actual costs of a particular operator or operation. Also, the cost for the bagged form of doloprill are hypothetical and currently lack an actual cost basis and may require additional (unknown at this time) handling costs in that form.

## 8.0 DRAFT ARTICLE: EVALUATION OF AERIAL FOREST OPERATIONS

By Jennie L. Cornell, John Sessions and John Garland<sup>4</sup>

### 8.1 Abstract

A helicopter operations problem was studied for a private forest landowner testing an experimental application of minerals on Douglas-fir (*Pseudotsuga menziesii*) in the Coast Range of Oregon to offset growth reductions from Swiss needle cast disease. A planning approach was needed to minimize costs for transportation and aerial application of the minerals. The methodology developed used mixed-integer linear programming techniques.

A conceptual model was developed for the operation as a transportation network diagram. Important cost and production elements were identified, and the application was studied in the field to gather more information on the interactions of variables for the operation. The mathematical mixed integer model was formulated based on information gathered from the case study and background references. The result of the mixed-integer model formulation was a cost minimization of a simplified two-unit version of the case study. The solution contained a transportation network option that minimized the total project cost of material applied for a combination of units with a shared transportation system and a selected mineral.

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<sup>4</sup> The authors are respectively, Graduate Research Assistant, Department of Forest Engineering, Oregon State University; Professor, Department of Forest Engineering, Oregon State University; Professor and Timber Harvesting Extension Specialist, Department of Forest Engineering, Oregon State University, Corvallis, Oregon 97331-5706. The mention of commercial operators and trade names of commercial products, equipment and software in this paper does not constitute endorsement or recommendation by the authors, or Oregon State University.

## 8.2 Introduction

Aerial operations play an important role in efficient and cost-effective management of forestlands. Helicopters are used for aerial seeding of harvested or burned areas, application of herbicides, insecticides and fungicides, fertilization, timber harvesting, delivery of water and retardant in fire suppression efforts, transportation of crews, equipment and supplies, slash disposal, emergency medical evacuations, cone collection, insect and disease surveys and for general reconnaissance.

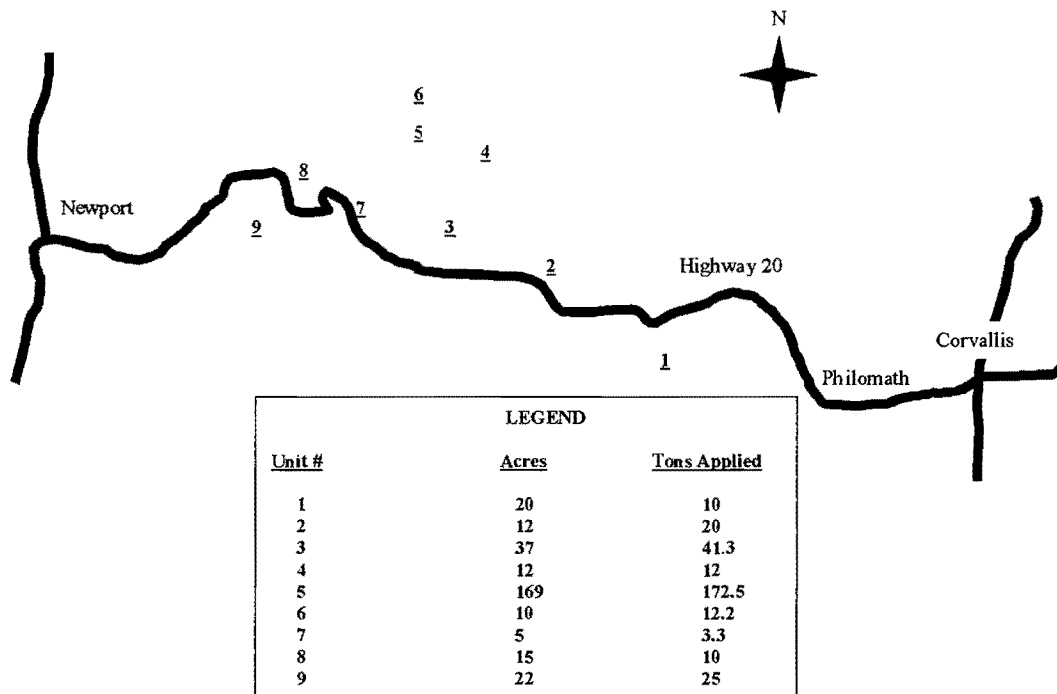
Planning for aerial operations has traditionally sought the use of the safest and least-cost approach for the helicopter, crew and support personnel. The focus of interest for this case study was the development of a planning approach that considers the economics of several options for the transportation and aerial application of specialized minerals to stands of Douglas-fir in the Coast Range of Oregon.

The overall operation includes the helicopter, crew, support personnel, and transportation and application options. Road improvement costs can contribute significantly to the total operations cost (Farley 1994). The objective was to develop a planning approach to evaluate a combination of heliports, aircraft, and transportation options to minimize overall costs under the constraints of operational safety while meeting the forest landowner's objectives. The method should be suitable for the case study and applicable to other forest operations involving helicopters. Recently, Sessions and Chung (1999) explored a modeling approach to minimize total operational costs for helicopter logging operations and transportation options.

A methodology for planning and evaluation of the case study was outlined using references for other forest planning problems and harvesting operations (Davis et al. 2001;

Matska 1997). A conceptual diagram identified the important variables for the operation and their relationships. Data was collected in the field application phase of the case study to support formulation of production and cost estimates in the planning model. The production and cost estimates were calculated in spreadsheet format for units 3, 4, 5 and 6 (Figure 8) in the case study. The operation was formulated for the mixed-integer model using units 4 and 5 and five transportation and application options. The spreadsheet calculations were used to verify the mixed-integer model solution.

Figure 8: Vicinity map for mineral amendment project



### 8.3 Methodology

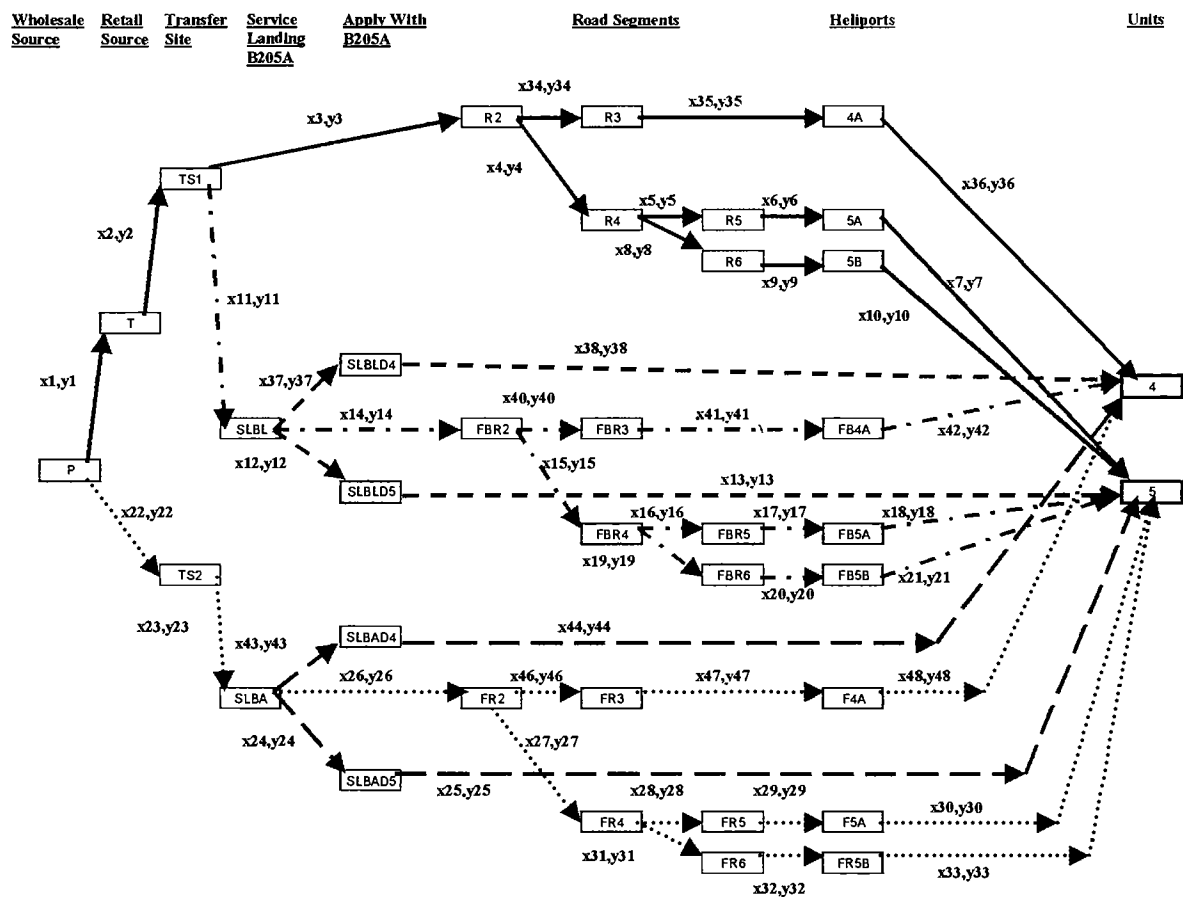
The solution for the case study transportation problem began with a flowchart of the important cost components for the project (Figure 9). From the flowchart framework, a methodology was developed to solve the questions of interest for costs and production. The mixed-integer linear programming model solution for a simplified (two application units) version of the project was part of this approach. Following is the descriptive list of steps in the methodology:

1. Describe the operations problem and the timeline for a needed solution
2. Identify desired goals and outcomes for the solution
3. Identify significant variables and factors of influence
  - a. Fixed and variable costs for transportation and application of materials
  - b. Operations factors/limitations
4. Formulate visual models to address the operations problem (Figure 10)
  - a. Simplified version (based on case study) of the transportation network with links and nodes
  - b. Expanded version (expansion to a landscape scale) of the transportation network with links and nodes
5. Develop linear equations for variables to use in mixed-integer linear programming software to represent a simplified version of the model
6. Solve a simplified version using generalized values for the variables
7. Test the solution of the mathematical model by comparison with selected formulations and outcomes from the case study





Figure 10: Visual concept diagram of transportation network for five options to transport and apply doloprill to units #4 and #5

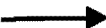

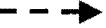
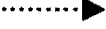



### Key to Concept Diagram (Figure 10)

#### Network Nodes:

<b>P</b>	Wholesale source of materials applied
<b>T</b>	Retail source of materials applied
<b>TS1</b>	Transfer site for bulk material
<b>TS2</b>	Transfer site for bagged material
<b>SLBL</b>	Service landing for B205A bulk material
<b>SLBA</b>	Service landing for B205A bagged material
<b>SLBLD4</b>	Dummy node for direct apply with B205A of bulk material to Unit 4
<b>SLBLD5</b>	Dummy node for direct apply with B205A of bulk material to Unit 5
<b>SLBAD4</b>	Dummy node for direct apply with B205A of bagged material to Unit 4
<b>SLBAD5</b>	Dummy node for direct apply with B205A of bagged material to Unit 5
<b>R2</b>	Road segment/node for conventional application with B47G3 and bulk material
<b>FBR2</b>	Road segment/node for ferry with B205A, apply with B47G3 and bulk material
<b>FR2</b>	Road segment/node for ferry with B205A, apply with B47G3 and bagged material
<b>4A</b>	Heliport for Unit 4, apply with B47G3 bulk material
<b>5A</b>	Heliport for Unit 5, apply with B47G3 bulk material
<b>5B</b>	Heliport for Unit 5, apply with B47G3 bulk material
<b>FB4A</b>	Heliport for Unit 4, ferry with B205A, apply with B47G3 bulk material
<b>FB5A</b>	Heliport for Unit 5, ferry with B205A, apply with B47G3 bulk material
<b>FB5B</b>	Heliport for Unit 5, ferry with B205A, apply with B47G3 bulk material
<b>F4A</b>	Heliport for Unit 4, ferry with B205A, apply with B47G3 bagged material
<b>F5A</b>	Heliport for Unit 5, ferry with B205A, apply with B47G3 bagged material
<b>FR5B</b>	Heliport for Unit 5, ferry with B205A, apply with B47G3 bagged material
<b>4</b>	Unit 4
<b>5</b>	Unit 5

#### Network Links:

<b>x24, y24</b>	Variables for link: variable and fixed costs; {0,1} variables
	Transportation route for bulk material; apply with B47G3
	Transportation route for bulk material; ferry with B205A; apply with B47G3
	Transportation route for bulk material; direct apply with B205A
	Transportation route for bagged material; ferry with B205A; apply with B47G3
	Transportation route for bagged material; direct apply with B205A

## 8.4 Case Study

The heliport facility location problem was identified through contact with a private forest landowner. The landowner was testing aerial applications of minerals on stands of Douglas-fir to offset stand growth reductions from Swiss needle cast disease (Filip et al. 2002). The landowner desired to minimize transportation and application costs for the mineral amendment project, and when needed, plan future projects on a landscape scale. The goal is to provide an acceptable distribution of minerals on targeted units for the least total project cost.

The operation involved various applications at different times. Dry material was applied in the winter and may include up to five different minerals. Then, a two-stage liquid sulfur application followed in late spring. The total 2002 acreage for the case study (dry material) application was 302 acres, with a combined amount of applied minerals of 306 tons. The application of large quantities of minerals during the winter season potentially increases road improvement and maintenance costs for the landowner and thus, increases overall project costs.

## 8.5 Study Site

The case study project covered nine application units in the central Coast Range of Oregon on private forestlands. The units varied from 5 acres to 169 acres, with tree ages from 2 to 30 years. The minerals were applied from January 16, 2002 to February 1, 2002. Four of the nine field units in the project were chosen to formulate cost and production estimates for a transportation network (units 3, 4, 5, and 6 in Figure 8). Two of the units (4 and 5) were used in

the simplified mixed-integer model formulation and share a common road transportation system.

Unit 5 had two heliports.

## 8.6 Transportation Network Options

The operation modeled includes five operational scenarios for applying one type of mineral to each one of the two field units. Assumptions for formulation of the options include: one main factory source of mineral, two primary transportation choices for mineral delivery to the transfer site (bag or bulk) and three choices for aerial delivery of the mineral to each unit.

The first option evaluated was the method by which the project was actually conducted. This includes:

- Ground transportation of the bulk material from the factory source to a retailer
- Ground transportation from a retailer to a transfer site
- Transfer from the retailer trucks to 13-ton agricultural trucks
- Ground transportation on forest roads with the 13-ton trucks to the heliports
- Transfer to a Bell 47G3 (B47G3) helicopter for aerial delivery of the material to the unit with a fiberglass bucket application system (Figure 11)

The second and third options involved the use of a Bell 205A1 (B205A1) helicopter to ferry the materials (bulk or bag) from the transfer site to the heliports, transferring materials to agricultural trucks and then transferring materials to the B47G3 helicopter for aerial delivery to the unit. The only difference between these two options is the form of the mineral (bag or bulk).

Figure 11: B47G3 helicopter with fiberglass bucket



The fourth and fifth options used the B205A1 helicopter to load the mineral (bulk or bag) at a transfer site in an application bucket, ferry to the application unit and then apply the mineral directly to the unit with no further transfers. The only difference between these two options is the form of the mineral (bulk or bag).

Assumptions for operation choices included no delays for delivery of the mineral to the transfer site or to the heliports. In the aerial ferry with the B205A1 to support the B47G3 application, production rates were assumed balanced for any given operation period. The production basis for the agricultural truck coincided with the lowest production rate for the application helicopter. The bagged material was assumed to be in specially packaged 1000-pound bags. The landowner assumed the bagged form of the mineral, if made available, may lower overall handling costs and limit the amount of fines in the material by reducing the number of times it had to be transferred. It would also be less exposed to the effects of weather (Gourley 2002).

## 8.7 Variables

A variable considered in the helicopter production was a maximum ferry distance estimated from three locations: From the designated heliport to the center of the application unit, from the transfer site to the center of the unit and from the transfer site to the designated heliport. Coordinate data for units, heliports and transfer sites were collected with a differential global positioning satellite (DGPS) system incorporated in the B47G3 helicopter, a hand-held GPS unit, landowner GIS maps and USGS maps. The latitude, longitude and elevation coordinate data

were used to calculate the flight path distance to estimate ferry distances. All estimated flight paths were at or below a 20% gradient.

Consideration was given to the heliport approach and departure flight paths to estimate a maximum forward acceleration rate and maximum payload to calculate helicopter production rates for application and ferrying. The acceleration rate was used for acceleration to ferry velocity from a heliport, service landing or to application velocity. A deceleration rate was used to decelerate from ferry velocity to application velocity and to decelerate to the heliport or service landing. The calibrated swath width, bucket application rate and application velocity were used to estimate production rates and application time.

Important cost factors included the helicopter direct operating costs, helicopter move-in costs to the heliports or service landing, the cost of the agricultural trucks (as a function of the estimated helicopter production per hour of flight time and number of trucks), the primary transportation costs to deliver the mineral to the transfer sites, the cost of the minerals, costs of heliport and road improvements and costs of road maintenance.

## 8.8 Production

To control variation in the case study, the same pilot, helicopter, support crew and agricultural trucks were used for the entire project. For the model production estimates it was assumed the production of the helicopter and the agricultural trucks was not limited by logistical constraints. Delays due to breakdowns, material handling, transfer problems and weather were not included in the hourly production estimates for the helicopters.

### 8.8.1 *Helicopters*

Production estimates for the helicopters were based on a maximum external HOGE (hover out-of-ground-effect) payload of 1000 pounds for the B47G3 and 3200 pounds for the B205A1 (Conklin and deDecker Associates, Inc. 2001 via Bell Helicopters Textron, Fort Worth, Texas, December 2002). The estimated maximum payloads were for relative comparison purposes only and do not necessarily represent the actual operating payloads for a given operation. Estimated payloads were reduced for some heliport and loading configurations because of terrain limitations and to adjust for potential safety hazards.

The production rate (tons-per-hour of flight time) for application was calculated using the maximum payload, a maximum ferry velocity, an average application velocity, bucket dispensing rate, swath width, flight path ferry distance and reload time. The total estimated cycle time for an application was a function of the calculated application time to apply a payload (based on application velocity, bucket application rate and swath width), reload time and travel time to and from the application unit. The travel time to and from the unit was calculated as a function of the total flight path distance to the center of the unit, an average estimated acceleration and deceleration rate and a maximum ferry velocity.

The production rate estimates for the B205A1 aerial ferry used an average cycle time based on the maximum payload, a maximum ferry velocity (adjusted for maximum payload), a total flight path ferry distance and a load or hook/unhook time. The travel time to and from the unit was calculated as a function of the total flight path distance to the heliport from the transfer site, an average estimated acceleration and deceleration rate and a maximum ferry velocity. No



other adjustments to the cycle time were made for delays, breakdowns, reconnaissance or other non-productive flight time elements.

Pilot estimates of a forward acceleration rate can range from 2 ft/sec<sup>2</sup> for the B47G3 (John Mateski, Western Helicopter Services, Inc., February 2002) up to 8 ft/sec<sup>2</sup> for the B205A1 (Ron Cline, Cline Air Services, LLC, February 2002) with full payloads. A conservative figure of 3.5 ft/sec<sup>2</sup> (John Sessions, OSU Forest Engineering Department, February 2002) was used as a maximum for both helicopters. The deceleration rate is assumed equal to the acceleration rate.

The maximum acceleration rate assumed an ambient air temperature below 50°F, no wind, elevations below 1200 feet above mean sea level and approach and departure flight paths below a 25% gradient. The maximum payload estimates and acceleration rate need to be adjusted for individual aircraft, steeper approach and departure angles and density altitude effects (higher ambient air temperatures, and/or a higher elevation).

#### 8.8.2 Agricultural Trucks

Production estimates for the agricultural trucks were based on the potential production of the application helicopter for a given heliport. The basis for helicopter production was 5 hours of productive flight time per day (100% utilization), and the estimated production rate for a selected aircraft and heliport or transfer site. When the daily total quantity exceeded 13 tons on a unit for the application with the B47G3, a minimum of two trucks were required. When the turnaround time for transfer and travel to a heliport was over 1.5 hours, three trucks were required. When the material was ferried by the B205A1 and applied with the B47G3, the same

assumptions applied for minimum number of trucks required. When the material was applied directly by the B205A1, no trucks were required.

## 8.9 Costs

Costs included: application and ferry with a helicopter, agricultural trucks, raw material, transportation, road and heliport improvements and road maintenance. Project costs were a combination of fixed and variable costs to deliver the mineral to a target unit. Fixed costs were assumed to be lump sum costs incurred as a result of move-in, road improvement or other activities. They were independent of the quantity of material applied. Variable costs were expressed as dollars-per-unit of mineral applied (\$/ton basis). The dollar-per-ton costs in the case study were assumed to be constant and did not vary with the quantity of mineral applied. For each option, unit and heliport, the costs were reduced to a \$/ton figure and include transportation and application costs (Table 6).

The helicopter and agricultural truck costs were derived from constructed, direct operating costs-per-hour of productive flight time for the helicopter and estimated helicopter production (Cornell 2003).

The costs for the helicopter, agricultural trucks, mineral and road improvements did not include profit or risk for the landowner or operator or opportunity costs or returns on investments for stand improvement. Other costs not included in the model formulation:

- Management overhead costs for the operator (project supervisor, planning work and preparation)

Table 6: Summary of cost estimates for transportation network options

Option Unit Heliport	Option 1 <sup>1</sup>			Option 2 <sup>2</sup>			Option 3 <sup>3</sup>			Option 4 <sup>4</sup>		Option 5 <sup>5</sup>	
	5	5	4	5	5	4	5	5	4	5	4	5	4
	5A	5B	4A	5A	5B	4A	5A	5B	4A	n/a	n/a	n/a	n/a
Variable Cost (\$/ton)	209.60	186.73	167.88	263.48	248.16	205.36	252.34	237.02	194.22	216.42	190.00	205.28	178.86
Fixed Cost (\$)	4574.00	10629.00	1510.00	2250.00	4250.00	1750.00	2250.00	4250.00	1750.00	1500.00	1500.00	1500.00	1500.00
Total \$/Ton	236.12	248.35	293.71	276.52	272.80	351.19	265.38	261.66	340.05	225.12	315.00	213.98	303.86
Shared Network \$/Ton	236.12	248.35	188.53	276.52	272.80	226.19	265.38	261.66	215.05	225.12	190.00	213.98	178.86
Combined \$/Ton		233.00										212.00	

Footnotes:

1 Bulk application with B47G3; ground transportation

2 Bulk application with B47G3; aerial ferry B205A1 from transfer site

3 Bag application with B47G3; aerial ferry B205A1 from transfer site

4 Bulk application with B205A1, ferry from transfer site

5 Bag application with B205A1, ferry from transfer site

- Support equipment cost (fuel truck, transport vehicles for crew, service truck)
- Project move-in and set up costs
- Management overhead and equipment costs for the landowner (project supervisor, transport vehicle, office support, planning work and preparation)
- Costs for delays, breakdowns, and non-productive time (such as moving between units, weather delays, reconnaissance)

### 8.9.1 *Helicopters*

The method of helicopter cost calculation used provides a consistent basis for estimating costs of different helicopters to facilitate a comparison of options. The cost estimates may not reflect current market conditions and are not intended to represent the actual costs for any particular operator. These constructed costs are likely to be low and should not be used to assess the economic viability of a project. Model users should use actual helicopter costs relative to their prospective project based on individual circumstances.

Direct operating cost estimates for the helicopters were derived from information supplied by an independent aviation consulting firm (Conklin and deDecker Associates, Inc. 2001 via Bell Helicopters Textron, Fort Worth, Texas, December 2002). The estimated direct operating cost for the B47G3 was \$426 per flight hour. The estimated direct operating cost for the B205A1 was \$1134 per flight hour. The basis for the B47G3 and the B205A1 was a 400-flight hour operating season. Details of the hourly direct operating cost estimates are included in another paper (Cornell 2003).

### 8.9.2 *Agricultural Trucks*

Costs for the agricultural trucks were based on estimates for: purchase price, annual maintenance costs and lifespan. The lifetime basis for the truck was 18,000 scheduled machine hours (SMH), with a five-month operating season and 1200 SMH per year (12 month year). The driver was included in the truck cost. The estimated cost for truck and driver was \$362 per day.

### 8.9.3 *Cost-per-Ton Calculations – Application*

The cost-per-ton of applied or ferried material for a helicopter was the operating cost-per-hour of flight time divided by the estimated production rate in tons-per-hour of productive flight time.

Helicopter costs for the B47G3 were \$28.74/ton from heliport 5B and \$43.93/ton from heliport 5A on unit 5 and were \$21.26/ton on unit 4. The ferry costs for the B205A1 were \$61.85/ton to heliport 5A and \$66.89/ton to heliport 5B on unit 5 and were \$37.73/ton on unit 4. Direct application costs for the B205A1 were \$73.67/ton on unit 5 and \$47.25/ton on unit 4.

The cost-per-ton of applied material for the agricultural truck was the total cost per day for each truck divided by the estimated minimum production rate in tons-per-day of the application helicopter for a given heliport or service landing.

The agricultural truck costs were \$14.67/ton to heliport 5B and \$22.42/ton to heliport 5A on unit 5 and were \$3.62/ton on unit 4 with the B47G3 direct application. The truck costs were \$9.78/ton to heliport 5B and \$14.95/ton to heliport 5A on unit 5 and were \$3.62/ton on unit 4

when used with the B205A1 aerial ferry option. There were no agricultural truck costs for the B205A1 direct application option.

#### 8.9.4 *Road Improvement and Maintenance, Move-In Costs*

Road improvement (fixed) and maintenance (variable) costs were estimated from values provided by the landowner and included costs for grading, rocking, and repairs prior to and after the operation (Paul Mortenson, Starker Forests, Inc., February 2002). Additional costs were included for grading and rock wear.

Improvement costs for roads, heliports and move-in to the heliports, ranged from \$1510 to \$10,629 for fixed costs with the B47G3 direct application. Variable costs ranged from \$0.25/ton to \$0.57/ton for this option for road maintenance. For the aerial ferry with the B205A1, the fixed costs ranged from \$1500 to \$4250, and there were no associated variable costs for road maintenance. The direct application with the B205A1 had a fixed cost of \$1500 and no variable costs for road maintenance.

Overall move-in costs to the operation area were not included with this analysis. A cost of \$250 was included for the move-in of the B47G3 to each heliport. The use of the B205A1 included a cost of \$1500 for move-in and improvements to a central service landing.

### 8.9.5 *Material and Delivery Costs*

The material and primary delivery costs for the bulk mineral were estimated at \$142.75/ton delivered to the transfer site. The cost for the bagged mineral was estimated at \$131.62/ton delivered to the transfer site (Mark Gourley, Starker Forests, Inc., February 2002; Rick Krohn, Western Helicopter Services, Inc, February 2002).

## 8.10 Mixed-Integer Linear Programming Model

### 8.10.1 *Concept Diagram*

The solution for the operations questions includes the model conceptualization to identify significant components of the transportation problem. Figure 10 is the visual representation of transportation and application options for the two units. The formulations for the mixed-integer model were derived from this visual model.

### 8.10.2 *Formulations of Equations*

The equations for the mixed-integer model included formulations for fixed and variable costs for links in the visual model. The formulation of the transportation problem for units 4 and

5 includes an objective function, 92 variables (46 were designated as (0,1) integers), and 82 constraint equations. The objective function is:

$$\text{Minimize: (Fixed Costs) + (Variable Costs) = } \sum f^k y^k + \sum c^k x^k$$

Subject to the following constraints:

Road triggers:

$$M^k y^k \geq x^k \quad \text{for } k = 1 \text{ to } n$$

Conservation of flow:

$$\sum_{h \in H_i} x_{hi} = \sum_{j \in J_i} x_{ij} \quad \text{for } i = 1 \text{ to } m$$

Integers:

$$y^k = \{0,1\} \quad \text{for } k = 1 \text{ to } n$$

where:

$n$  = number of links in network

$m$  = number of nodes in network

$k$  = link designator

$f^k$  = fixed cost coefficient for  $y^k$  variable for link  $k$

$y^k = 0,1$  variable indicating whether or not link  $k$  is used

$c^k$  = variable cost coefficient for  $x^k$  variable for link  $k$

$x^k$  = volume transported over link  $k$

$M$  = a large number greater than the maximum potential quantity of material to be hauled over that transportation link

$i$  = node designator

$h$  = designator for link entering a node

$j$  = designator for link leaving a node



$H_i$  = set of links entering node  $i$

$J_i$  = set of links leaving node  $i$

The fixed cost coefficients,  $f^k$ , are the cost coefficients for the  $y_k$  variables shown in Figure 10. The variable cost coefficients,  $c^k$ , are the cost coefficients for the  $x_k$  variables shown in Figure 10.

## 8.11 Results

The mixed-integer linear programming model for units 4 and 5 in the case study project was solved with commercial linear programming software (Hyper LINDO® 6.1, 2002). The lowest cost route for the two field units favored the direct application of “bagged” material with the B205A1 (Table 6, Option 5).

### 8.11.1 *Production*

The range of production estimates are summarized for units 4 and 5 under the five transportation and application options in Table 7. The lowest cost transportation route provided some of the highest production rates for the helicopter (Option 5). The highest production rate estimated in unit 4 with the direct application by the B205A1 is 24 tons-per-flight-hour and unit

Table 7: Empirical model production estimates for helicopters for transportation network options (tons/hour)

Option Unit Heliport	Option 1 <sup>1</sup>			Option 2 <sup>2</sup>			Option 3 <sup>3</sup>			Option 4 <sup>4</sup>		Option 5 <sup>5</sup>	
	5	5	4	5	5	4	5	5	4	5	4	5	4
	5A	5B	4A	5A	5B	4A	5A	5B	4A	n/a	n/a	n/a	n/a
B47G3 (apply)	9.7	14.8	20.0	9.7	14.8	20.0	9.7	14.8	20.0	-	-	-	-
B205A1 (apply)	-	-	-	-	-	-	-	-	-	15.4	24.0	15.4	24.0
B205A1 (ferry)	-	-	-	18.3	16.9	30.0	18.3	16.9	30.0	-	-	-	-

Footnotes:

- 1 Bulk application with B47G3; ground transportation
- 2 Bulk application with B47G3; aerial ferry B205A1 from transfer site
- 3 Bag application with B47G3; aerial ferry B205A1 from transfer site
- 4 Bulk application with B205A1, ferry from transfer site
- 5 Bag application with B205A1, ferry from transfer site

5 at 15.4 tons-per-flight-hour. The lowest production rate estimated in unit 4 was with the current method of application by the B47G3 (Option 1) at 20 tons-per-flight-hour and in unit 5 from heliport 5A at 9.7 tons-per-flight-hour.

#### 8.11.2 *Costs*

The estimated total costs for Option 5 for the two units was \$39,060 for 184.5 tons of applied material, a cost of \$212/ton using direct application with the B205A1 helicopter of the bagged mineral. The current method of application with the B47G3 helicopter (Option 1) had a total estimated cost of \$42,991 for 184.5 tons of applied material, a cost of \$233/ton for the two units.

#### 8.12 Discussion

Mixed-integer linear programming is suitable for modeling the heliport facility location problem. The result of the mixed-integer programming formulation was a cost minimization of the simplified two-unit version of the case study. The solution contained a transportation and application option that minimized the total cost of mineral applied to a combination of units with shared transportation routes. A relative comparison of options indicates Option 5 resulted in an estimated cost-per-ton that was 9% lower than for the current application approach (Option 1).

A crucial part of the formulation is to have significant cost variables on the same basis. For this operation, the common basis was dollars-per-ton (\$/ton) of applied mineral. This includes fixed and variable costs for the transportation and application aspects of the operation.

#### 8.12.1 *Variables*

The most significant independent variable for helicopter production was the total flight path distance flown per cycle. Other variables that can impact the cost-per-ton include production differences due to support crew and individual pilot skill levels, logistical planning for delivery of materials to match the production of the helicopter, delays due to mechanical breakdowns, material handling and transfer problems, the application rate for the minerals, the form and quantity of minerals, the variety of different types of minerals to be applied and weather (Rick Krohn, Western Helicopter Services, Inc., February 2002; John Mateski, Western Helicopter Services, December 2001, February 2002). The quantity, form and physical consistency of the minerals applied can impact the bucket application flow rate and overall productive capacity of the helicopter as was observed in the case study. Some minerals cannot be mixed due to their chemical reactivity and require separate application operations (Mark Gourley, Starker Forests, Inc., December 2001).

Observation of the case study helped identify significant cost variables that affect the cost-per-ton of delivered and applied mineral. Variables that affect cost-per-ton of delivered material include the hourly cost and production of the helicopter, the road and heliport

improvement costs, primary transportation costs and the number of agricultural trucks required for a given heliport.

### 8.13 Applications/Limitations of Model

The mathematical mixed-integer model formulation was suitable for modeling the case study. Use of a defined methodology to formulate fixed and variable costs on \$/ton (i.e. common) basis is critical to building a solution framework with this type of mathematical model approach.

Potential nonlinear production relationships were not included in the mathematical models. Fixed estimates based on assumed static parameters were used. For example, the average flight path distance for each application option was from a given heliport or transfer site to the geographic center of a unit, or transfer site to a heliport.

The model can integrate costs for an overall operation where there are shared transportation routes, service landings, or heliports, over a combination of transportation and application options, and can allocate the costs appropriately for an operation with several units for a given quantity of applied materials. Although helicopter operations typically focus on minimizing the helicopter operating cost, the case study indicates that road costs can contribute significantly to the operations cost for a project.

The source and content of cost information and the basis for cost and production estimates need to be identified. Solution values for the case study included constructed cost estimates without profit and risk for the operator or landowner and are for relative comparison

only. Production estimates were based on general, estimated performance and production characteristics for selected helicopters and equipment and may vary by individual aircraft and operator. The transportation network options with the “bagged” material were hypothetical and currently lack an actual cost estimate basis for the form or quantity of materials needed for the operation.

The helicopter production estimates were based on the potential delivery rate per hour of productive flight time for the helicopter and were calculated from an estimated delay-free cycle time. The helicopter costs were based on defined direct operating costs that do not represent a specific aircraft or operator.

#### 8.14 Additional Research Needs

The potential exists to expand the simplified version of the case study problem to a more complex problem. The more complex problem may include: a variety of applied minerals, both dry and liquid form; one or more aircraft; several applications over an extended time period; and several transportation and application options. The approach for a solution to a larger-scale and more complex problem, may follow a process that is an extension of the case study methodology. The methodology for a larger-scale problem or a landscape-scale model would include:

1. A definition of the assumptions and constraints for the larger-scale model
2. Establishing common basis relationships for important cost and production variables in the expanded model

3. Formulation of the mathematical model to include the potential for non-linear cost and production variables
4. Solve the larger-scale model using formulations for important cost and production variables
5. Verify a sample of the solution of a larger-scale model with field tests, and/or comparisons with actual operation data, and/or comparison with modeled operations based on historical production and cost data

Additional research is needed to verify production estimates for helicopters and support equipment in the operation with the different types and quantities of minerals. A major component of the cost of the overall operation hinges on the production capacity of the helicopter. This capacity depends upon the calibrated application rate, ferry distance and velocity, heliport approach and departure flight paths, pilot skill level, productive flight hours, and delays due to breakdowns, material handling problems and logistics, moving to and from units and weather factors.

There is potential to address nonlinear relationships in costs and production through various techniques and strategies with linear programming formulations as suggested by Schrage (1984). In addition, more advanced software systems allow for incorporation of nonlinear variables in the formulations (Schrage 1997).

### 8.15 Summary

Mixed-integer linear programming can be a useful tool for evaluating and planning aerial forest operations such as the mineral amendment case study and other aerial forest operations. This research indicates important variables and factors in the operation can be formulated for the mixed-integer linear programming model. The model may then be used to evaluate several potential transportation and application options to find a feasible minimum-cost solution to a logistically complex planning problem.

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## 9.0 FLIGHT DATA ANALYSES

The purpose of evaluating detailed data recorded with Ag-Nav<sup>®</sup>2 differential global positioning satellite (DGPS) system was to gain an understanding of the flight characteristics of the B47G3 helicopter to estimate production on future operations. The analyses focus on flight data for one type of mineral applied on all nine field units in the case study. The mineral was doloprill, a pelletized form of dolomitic lime with a molasses binder and a 9% magnesium content. There were a total of 459 cycles for this mineral. An illustration of cycle time elements for a complete cycle is in Appendix A, Figure 23.

There were four objectives for the flight data analyses: first, to compare the empirical model estimates for delay-free cycle time to actual flight data on selected units; second, to compare the relative effect a restricted heliport approach and departure path on cycle time between two heliports; third, to evaluate the influence of acceleration and deceleration on elapsed cycle time; and fourth, to derive a statistical relationship from the case study flight data to estimate cycle time for project planning and cost estimations.

### 9.1 Data Management

All 459 cycles were part of the sample population for analysis purposes. Each cycle was assigned a random number using the Excel<sup>®</sup> random number function. The cycles were then sorted by random number in ascending order. The samples were selected from this sorted cycle

list beginning at the top of the list and working sequentially through the list, either for the entire sample, or by each unit. From the total 459 cycles, 195 cycles with recorded delays, missing data, or that were suspect were excluded from the analyses. The resultant population was 264 delay-free cycles.

#### 9.1.1 *Random Sample Selection*

The empirical model estimates were compared to actual flight data for units 3, 4, 5, and 6. A random 10-cycle sample was chosen from each of the four units. The empirical model estimates were plotted with the flight data for each unit on a graph for comparison.

The effect of heliport approach and departure flight paths was evaluated with a comparison of random 25-cycle samples for units 3 and 5. The relative effect of acceleration and deceleration was explored with the 25-cycle sample from unit 3. Simple linear regression models were developed to estimate total cycle time for a specific heliport on each unit and then compared for influences on production and cost. Simple linear regression equations were developed for unit 3 with and without acceleration/deceleration data and then compared over a range of flight path distances.

A random 50-cycle sample was selected from all units to develop a regression model to estimate an average total cycle time. A second 50-cycle sample from all units (exclusive of the first sample) was compared to the regression model to evaluate the ability of the regression model to estimate an average total cycle time.

### 9.1.2 *Data Conversion*

The cycle data for selected samples from the Ag-Nav<sup>®</sup>2 DGPS system was converted from binary code data files to spreadsheet format using the CROP2TXT software from Ag-Nav, Inc. The converted flight data was used to calculate total flight path distance per cycle; to estimate a maximum difference in elevation per cycle; to calculate average acceleration and deceleration; to determine reload time; and determine time and distance for the helicopter to accelerate to translation and flare to load (average airspeed below 25 mph) (Figure 5).

## 9.2 General Helicopter Production

The time study forms for data collection (Appendix G) were used to record shift level flight time, delays and gross production information for the case study. This information was used to calculate the productivity and efficiency for the project (Table 8).

## 9.3 Empirical Model Comparison

The data plotted for the 10-cycle samples for unit 6 and unit 5 are shown in Figures 12 and 13. Graphs for unit 3 and 4 are in Appendix I.

Table 8: Production summary from shift level data for flight hours and tons applied on mineral amendment project

	Total Flight Time (minutes)	Productive Flight Time (minutes)	Non- Productive Flight Time <sup>4</sup> (minutes)	Productivity <sup>1</sup>				
				Total Tons (tons)	Total Acres (acres)	Acres (ac/pfh) <sup>3</sup>	Tons (tons/pfh)	Efficiency <sup>2</sup>
Dolopryll:	1494	1264	230	201.3	302	14.34	9.56	84.6%
All Minerals:	2172	1916	256	306.2	302	9.46	9.59	88.2%

Footnotes: 1 Productivity = (area treated)/(operational time to treat)

2 Efficiency = (application time)/(total operational time)

3 pfh = productive flight hour = productive flight time / 60 minutes/hour

4 Includes travel time between units and delays

Figure 12: Comparison of empirical model estimate and flight data from unit 6 for 10 random delay-free cycles

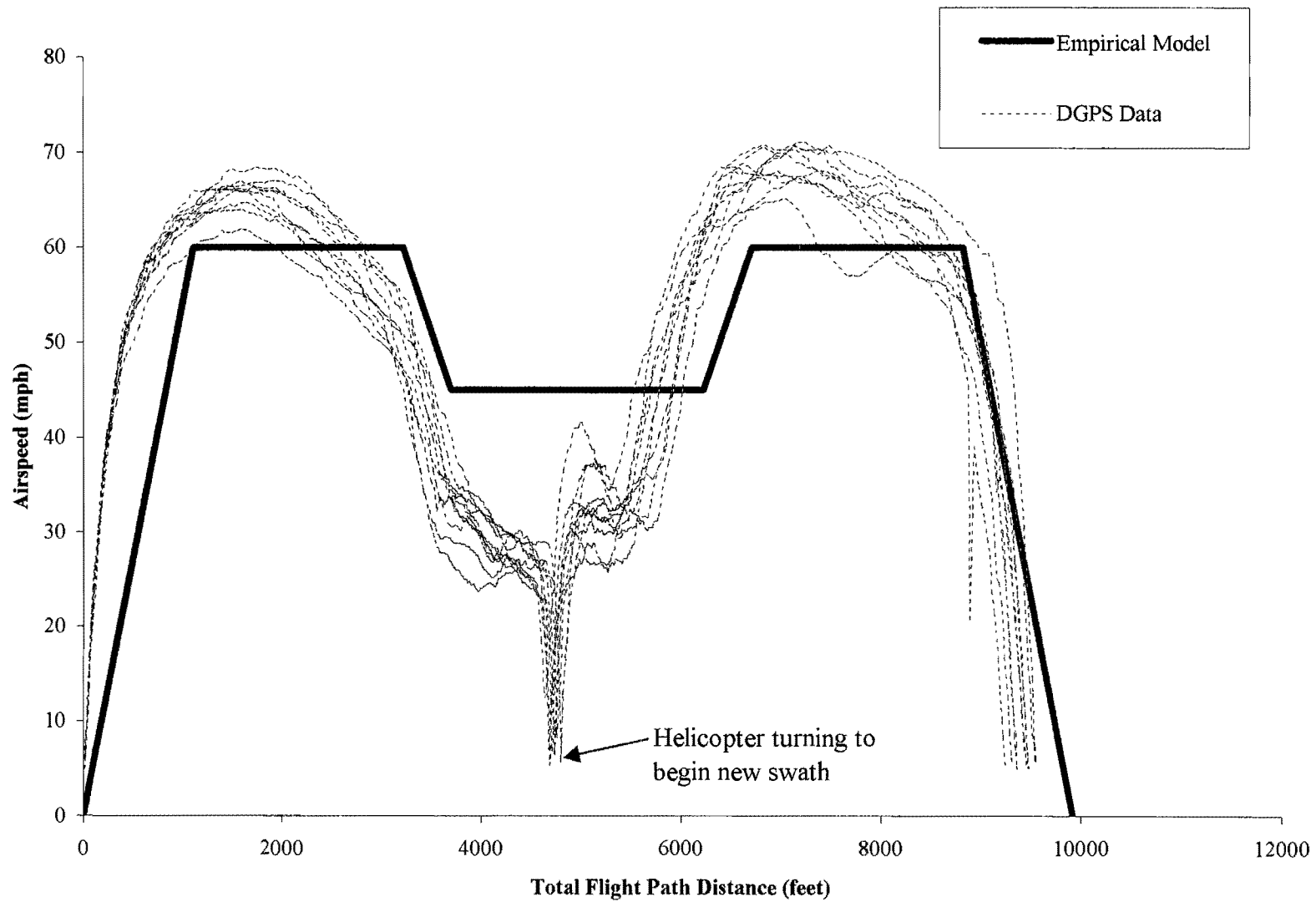
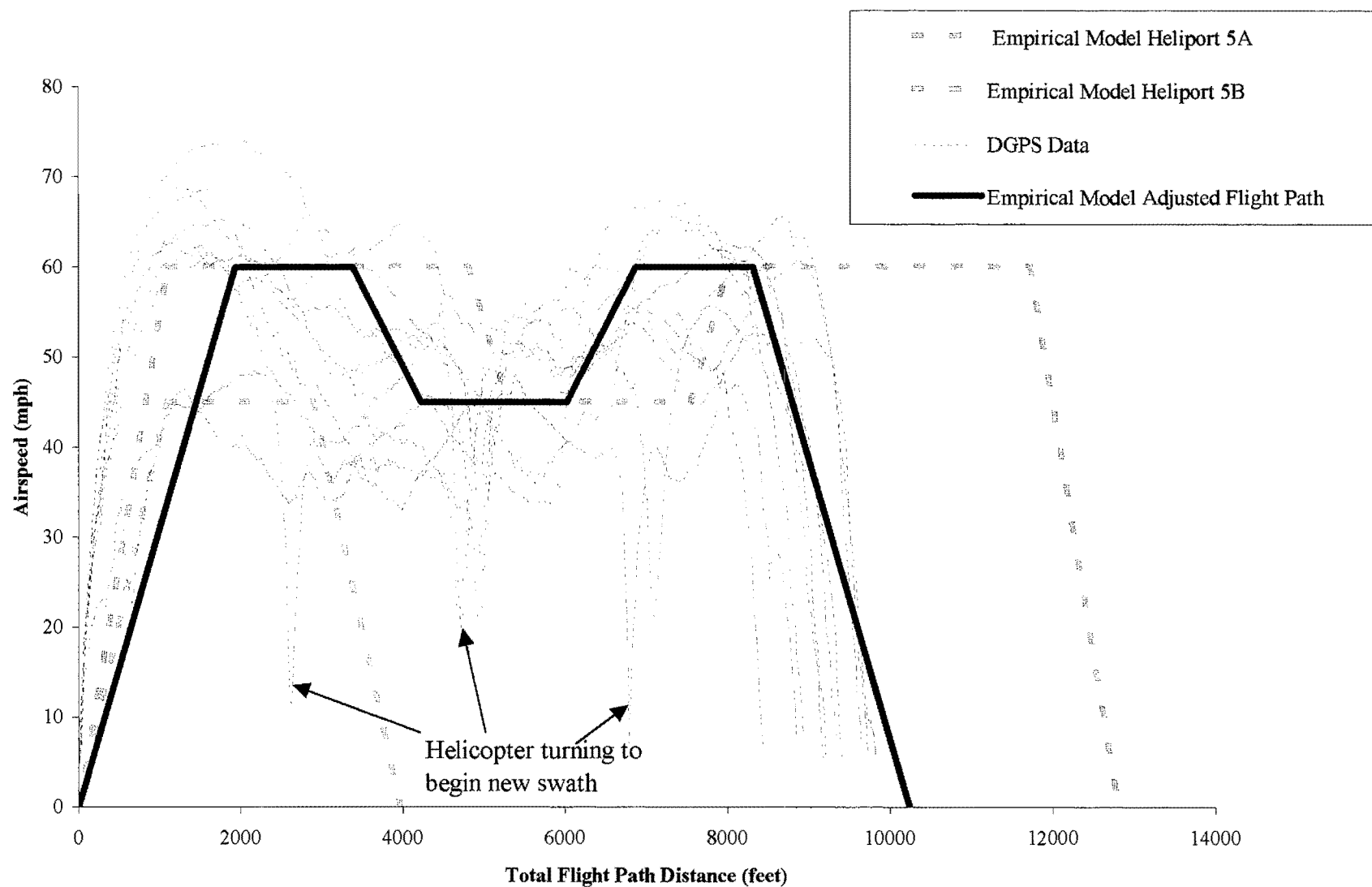


Figure 13: Comparison of empirical model estimate and flight data from unit 5 for 10 random delay-free cycles



A comparison of the project's empirical model to actual flight data (Figure 12) illustrates the model gave a fairly good representation of the actual flight pattern of the helicopter for the heliport on unit 6.

Unit 5 had two heliports, 5A and 5B. Heliport 5B was on the southwest edge of the unit; heliport 5A was approximately one mile east of the center of the unit. Comparison of the empirical model to flight data in Figure 13 indicates the actual flight pattern for this sample falls somewhere between the two empirical model estimates (one for each heliport). Most of the flight data for this sample were loads flown from heliport 5B. Alternatively, when it is assumed that the flight path of the helicopter from heliport 5B is adjusted to follow a pattern allowing the aircraft to align with the longest possible application path in the unit (instead of flying to the center of the unit), the result is the adjusted flight path pattern in Figure 13. The empirical model based on the adjusted flight path more closely follows the actual flight path pattern. When the heliport is on the unit, a more appropriate approach may be to use an adjusted flight path distance to estimate an average total cycle time.

### 9.3.1 *Differences in Model and Actual Flight Data*

Although the empirical models provide a good estimate of average total cycle time for a given heliport, there were some differences from the actual flight data. One difference is the estimated load time: the model estimate was 5 seconds and the actual load times were between 12 to 15 seconds. One reason for this difference was the unanticipated difficulty of unloading the mineral from the bag scale on the agricultural truck. The mineral did not flow smoothly from



the loading bag; thus, it took longer than expected to fill the bucket. A second difference was the estimated acceleration and deceleration for the helicopter. The model estimated  $3.5 \text{ ft/sec}^2$  and the flight data indicated rates between  $4 - 6 \text{ ft/sec}^2$ . A third difference was the pilot did not always fly the calibrated airspeed due to problems with the mineral sticking in the bucket. It took longer on some units to empty the bucket due to wet weather affecting the consistency and flow rate of the mineral because of the amount of fines and the breakdown of the molasses binder. A fourth difference was underestimating the distance the helicopter will fly. This was influenced by several factors, including: using the center of the unit as the endpoint for the average flight path ferry distance when heliports were within the unit; when additional distance was required to clear obstacles and terrain; increased maneuvering distances to approach and depart restricted heliports; and when irregular unit boundaries and short application flight paths increased the number of turns the helicopter made during application. Finally, the empirical model did not account for the effect of turns on time and flight distance for multiple application swaths during a cycle.

#### 9.4 Comparison of Heliports

Heliport approach and departure pathways can affect production and costs for the helicopter. The approach gradient and obstructions influence the flight path, the flight distance and the total cycle time (O'Brien and Brooks 1996). A comparison of 25-cycle samples from two heliports was made for units 3 and 5. Unit 3 data represents a heliport with an unrestricted approach and departure flight path. The helicopter had a direct approach and could descend from

the heliport after loading. Unit 5 data represents a heliport with a restricted approach and departure flight path. The helicopter had to maneuver around trees to approach and then after loading, the helicopter had to turn approximately 90 degrees and ascend at a 10-degree angle to clear the trees.

The flight data for the 25-cycle samples from units 3 and 5 were used to develop a simple linear relationship between the total cycle time (seconds) and the total flight path distance (feet) for each heliport scenario. Figure 14 is a graph of the outputs from the relationship for each heliport over a range of total flight path distances. For practical comparison purposes, the lines are nearly parallel, with the restricted heliport having a total cycle time greater than for the unrestricted heliport over the range of flight path distances shown. Figure 15 illustrates the potential effect on helicopter production for each heliport configuration. Figure 16 illustrates the potential impact on the estimated helicopter cost-per-ton of applied material.

## 9.5 Acceleration Effect on Time Estimates

The data for the 25-cycle sample from unit 3 were used to evaluate the relative influence of acceleration and deceleration when estimating elapsed time (seconds) as a function of flight path distance (feet). The flight data was graphed as total elapsed time versus total flight path distance, with a maximum total elapsed time of 129.2 seconds and a maximum total flight path distance of 6750 feet for the data set. First, a line was fitted to the cycle data with the time and distance for acceleration to translation airspeed (airspeed above 25 mph) and flare to decelerate to reload (airspeed below 25 mph) included in the elapsed cycle time. Next, a line was fitted to

Figure 14: Heliport approach and departure flight paths and effects on total cycle time  
(Lines fitted from 25 random delay-free cycles for each unit)

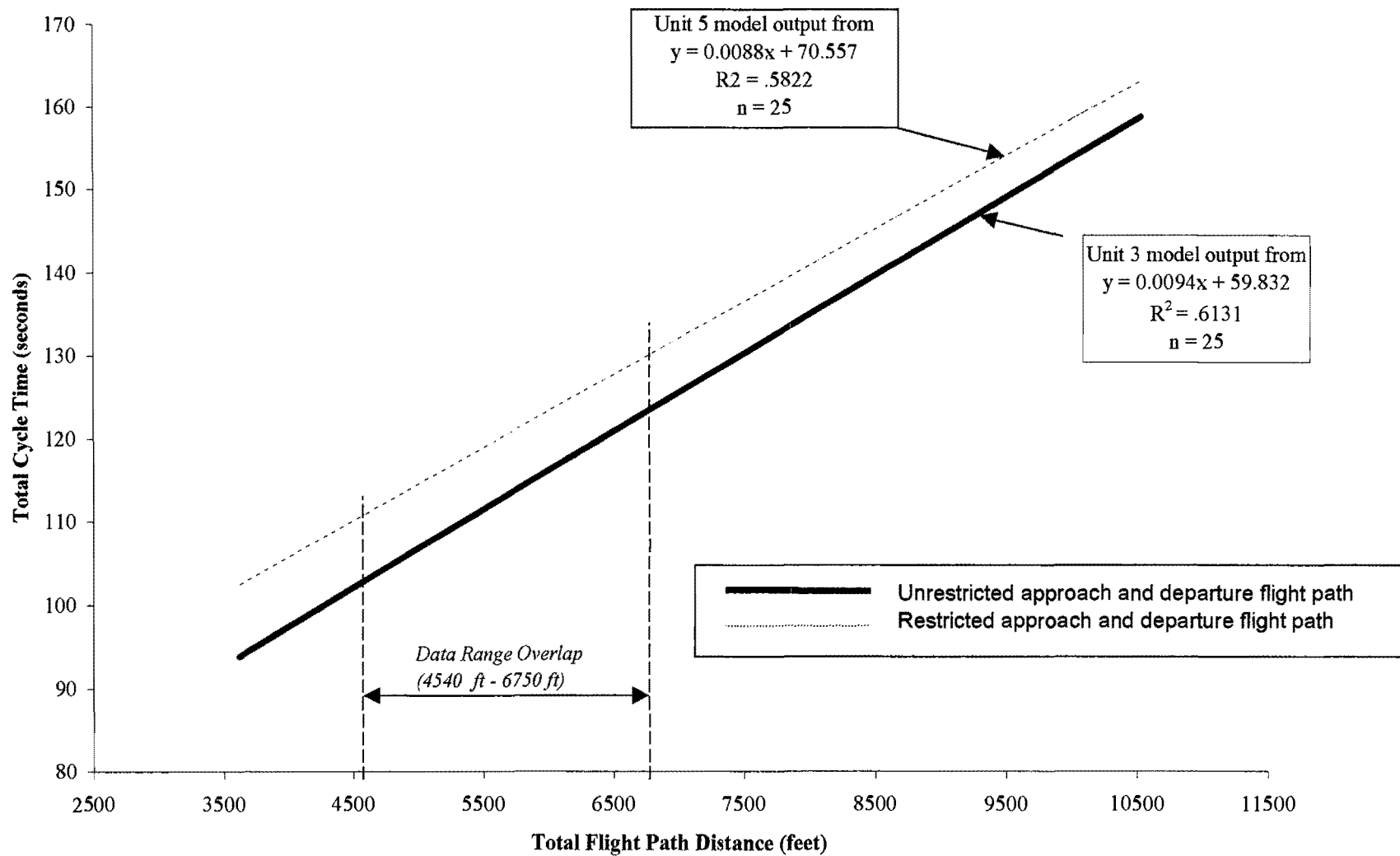


Figure 15: Influence of heliport approach and departure path on helicopter production  
(Lines calculated from total cycle time (TCT) regressions (Figure 14) for a 1000-pound payload)

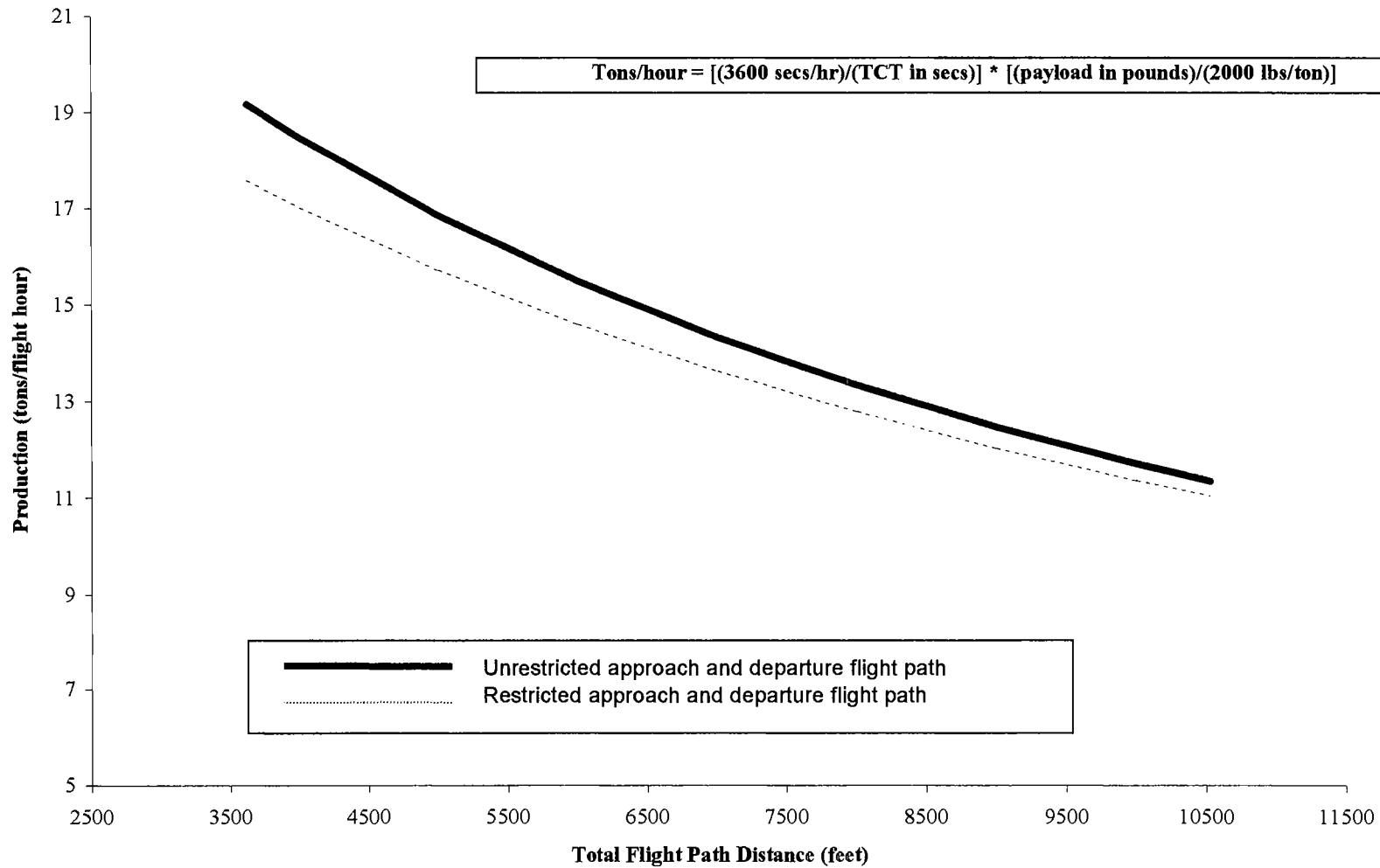
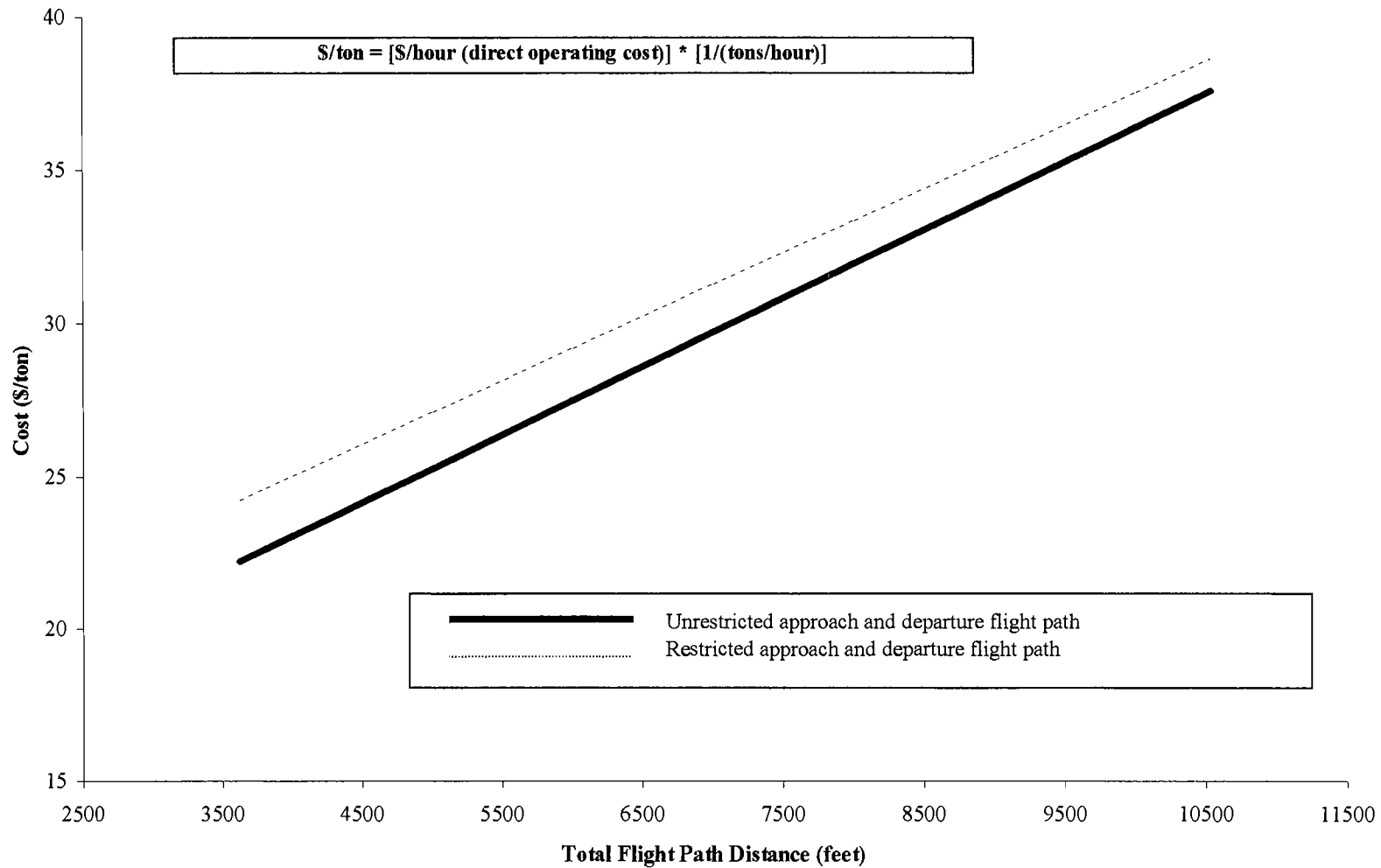


Figure 16: Influence of heliport approach and departure path on helicopter cost-per-ton  
(Lines calculated from estimated production chart (Figure 15) and the helicopter direct operating costs)

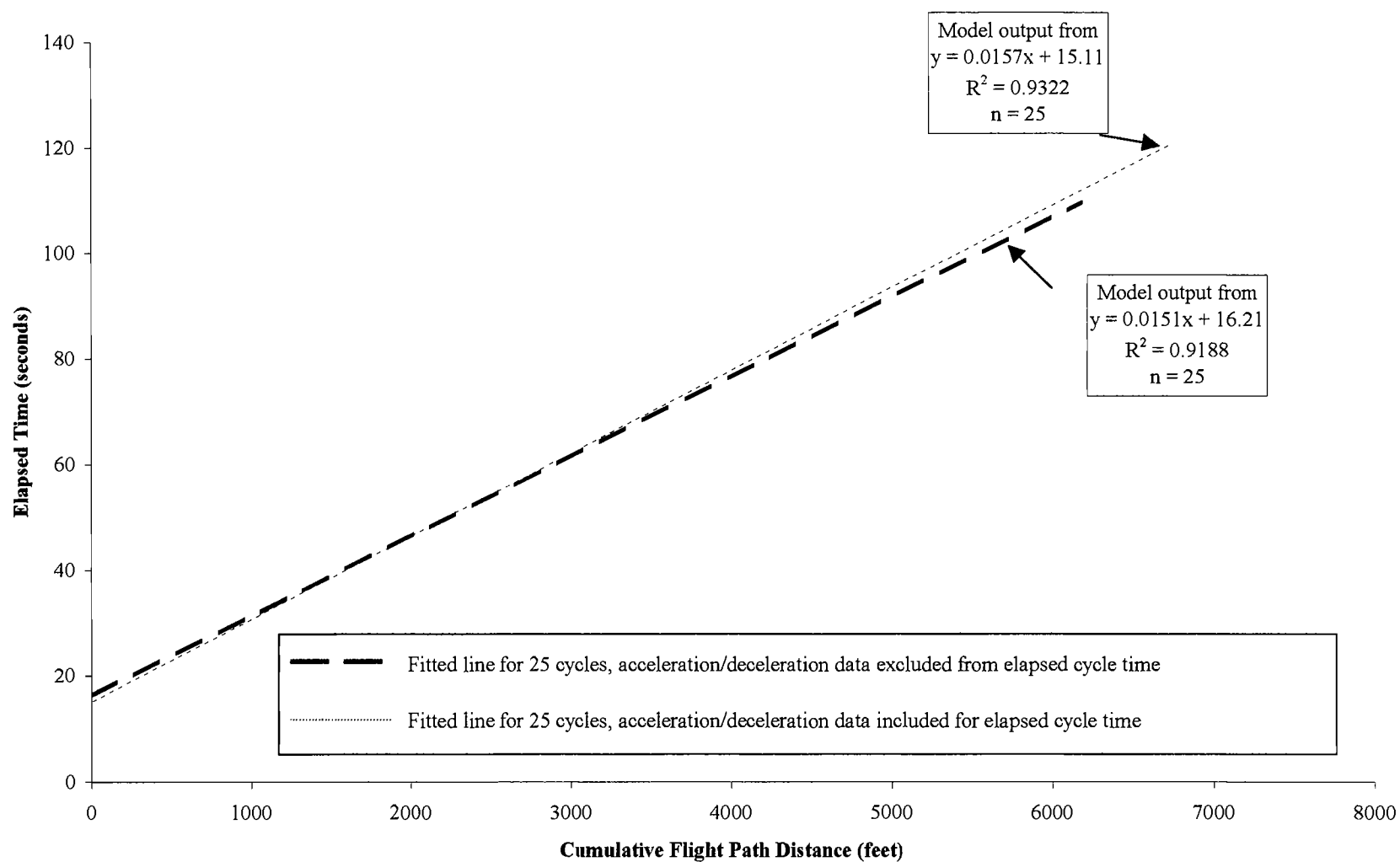


the cycle data that excluded the acceleration and deceleration components of elapsed cycle time. Simple linear relationships were developed for each line (Figure 17). From a practical perspective, the linear relationship constructed using all of the data is quite similar to the linear relationship constructed with the data that excludes the acceleration and deceleration components. Detailed plots of the complete flight data are in Appendix I.

## 9.6 Other Considerations

Heliport approach and departure flight path access has an effect on the production and cost of the helicopter. Payload capability is perhaps the performance characteristic of greatest economic importance for some operations (Stevens and Clark 1974). In general, reduced payloads from restricted heliports decrease production and increase cost. Heliport access also has a direct effect on risk management for an operation. Restricted heliports can reduce pilot visibility and increase the performance demands on the helicopter (Stevens and Clark 1974). If the straight-line flight path gradient is greater than 29%, it is not safe to fly and this effect is exaggerated on short distances (O'Brien and Brooks 1996). Restricted heliports with obstacles and/or steep approach and departure paths can increase operational costs and risk to the pilot, aircraft and support personnel.

Figure 17: Comparison of fitted lines for influence of acceleration and deceleration on elapsed time estimates for unit 3



## 9.7 Production Estimate Model

A production model for the B47G3 was developed with a random 50-cycle sample from all of the units. The simple linear regression estimates a total cycle time in seconds as a function of the estimated total flight path distance in feet. The regression has a good fit within the range of data in the sample. The estimated cycle time can be used to calculate helicopter production for an average payload of doloprill for a range of flight path distances within the parameter and operational limits of the project.

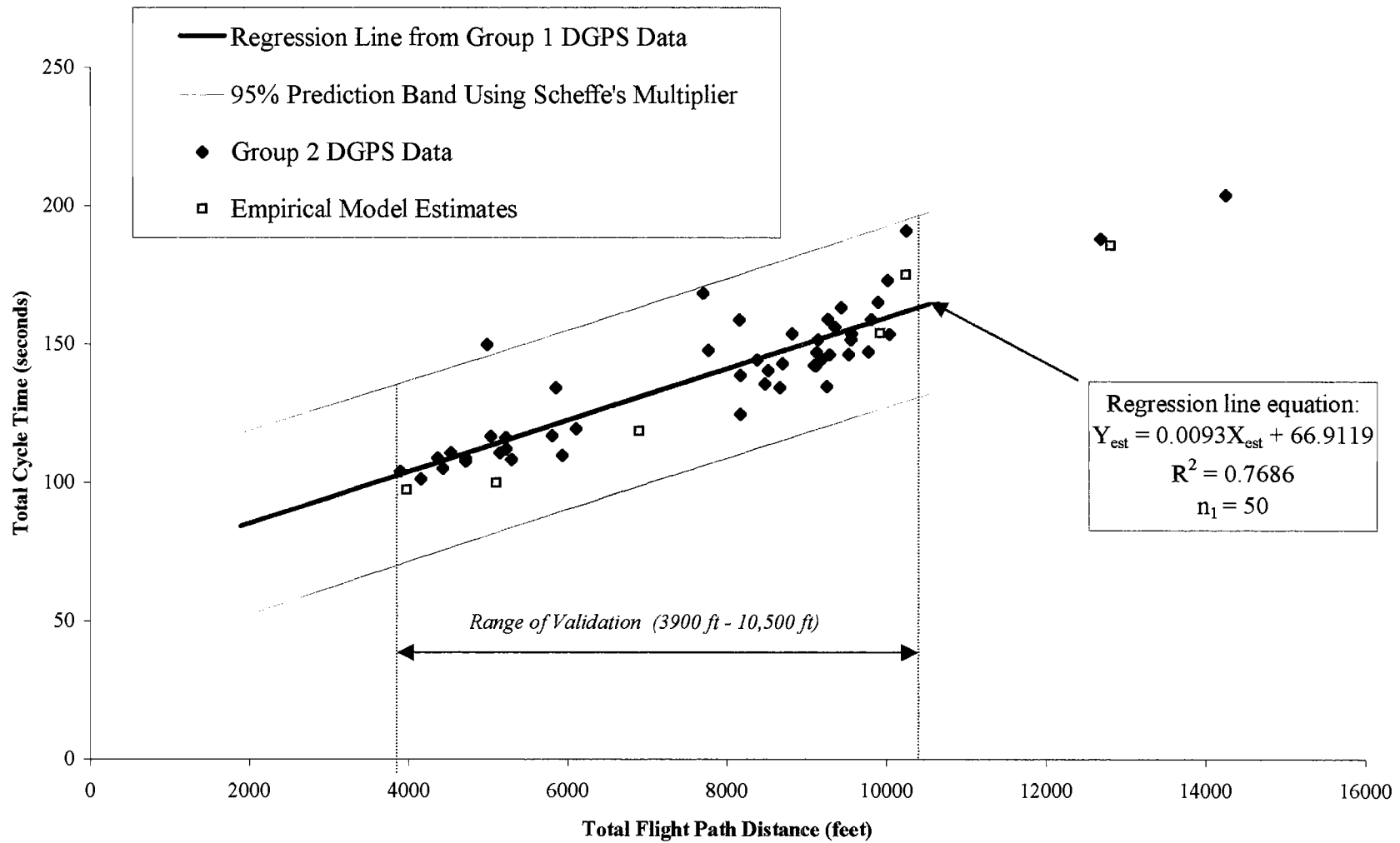
A second random 50-cycle sample from all of the units and data from the empirical model estimates were compared to the simple linear regression. The second data set indicates the regression model is a reliable estimator of average total cycle time within the parameter limits of the data sets (i.e. between 3900 feet and 10,500 feet total flight path distance).

### 9.7.1 *Use of Regression to Describe Cycle Time as a Function of Flight Path Distance*

Initial investigation of the 50-cycle sample revealed the data was suitable for modeling with linear regression. The variables met statistical assumptions for linearity, a normal population distribution, equal variance and independence (Ramsey and Schafer 1997). Appendix I includes graphs used to evaluate the variables. S-Plus 2000<sup>®</sup>, a commercial statistical software program, was used for the majority of statistical calculations.



Figure 18: Regression of total cycle time on total flight path distance with 95% prediction band and range of validation data



### 9.7.1.1 Regression Variables

The dependent variable for the regression was total cycle time in seconds. Initial independent variables included the average total flight path distance (feet), the maximum difference in elevation on the flight path for a cycle (feet) and the area (acres) of the unit. The most significant independent variable for the regression was the average total flight path distance. An extra-sum-of-squares F-test between the model with three variables (full model) and the model with one variable (reduced model) yielded an  $F_{2,46} = 0.370198$ , with a corresponding one-sided p-value = 0.6926. The high p-value indicates the reduced model with one variable (average total flight path distance) is favored over the full model with three variables. Supplemental detailed calculations are in Appendix I.

### 9.7.1.2 The Regression Equation

A simple linear regression equation of the form:

$$Y_{\text{est}} = 0.0093X_{\text{est}} + 66.9119$$

where:

$Y_{\text{est}}$  = prediction estimate for average total cycle time (seconds)

$X_{\text{est}}$  = estimated average total flight path distance (feet)

provided a reliable estimation of average total cycle time within the data range indicated.

The regression has a  $R^2 = 0.7686$ , with a residual standard error of 12.64 on 48 degrees of freedom. Due to compound uncertainty in estimating several means simultaneously, the Scheffe'

method was used to construct the 95% prediction band for the regression line illustrated in Figure 18 (Ramsey and Schafer 1997). The prediction band was constructed using the following equation:

$$Y_{\text{est}} \pm M * SE_{\text{est}}$$

where:

$$M = \text{Scheffe' multiplier} = [2 * F_{2,n-2}(.95)]^{1/2}$$

$n$  = sample size

$$SE_{\text{est}} = [(se.\text{fit}^2) + (\sigma^2)]^{1/2}$$

$se.\text{fit}$  = standard error of the fitted value (from S-Plus 2000® output)

$\sigma$  = residual standard error of the regression (from S-Plus 2000® output)

The sample size for the regression model is 50 and  $F_{2,48}(.95) = 3.190727$ , which results in  $M = 2.5219$ . Due to the compound uncertainty, this gives a slightly wider prediction band than a  $t$ -multiplier of 2.00 for a 95% confidence level on 48 degrees of freedom.

### 9.7.2 *Limitations of Simple Linear Regression for Estimating Production*

Additional cycle data is needed to check the reliability of the regression model beyond the limits and conditions of the data sets. Data parameter limits include: regression data limits with a total flight path distance range from 1900 feet to 10,500 feet; the second (validation) data set limits with a total flight path distance range from 3900 feet to 14,250 feet; one type of mineral; the B47G3 helicopter with a skilled pilot (described in Section 5.3); and the weather and operations conditions found in the case study. An assumption for use of the regression include

all of the data set parameters are static as one variable of interest is changed over a projected range of conditions (e.g. equivalent helicopter performance while varying payload over a range of flight path distances). For complete production and cost estimates, delays and other operational costs discussed previously should be included.

### 9.7.3 *Other Applications*

If it is assumed small changes in parameters, such as payload, does not substantially affect performance, regression may be used to generate general relationships and trends for helicopter production and costs over a range of flight path distances. These types of estimates may be useful to plan projects with similar conditions and materials. Figure 19 illustrates the production trend for the B47G3 helicopter for two payloads over a range of total flight path distances using the regression to estimate total cycle time. Figure 20 illustrates the cost trend for the helicopter for two payloads over a range of total flight path distances based on the production estimates from Figure 19.

With additional data collection and analysis, other regression equations may be developed for different pilots, helicopter types, materials, flight path distances and operational conditions to estimate production and costs. Automated flight data recording systems, such as the Ag-Nav<sup>®</sup>2 DGPS system, could be used to evaluate flight characteristics and performance under varying circumstances to develop regression relationships to assist in project planning.

Figure 19: Projected production estimates for B47G3 based on regression line in Figure 18

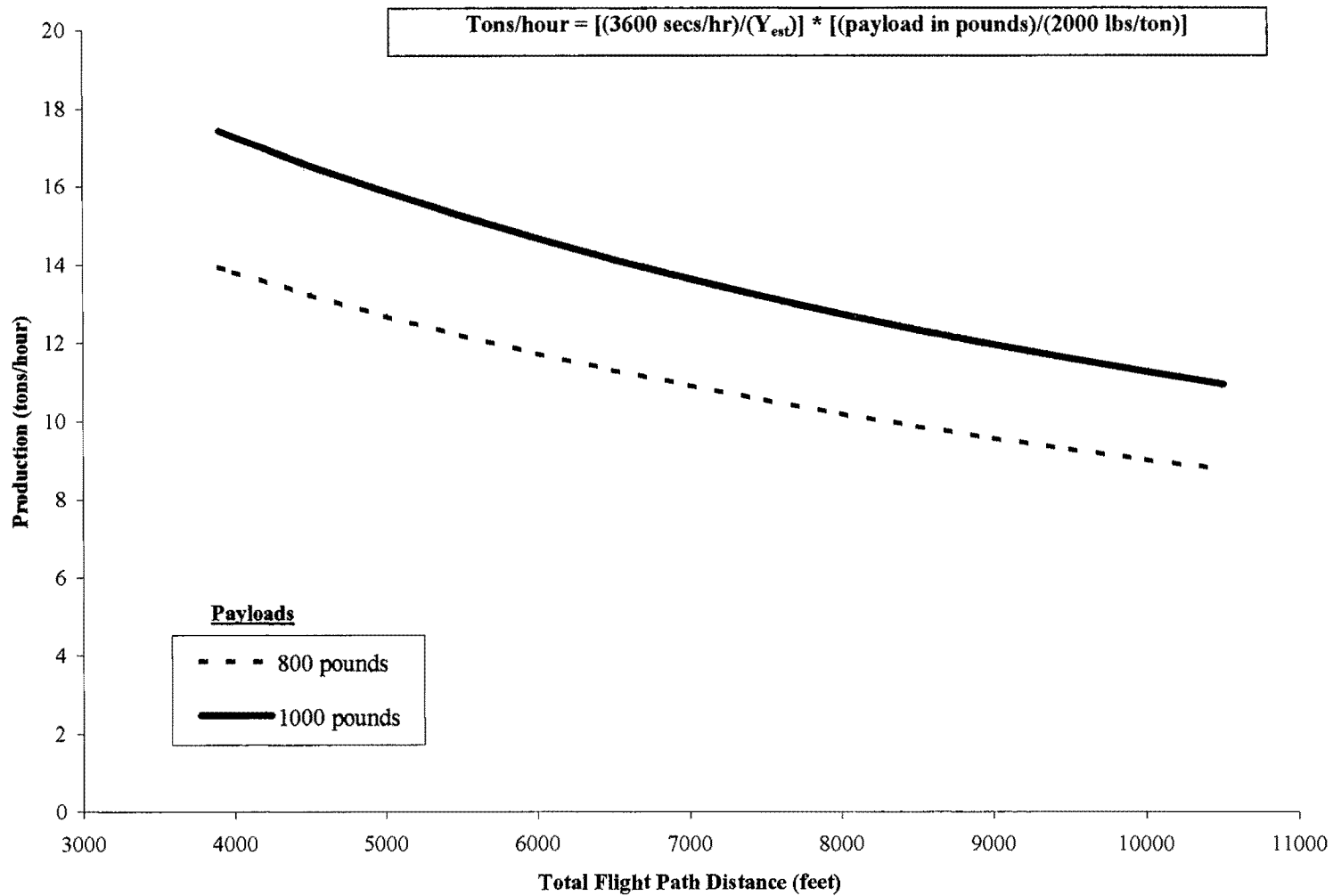
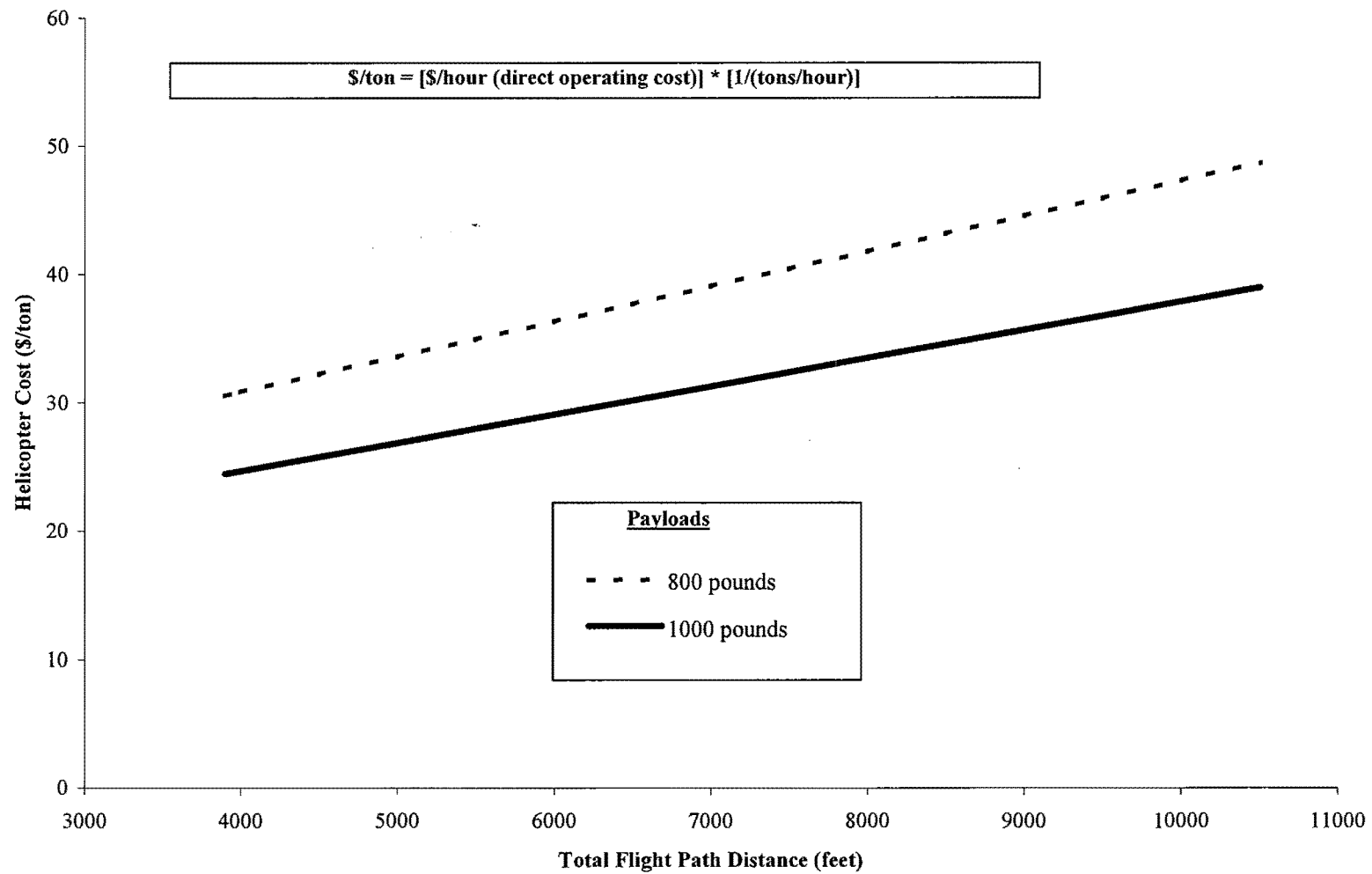


Figure 20: Projected helicopter cost estimates for B47G3 based on production estimates (Figure 19)



## 9.8 Discussion

The comparison between the 10-cycle samples of flight data for units 3, 4, 5 and 6 and the empirical production model estimates indicate the empirical models provide a good estimate of average total cycle time. When heliports are located on a unit, the distance from the heliport to the center of the unit may not give an accurate estimate of the average total flight path distance and adjustments should be made for the helicopter to align with an application approach path (see earlier discussion in Section 9.3).

Heliport approach and departure pathways can affect helicopter production and costs. The 25-cycle sample comparisons between unit 3 and unit 5 for an unrestricted heliport and a restricted heliport illustrate this effect. An abundance of restricted heliports on a project could contribute to an overall project cost increase compared to a project with unrestricted heliports.

Under the conditions of this project, the 25-cycle sample data for unit 3 indicates the influence of acceleration and deceleration on total elapsed time for a cycle is consistent and predictable over the range of data. A simple linear relationship between total elapsed cycle time and total flight path distance accounts for this consistent component of total elapsed cycle time. The controlling variable for total elapsed time and total cycle time is the total flight path distance for a delay-free cycle.

Helicopter production estimates for the case study were estimated with simple linear regression. An equation to estimate average total cycle time from a 50-cycle data sample was developed and compared to a second random 50-cycle sample and empirical model estimates. The regression appears to adequately estimate average total delay-free cycle time for the conditions and limits of the case study. Earlier research with helicopter logging indicates

helicopter cycle times are not linear with distance until cruise speed was reached between 1640 and 4920 feet (500 to 1500 meters) (Halkett 1982). The data analysis from the case study cannot definitively confirm or refute this statement. The regression from the case study data suggests the helicopter cycle time is linear with total flight path distance over a total flight path distance range from 1900 feet to 10,500 feet and was validated with the second data set for distances between 3900 feet to 10,500 feet. There were insufficient data points in the validation sample to confirm the linearity of the regression below 3900 feet total flight path distance. The regression could be used to estimate production and costs for a project operating under conditions similar to the case study (e.g. same mineral, comparable aircraft, skilled pilot, experienced support crew with similar equipment, etc.) for the range of validation.



## 10.0 CONCLUSIONS, DISCUSSION, AND RECOMMENDATIONS

### 10.1 Conclusions

Once specifics are known about equipment and the operator for a project, mixed-integer linear programming is suitable for modeling the heliport facility location problem. However, the approach taken to address the operations problem for the case study as a cost minimization for a transportation network may not be suitable for precise estimates to select specific equipment and/or operators.

The helicopter hourly direct operating cost estimates used may not reflect current market conditions, do not represent the actual costs for any particular operator and need to be adjusted to reflect actual helicopter operating costs and conditions for a prospective project. Also, the cost for the bagged form of doloprill are hypothetical and currently lack an actual cost basis and may lack additional handling costs for the mineral in that form.

The solution of the mixed-integer model formulation was a cost minimization for the simplified two-unit version of the case study. The solution contained transportation and application options that minimized total cost of doloprill applied to a combination of units with shared routes. The mixed-integer approach is suitable for modeling other similar operations. Use of a defined methodology to estimate fixed and variable costs on a common (e.g. \$/ton) basis is crucial to build a solution framework that uses this type of mathematical model approach.

Road costs, heliport and service landing improvement and maintenance costs, heliport and service landing move-in costs comprise the ground transportation segment of the conceptual network. The application and ferry costs were derived from empirical production estimates for the B47G3 and B205A helicopters. The production estimates should be verified for a particular pilot, aircraft, application type and operational conditions. These costs should be validated with historical records or from estimates by the operator, or by sampling and analysis of flight data for an ongoing operation.

Analysis of the differential global positioning satellite (DGPS) flight data indicates the empirical production models for the B47G3 helicopter are satisfactory and could be used to estimate helicopter production for a similar operation. A maximum feasible acceleration and deceleration rate may be used to estimate a segment of the total flight path distance with the empirical model, but the rate appears to be inconsequential for an overall estimate of an average total cycle time for the flight path distances observed. The influence of acceleration and deceleration on total elapsed time for a cycle is consistent and predictable over the range of data and can be accounted for with a simple linear relationship between total elapsed cycle time and total flight path distance.

Heliport approach and departure flight paths affect total cycle time and can influence risk management decisions. The flight data analysis indicates a heliport with obstructed and/or restricted approach and departure paths can increase the total cycle time from that heliport, limit payload capacity, decrease helicopter productivity and increase application costs. There is additional risk to personnel when the pilot has to maneuver around obstructions to land or load and also when the helicopter requires maximum power and performance to approach or depart.

It is important to recognize restricted heliport flight paths to adjust cost and production estimates accordingly and to consider the additional risk in operational planning.

The total flight path distance of the helicopter is the primary contributing factor to determine average total cycle time and estimate production for a unit. The regression developed from the 50-cycle sample has a positive linear relationship between average total cycle time and the average total flight path distance within the limits of the data sets. The empirical model estimates fall within the 95% prediction band of the regression. In conjunction with specified limits and static assumptions, this regression could be used for future planning purposes to estimate production for the selected mineral with a comparable helicopter and skilled pilot under similar conditions.

## 10.2 Discussion

The results of this case study analysis indicate the heliport facility location problem can be evaluated using a mathematical modeling approach, such as mixed-integer linear programming. A defined methodology is used to identify important costs and variables and then formulate a solution framework. Significant costs include the road, heliport, service landing improvement and maintenance costs, hourly helicopter costs and agricultural truck costs. Important variables include the number of agricultural trucks needed on a heliport, total flight path distance of the helicopter, payload, and heliport and service landing location and access. For each heliport and service landing, consideration was given to the approach and departure

path for the helicopter and adjustments were made to payloads and/or acceleration/deceleration rates for empirical production estimates.

Although helicopter operations typically focus on minimizing the helicopter operating cost, the case study indicates that road costs can contribute significantly to the operations cost for a project. The helicopter cost for the B205A1 in Option 5, was \$73.67/ton for unit 5, and \$47.25/ton for unit 4. The helicopter cost for the B47G3 in Option 1, was \$43.93/ton for heliport 5A, \$28.74/ton for heliport 5B and \$21.26/flight hour for unit 4. As a relative comparison, the cost for the B205A1 to deliver bagged material to unit 5 was approximately 68% to 156% greater than for the B47G3 to deliver bulk material. For unit 4, the B205A1 hourly cost was approximately 122% greater. Even with the higher helicopter cost, Option 5 minimized the total operational cost, considering the transportation and aerial application costs together.

#### 10.2.1 *Operational Considerations for Relative Comparison*

##### 10.2.1.1 Ferry Distance

Using the empirical estimates for the case study problem, the B205A1 had a longer estimated ferry distance from the transfer site compared to the B47G3 from each heliport: 2.6 miles to unit 5 for the B205A1 versus 1.0 mile from heliport 5A and 0.2 mile from heliport 5B for the B47G3.

Due to the nature of the mineral applied, the estimated application rate for both helicopters was similar, but production rates varied due mainly to payload differences. The mineral had a maximum application swath width of 50 feet. The B47G3 had an estimated payload of 1000 pounds for heliport 5A; 800 pounds for heliport 5B; and 1000 pounds for unit 4. The B205A1 had an estimated payload of 3200 pounds for direct application of bagged material for unit 5 and 4. The estimated production for the B47G3 was 9.7 tons/hour on heliport 5A; 14.8 tons per hour on heliport 5B; and 20.0 tons/hour on unit 4. The estimated production for the B205A1 was 15.4 tons/hour for unit 5 and 24 tons/hour on unit 4. Although the empirical model has not been tested for validity for the B205A1 and the B47G3 has limited validation over a range of total flight path distances, Figure 21 illustrates the relative differences in production as a function of one-way ferry distance from a common heliport or transfer site for the B47G3 and the B205A1. The lines on the production graph were fitted to empirical model production estimates over a range of one-way ferry distances. As should be expected, relative helicopter production (Figure 21) indicates the B205A1 had higher production than the B47G3 over the charted range of one-way ferry distances from a common heliport or transfer site. For both helicopters, the longer the one-way ferry distance, the lower the estimated production.

Pending validation of the empirical model estimates for the helicopters over the charted range of one-way ferry distances, Figure 22 could provide a potentially useful comparison of aircraft costs, although limited in scope. Considering only helicopter direct operating cost (exclusive of other significant project costs), the B47G3 had a lower cost-per-ton than the B205A1 for distances up to 0.65 mile with an 800 pound payload of bulk material and up to 1.23 miles with a 1000 pound payload of bulk material. Beyond 1.23 miles, the B205A1 has a lower cost-per-ton of applied bagged material. The relative cost lines were constructed from direct

Figure 21: Relative helicopter production for application based on empirical model estimates over a range of one-way ferry distances

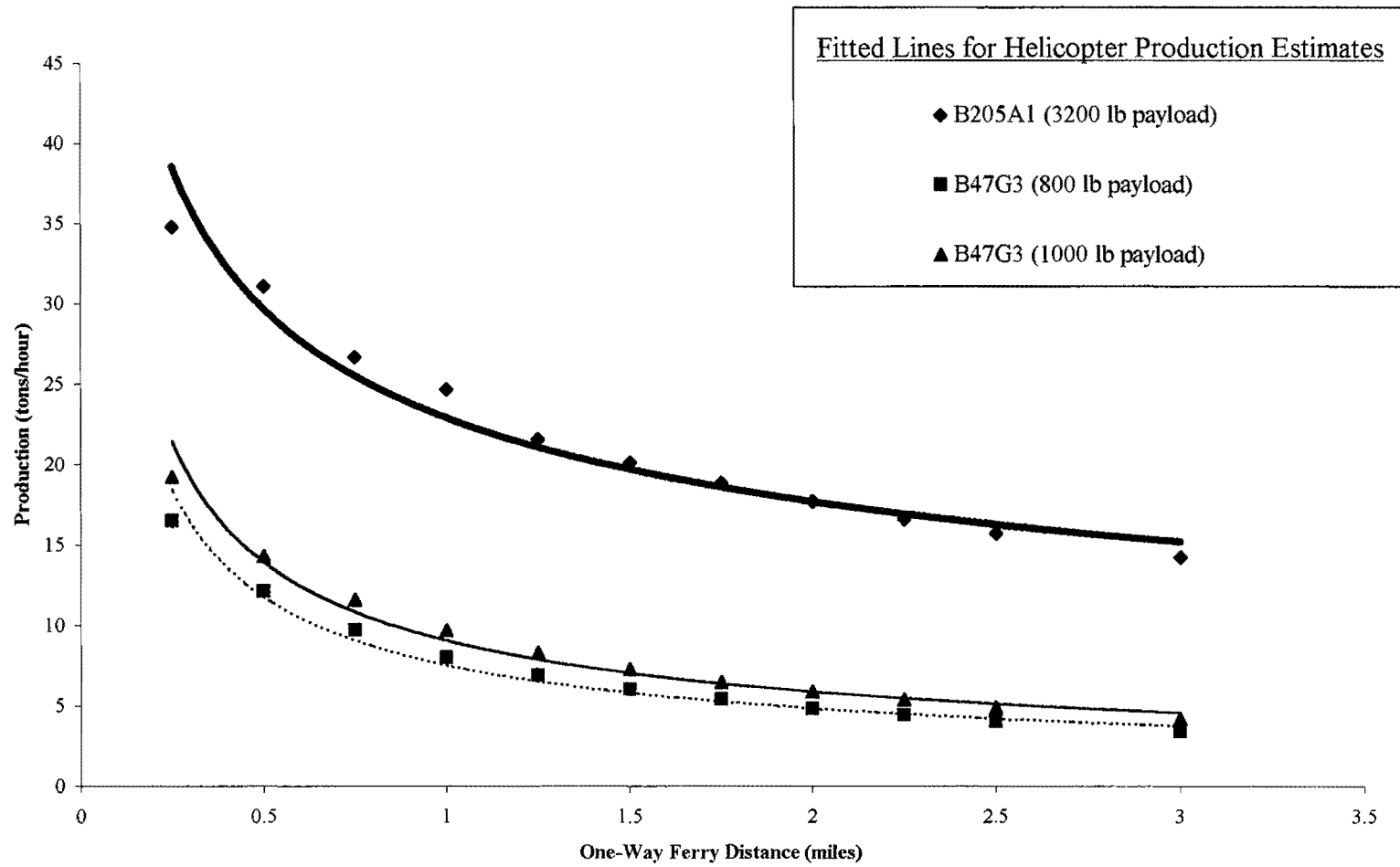
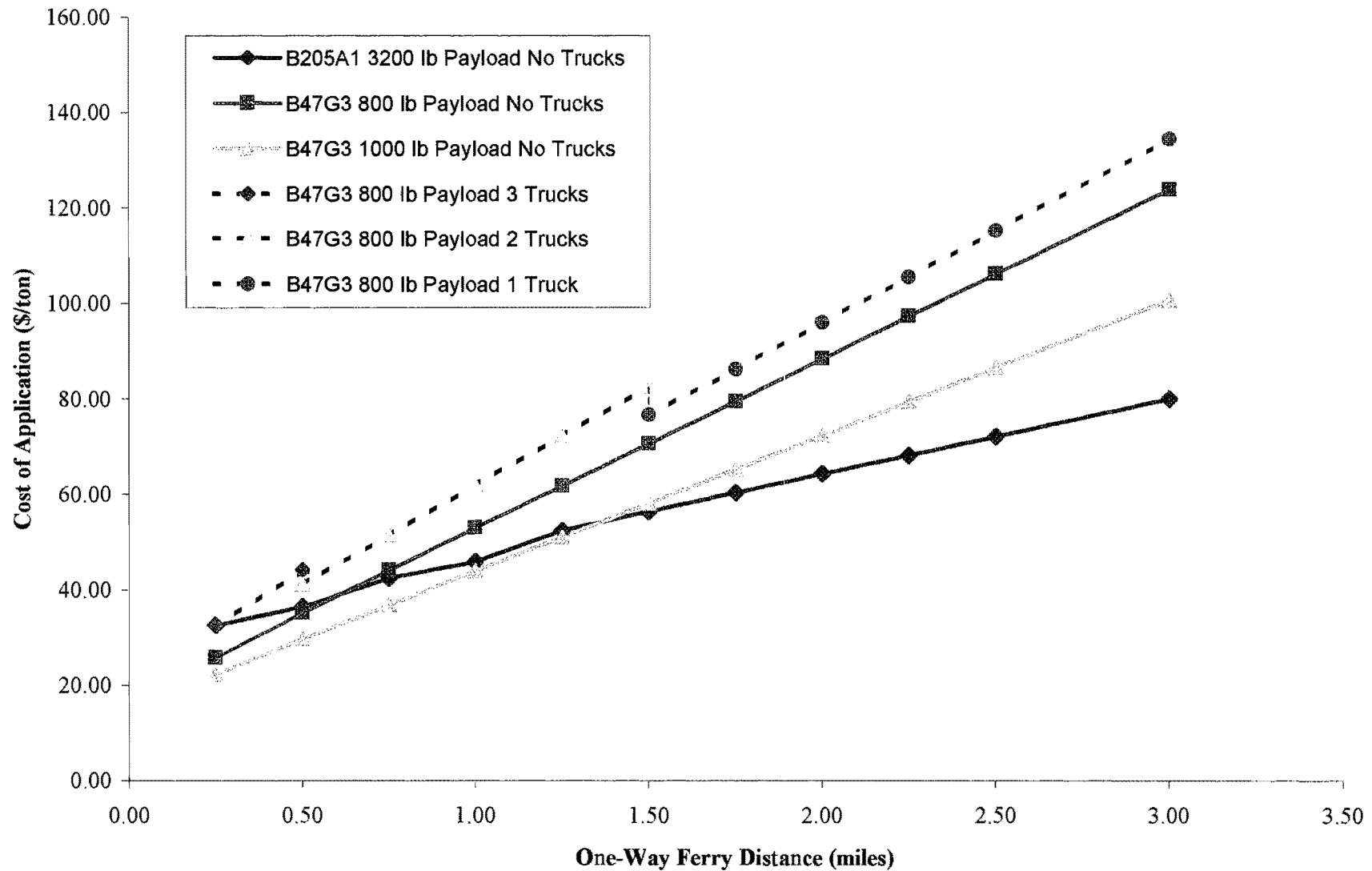


Figure 22: Relative helicopter application costs based on empirical production estimates (Figure 21) and hourly direct operating costs over a range of one-way ferry distances (Including example break points for truck usage)



hourly operating costs and empirical model production estimates for each helicopter over a range of one-way ferry distances.

Although suitable for evaluation of individual heliport or transfer site locations, this graphical method of portraying the relative cost relationships between aircraft application options is limited for project planning. First, the one-way ferry distances were from one common heliport or transfer site where all other costs and factors were assumed equal. Second, the costs were for the application phase of the operation only. Third, other significant cost variables for the project (e.g. the agricultural truck costs) were not included. As an example, to match production for the B47G3 and an 800 lb payload assume three agricultural trucks are required up to a 0.5 mile ferry distance; two trucks are required for a 0.5 to 1.5 mile ferry distance; and beyond a 1.5 mile ferry distance one truck is required. The costs for the agricultural trucks combined with the B47G3 (800 lb payload) is represented by the dashed line in Figure 22. This changes the shape of the cost curve and the ferry distance at which the B47G3 with an 800 lb payload is more cost effective than the B205A1. Due to the interactions of multiple project costs, consideration of only the helicopter costs may not minimize the total project costs for an operation.

On a project basis, a more relevant comparison of costs for each helicopter should include all associated project costs, such as the cost of the agricultural trucks and road improvements for each transportation and application option for multiple choices of heliports, service landings, transfer sites and estimated ferry distances. This research paper has shown the mixed-integer linear programming model is suitable for this type of heliport facility location problem to minimize project costs.



#### 10.2.1.2 Helicopter Performance

The two helicopters evaluated in this project were considered to have similar performance characteristics when operating with a full payload (Mateski 2002; Branham 2002). Different types of helicopters may have different performance characteristics and limitations when used under the conditions in the case study. Evaluation of each helicopter type is needed to determine the maximum payload, maximum acceleration, maximum airspeed and flight characteristics for a specific application under anticipated conditions for an operation.

The flight data analysis suggests that within the range of total flight distances in the data sample, the maximum difference in elevation between the load point and the application flight line did not significantly affect the total cycle time. For longer flight distances with a positive change in elevation, it would be plausible to assume the total cycle time will be affected. Based upon the results of prior helicopter logging research, the performance capability for rate of climb of an individual aircraft may become a significant factor when estimating an average total cycle time (Heinimann 1996).

#### 10.2.1.3 Physical Properties of Applied Minerals

As mentioned previously, the physical properties of the applied mineral can influence the productive capacity of the helicopter. In the case study, the doloprill was in a pelletized form with an average pellet size of approximately 0.25 to 0.50 inches. The material had a relatively low bulk density which limited the application swath width to approximately 50 feet with the

given bucket application system (bucket application rate of 435 pounds per acre). The material was also prone to disaggregating during handling which generated fines that settled out and tended to clog the augers on the agricultural trucks. With the molasses binder, the pellets and the fines were sensitive to moisture. When the material was exposed to rain or snow, it tended to stick to the bin, auger and scale bag on the agricultural truck and the application bucket. This created problems with accurately weighing a payload, filling the bucket and emptying the bucket during application. The stickiness of the material reduced the flow rate during application and increased the application time. The pilot made on-the-fly adjustments by applying slower than the calibrated application airspeed to distribute the material uniformly.

Some of the other minerals applied during the case study could not be mixed due to problems with chemical reactivity. These minerals were mixed on site then loaded directly in the bucket and applied separately. On some of the units, the helicopter flew the same area up to five times to distribute all of the minerals and the operation incurred up to three separate move-ins for some heliports.

Other minerals (e.g. sulfur) applied with a spray application require a plentiful source of water in close proximity to the operation. The form (i.e. liquid or powder), solubility and purity of the mineral is considered to calculate the desired mix concentration for a calibrated application rate. In addition, specialized equipment (such as trucks with tanks and internal agitators) is sometimes required to mix the material on site.

### 10.2.2 *Summary*

Although the estimated costs for the simplified version of the case study problem may not reflect actual helicopter costs for the operation, the model results may be used for a relative comparison of transportation and delivery options as a function of one or more important variables (e.g. ferry distance). If the solution for the network solely minimized helicopter costs without considering road, heliport and service landing costs, the overall project cost likely would have increased. Table 9 is a summary of the cost components in the case study as a percentage of the transportation network option per ton costs of delivered mineral. The mixed-integer linear programming model can adequately estimate combined transportation and aerial application costs as a part of a designed methodology for project evaluation to minimize total costs.

## 10.3 Recommendations

The potential exists to expand the simplified version of the case study problem to a more complex problem. The more complex problem may include: a variety of applied minerals, both dry and liquid form; one or more aircraft; several applications over an extended time period; and several transportation and application options. To approach a solution for a larger-scale and more complex problem, users may follow a process that is an extension of the case study

Table 9: Summary of cost components as a percentage of transportation network option costs

Option	Option 1 <sup>1</sup>			Option 2 <sup>2</sup>			Option 3 <sup>3</sup>			Option 4 <sup>4</sup>			Option 5 <sup>5</sup>		
Unit	5	5	4	5	5	4	5	5	4	5	5	4	5	5	4
Heliport	5A	5B	4A	5A	5B	4A	5A	5B	4A	5A	5B	4A	5A	5B	4A

Total \$/Ton	236.12	248.35	293.71	276.52	272.80	351.19	265.38	261.66	340.05	225.12	225.12	315.00	213.98	213.98	303.86
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<b>Helicopter</b>	19%	12%	7%	38%	35%	17%	40%	37%	17%	33%	33%	15%	34%	34%	16%
<b>Agricultural Truck</b>	9%	6%	1%	5%	4%	1%	6%	4%	1%	0%	0%	0%	0%	0%	0%
<b>Improvements/Move-in</b>	11%	25%	43%	5%	9%	42%	5%	9%	43%	4%	4%	40%	4%	4%	41%
<b>Doloprill</b>	59%	56%	48%	51%	51%	40%	49%	50%	38%	62%	62%	44%	61%	61%	43%
<b>Primary Transportation</b>	1%	1%	1%	1%	1%	1%	1%	1%	0%	1%	1%	1%	1%	1%	1%

Footnotes:

- 1 Bulk application with B47G3; ground transportation
- 2 Bulk application with B47G3; aerial ferry B205A1 from transfer site
- 3 Bag application with B47G3; aerial ferry B205A1 from transfer site
- 4 Bulk application with B205A1, ferry from transfer site
- 5 Bag application with B205A1, ferry from transfer site

methodology. The methodology for a larger-scale problem or a landscape-scale model would include:

1. A definition of the assumptions and constraints for the larger-scale model
2. Establishing common basis relationships for important cost and production variables in the expanded model
3. Formulation of the mathematical model to include the potential for non-linear cost and production variables
4. Solve the larger-scale model using formulations for important cost and production variables
5. Verify a sample of the solution of a larger-scale model with field tests, and/or comparisons with actual operation data, and/or comparison with modeled operations based on historical production and cost data

#### 10.3.1 *Research Needs*

Additional research is needed to verify production estimates for helicopters, support equipment and operations costs with different types, forms and quantities of minerals over a range of longer ferry distances and various road and heliport networks. A significant cost component of the overall operation hinges on the production capacity of the helicopter. This capacity depends upon aircraft performance characteristics, payload, calibrated application rate, ferry distance and velocity, heliport approach and departure paths, pilot skill level, productive flight hours, delays due to breakdowns, material handling problems and logistics, moving to and

from units, and finally weather factors. Similar research is likely needed for fixed-wing applications.

The use of modern technology, such as the Ag-Nav<sup>®</sup>2 DGPS system, to record accurate time and three-dimensional flight data during an operation can further assist development of helicopter production models for a variety of aircraft over a range of applications.

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**APPENDICES**

## Appendix A: Time-Study Elements & Variables

**Goal:** Produce predictive equations that describe delay-free time for the average total productive cycle time as a function of non-timed operational components.

### Dependent Variables

Cycle Time (Productive)  
     Reload  
         Reload in  
         Reload hover  
         Reload out  
     Outhaul  
         End Reload to  
             Start of application  
     Inhaul  
         End of application to  
             Start of Reload  
     Application  
         Start of application to  
             End of application  
         Includes turning time

### Independent Variables

Payload  
 Flight Path Distance  
     Outhaul  
     Inhaul  
 Difference in Elevation  
     Maximum from heliport to  
         ave. of application unit  
 Application airspeed  
 Application rate  
 Swath width  
 Number of turns  
 Weather  
 Density altitude  
 Unit acres

### Non-Productive Flight Time Elements

Refuel  
     Flare to land; lift to hover and reload  
 Reconnaissance  
     General  
     Mapping unit boundary  
 Travel to next unit  
 Travel to next heliport  
 Calibration  
 Aborted delivery  
 Delays

### Non-Flight Time Elements

Refuel  
     Landed and refueling  
 Pre-flight preparation and inspection  
 Personal time/breaks  
 Mobilization  
 Delays

### Sources of Variation and Controls

Fixed: Keep the same pilot, aircraft, equipment, and personnel throughout the project.

Measure: Total productive cycle time per payload of materials, and associated flight data for each unit.

Randomize: Randomly pick a sample of productive cycles for one type of material applied from each of the nine application units for analysis of the flight characteristics of the helicopter.

Ignore/accept as is: Weather delays, variations in heliport configurations, sequencing of the operation and logistics, orientation of the heliport to unit, size of the units, and vegetation cover on the units.

### **Breakdown of Productive Cycle Time Elements for Time Study Using Ag-Nav<sup>®</sup> 2 DGPS Technology and Software:**

#### **Reload:**

**Hover Phase:** The time the helicopter is in a hover while reloading

**Out Phase:** From the time/position the helicopter leaves the reload hover to the time/position of translation (from less than 5 mph to 25 mph)

**In Phase:** From the time/position of flare to the reload position (airspeed starts to drop below the ave. indicated airspeed to less than 5 mph)

**Outhaul Phase:** From time/position of translation (airspeed greater than 25 mph) to time/position of starting/continuing application on operations unit  
-Start of application (spray “on” indicator)

**Inhaul Phase:** From the time/position of finishing a load or an operations unit to the time/position of flare (airspeed drops below ave. indicated airspeed)  
-End of application (spray “off” indicator)

**Cycle Time:** From the start of the “hover phase” during reload, through the entire cycle until to the beginning of the next “hover phase” during reload.

**Operations Unit Phase:** From time/position of starting/continuing application on operations unit to the time/position of finishing an application (the time spent on the Operations Unit during the application of the material – includes orientation, application/coverage, and turning). Can be delineated by the “spray on” and “spray off” indicator for any pass.

### **Breakdown of Non-Productive Time Elements Using Data Forms**

#### **Non-Flight:**

Pre-flight prep and inspection

Warm-up/cool down

Personal time/breaks

Mobilization

Drive to/from project area

Landed and refueling

Delays

Mechanical repairs helicopter

Mechanical repairs support equipment

Mechanical repairs bucket/application equipment

Waiting for Support equipment/personnel to reach next set-up

Waiting for delivery of materials

Other

**Flight:**

## Mobilization

Fly to/from project area from helibase

Fly to next unit

Fly to next heliport

## Reconnaissance – general

Reconnaissance – unit boundary mapping, etc.

## Calibration

Aborted delivery of load

## Delays

Mechanical repairs support equipment

Mechanical repairs bucket/application equipment

Waiting for support equipment/personnel to reach next set-up

Waiting for delivery of materials

Other

**Other Data Collected**Helicopter Non-Productive Time Elements

Material applied

Application rate

Daily Operations Summary

Weather (per hour of flight time)

Equipment

Personnel

Helicopter Payload Tally

Load #

Time loaded

Payload

Helicopter Load Time Element (Use Ag-Nav<sup>®</sup>2 data)

Load #

Start/stop hover time

Daily Hauling Summary

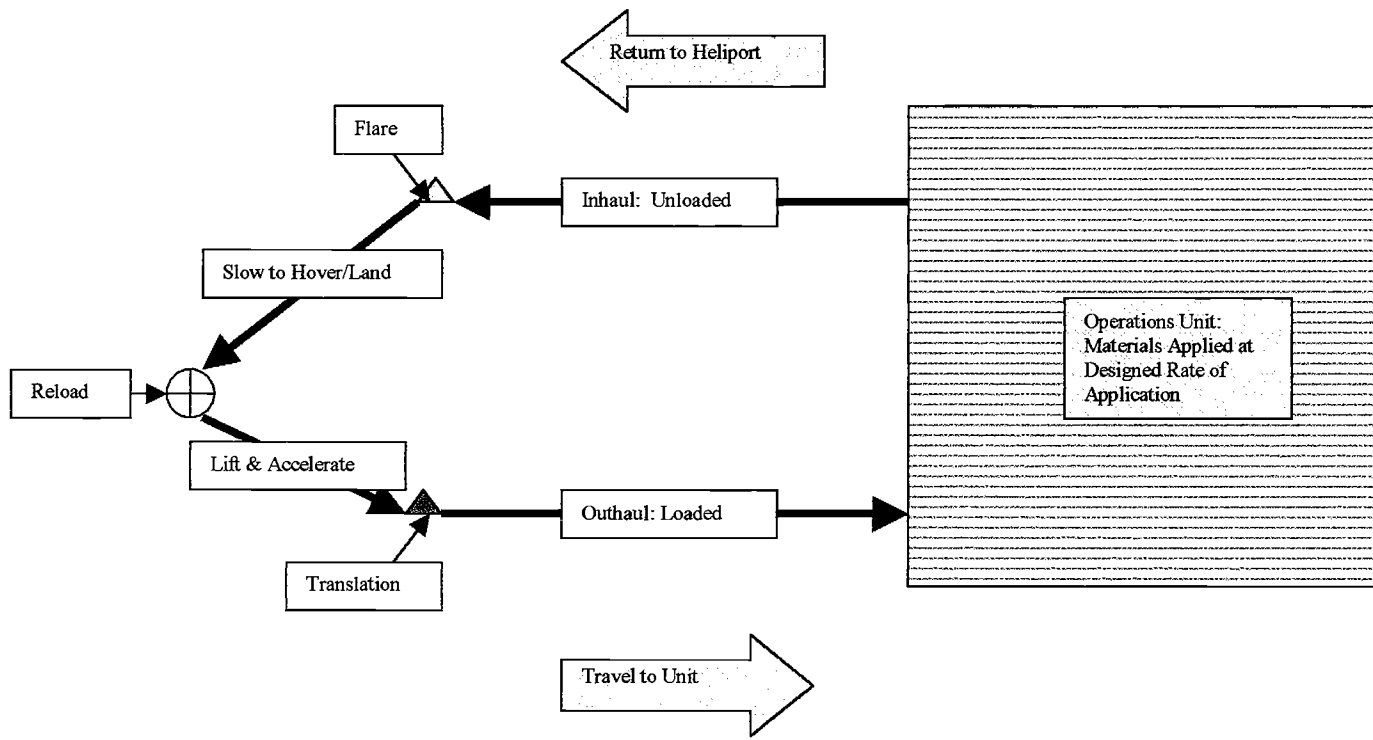
# Trips to each heliport

Mileage traveled to each heliport (round trip)

Time to travel to/from each heliport from transfer site area

Time to load at transfer site/unload at heliport

Figure 23: Cycle time elements





### **Key to Cycle Time Elements Diagram**



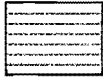
Heliport: reload materials; service landing



Translation: relative speed of helicopter is such that flight is transferred from vertical lift to forward travel



Flare: relative speed of helicopter slows for approach heliport for landing or hover to reload



Operations Unit: Area to which material is applied at a predetermined rate of application

**Outhaul:** Time/distance helicopter travels from point of translation to operations unit loaded to begin application; airspeed is estimated to be equivalent to application airspeed

**Inhaul:** Time/distance helicopter travels from operations unit unloaded after finishing a load to the point of flare; airspeed is estimated to be slightly higher than application airspeed

**Lift and Accelerate:** The time from when loading is completed to the point of translation of the aircraft

**Slow to Hover/Land:** The time from when the helicopter flares to when it comes into a hover or lands for reloading

**Hover and Reload:** The time it takes to reload the helicopter with the desired payload of materials

**Appendix B: Production and Cost Estimate Spreadsheets**

B.1	Helicopter Cost Estimates for B47G3 Helicopter.....	131
B.2	Helicopter Cost Estimates for B205A1 Helicopter.....	133
B.3	Truck Driver Cost.....	135
B.4	Agricultural Truck Cost Sheet.....	136
B.5	Production and Cost Estimates for Unit 4.....	138
B.6	Production and Cost Estimates for Unit 5.....	161

<b>Direct Cost - \$</b>	<b>Bell 47G3</b>
Fuel (1)	45.90
Fuel Additives	0.00
Lubricants	1.38
Maintenance Labor (2)	42.48
Parts Airframe/Eng/Avion (3)	17.00
Engine Restoration (4)	25.50
Thrust Reverser Overhaul	0.00
Propeller Overhaul	0.00
APU Overhaul	0.00
Dynamic Comp/Life Ltd Parts	32.75
Misc. Exp. - Landing/Parking	0.00
-Crew Expenses	0.00
-Supplies/Catering	0.00
-Other	0.00
Fractional Cost/Hour + Tax	0.00
<b>Total Direct Cost/Flight Hour</b>	<b>165.01</b>
Ave. Speed - Kts. (5)	74
Ave. Max Cruise Speed - MPH (5A)	98
Ave. Cruise Speed - MPH (5B)	60
<b>Cost per Nautical Mile (5)</b>	<b>2.23</b>

---

FOOTNOTES - \$ Operation: 1-2 Aircraft Date: 2/4/2002

<b>Type of Operation:</b>	<b>Utility</b>
1) Fuel Cost	2.55
Gallons/Hour	18
2) Maint. Labor Cost/Hour	59.00
Maint. Hours/Flight Hourse	0.72
3) Incl. Engine Parts Cost	Yes
Engine Model	TVO-435
4) Overhaul Cost source	Lycoming
5) Block Speed Source	90% Vcruise
5A) IHTG S-217 11/93 NFES #2390	Estimated
5B) From operator	Estimated
6) Crew Salary Source	Estimated
Number of Crew	1
7) Insured Hull Value	108,500.00
Hull Insurance Rate (%)	15.5
8) Modernization	0.1% x Price
9) Refurbish Labor Hrs/Seat	5
10) Comp. Mx Program Source	MxManager
11) Weather Service Source	Typical
12) Depreciation Rate	10% per year
13) Operator ave./helicopter	400

\*Unless otherwise noted, base helicopter costs are from Conklin and deDecker Associates, Inc.

**B.1 Helicopter Cost Estimates for B47G Helicopter\***

132

<b>Fixed Cost - \$</b>	<b>Bell 47G3</b>	
Crew Salaries - Captain (6)	45,000	
- Co-pilot	0	
- Flt Eng/other	0	
- Benefits	11,250	
Number of Seats		2
Hangar - Typical	5,600	
Insurance - Hull (7)	16,818	
Admitted Liability	1,950	
Legal Liability	8,000	
Recurrent Training	1,150	
Aircraft Modernization (8)	109	
Navigation Chart Service	219	
Refurbishing (9)	590	
Computer Mx. Program (10)	2,050	
Weather Service (11)	665	
Other Fixed Costs	0	
Fractional Cost/Yr + Tax	0	
Book Depreciation (12)	10,850	
<b>Total Fixed Cost/Year</b>	<b>104,250</b>	
<b>ANNUAL BASIS - \$</b>	<b>Utility</b>	
Utilization - Hours (13)	400	
Direct Cost	66,003	
Fixed Cost	104,250	
<b>Total Cost (Book Depn)</b>	<b>170,253</b>	
- Per Flight Hour	426 \$/flight hour	

\*Unless otherwise noted, base helicopter costs are from  
Conklin and deDecker Associates, Inc.

<b>Direct Cost - \$</b>	<b>Bell 205A1</b>
Fuel (1)	208.98
Fuel Additives	0.00
Lubricants	6.27
Maintenance Labor (2)	119.07
Parts Airframe/Eng/Avion (3)	17.00
Engine Restoration (4)	25.50
Thrust Reverser Overhaul	0.00
Propeller Overhaul	0.00
APU Overhaul	0.00
Dynamic Comp/Life Ltd Parts	32.75
Misc. Exp. - Landing/Parking	0.00
-Crew Expenses	0.00
-Supplies/Catering	0.00
-Other	0.00
Fractional Cost/Hour + Tax	0.00
<b>Total Direct Cost/Flight Hour</b>	<b>409.57</b>
Ave. Speed - Kts. (5)	74
Ave. Max Cruise Speed - MPH (5A)	98
Ave. Cruise Speed - MPH (5B)	60
<b>Cost per Nautical Mile (5)</b>	<b>5.53</b>

---

**FOOTNOTES - \$ Operation: 1-2 Aircraft Date: 2/4/2002**

<b>Type of Operation:</b>	<b>Utility</b>
1) Fuel Cost	2.43
Gallons/Hour	86
2) Maint. Labor Cost/Hour	63.00
Maint. Hours/Flight Hourse	1.89
3) Incl. Engine Parts Cost	Yes
Engine Model	T5313B
4) Overhaul Cost source	Estimated
5) Block Speed Source	90% Vcruise
5A) IHTG S-217 11/93 NFES #2390	2001 R & W
5B) From operator	Estimated
6) Crew Salary Source	Estimated
Number of Crew	1
7) Insured Hull Value	1,077,500.00
Hull Insurance Rate (%)	7
8) Modernization	0.1% x Price
9) Refurbish Labor Hrs/Seat	5
10) Comp. Mx Program Source	MxManager
11) Weather Service Source	Typical
12) Depreciation Rate	10% per year
13) Operator ave./helicopter	400

**\*Unless otherwise noted, base helicopter costs are from Conklin and deDecker Associates, Inc.**

**B.2 Helicopter Cost Estimates for B205A1 Helicopter\***

134

<b>Fixed Cost - \$</b>	<b>Bell 205A1</b>	
Crew Salaries - Captain (6)	50,800	
- Co-pilot	0	
- Flt Eng/other	0	
- Benefits	12,700	
Number of Seats		14
Hangar - Typical	15,900	
Insurance - Hull (7)	75,425	
Admitted Liability	4,875	
Legal Liability	8,000	
Recurrent Training	5,775	
Aircraft Modernization (8)	1,078	
Navigation Chart Service	219	
Refurbishing (9)	4,410	
Computer Mx. Program (10)	2,050	
Weather Service (11)	665	
Other Fixed Costs	0	
Fractional Cost/Yr + Tax	0	
Book Depreciation (12)	107,750	
<b>Total Fixed Cost/Year</b>	<b>289,647</b>	
<b>ANNUAL BASIS - \$</b>	<b>Utility</b>	
Utilization - Hours (13)	400	
Direct Cost	163,828	
Fixed Cost	289,647	
<b>Total Cost (Book Depn)</b>	<b>453,474</b>	
- Per Flight Hour	1134 \$/flight hour	

\*Unless otherwise noted, base helicopter costs are from  
Conklin and deDecker Associates, Inc.

Labor Data(1):

Truck driver(2) =           17.27 \$/SMH  
                                      17.56 \$/PMH

(1) Labor rates provided by Associated Oregon Loggers; burden rate for FICA, health insurance, retirement, disability insurance and other is 35%.

(2) PMH/SMH based on utilization of truck

## B.4 Agricultural Truck Cost Sheet

136

### Equipment:

Name: Agricultural Truck  
Type: 13 Ton Ag-Type  
HP:

### Associated Job/Costing Reference:

Name: Nutrition Project  
Dates: 3/1/02  
Type/desc: Specialized nutrient applications

### Ownership Costs

#### Depreciation:

(P) Purchase Price: 80,000.00

(S) Salv Value: 4,000.00

Annual Dep'n: 5,066.67

Average Annual Investment: 44,533.33

Interest, Insurance, Taxes: 4,453.33

Overhead: 720.00

Total Int.+Ins.+Tax+OH = 5,173.33

Fixed Cost = Annual Dep'n + IIT = \$/yr

Fixed Cost = 5,066.67 + 5,173.33 = \$/yr 10,240.00

Driver(3): Fixed Cost = 17.27 \$/SMH X 1200 SMH/hr 20,724.00

TOTAL FIXED COST = 30,964.00 \$/year

### Operating Costs

#### Fuel, oil, lube, tires (1):

Fuel, Oil, Lubrication, Tires: 1.30 \$/PMH

Total FOLT= 1.30 \$/PMH

#### Repair & Maintenance(2):

Cost: 10,947.78 \$/year

Cost/PMH = 10,947.78 \$/year / 1180 PMH = 9.28 \$/PMH

Operating Cost = ( F&L + R&M ) x PMH/year

Operating Cost = 10.58 \$/PMH x 1180 PMH/year = 12,483.78 \$/year

TOTAL OPERATING COSTS = 12,483.78 \$/year

(1) Basis: 15% of Total Fixed Cost for Truck

(2) Basis: Estimated from operator = 25% \* AAI \* % util

(3) Basis: Salaried

(4) Basis: 18,000 SMH Total Life; Operate 5 months/year for 1200 SMH/year

(5) Basis: 17,700 PMH Total Life; Operate 5 months/year for 1180 PMH/year



## B.4 Agricultural Truck Cost Sheet

137

**Equipment:**

Name: Agricultural Truck  
 Type: 13 Ton Ag-Type  
 HP:

**Associated Job/Costing Reference:**

Name: Nutrition Project  
 Dates: 3/1/02  
 Type/desc: Specialized nutrient

SMH = 1,200 hours/yr = 240 hours/month  
 PMH = 1,180 hours/yr = 236 hours/month  
 FC = 30,964.00 \$/year Total Fixed Cost  
 OC = 12,483.78 \$/year Total Operating Cost

Modified Method 3: Average Machine Cost/Month

Machine Cost/Month = (FC/SMH/yr X SMH/month) + (OC/PMH/yr X PMH/month)

Machine Cost/Month =  $\frac{30,964.00 \text{ FC}}{1,200 \text{ SMH/year}} \times 240 \text{ SMH/mo}$   
 +  $\frac{12,483.78 \text{ OC}}{1,180 \text{ PMH/year}} \times 236 \text{ PMH/mo}$

**Operating Season (4):**

Machine Cost/Month = 6,192.80 (FC) + 2,496.76 (OC) = 8,689.56 \$/Month

Method 1: Hourly Machine Cost/SMH (4)

Hourly Machine Cost/SMH = (FC + OC)/SMH/yr

Hourly Machine Cost/SMH =  $\frac{30,964.00 + 12,483.78}{1,200 \text{ SMH/yr}}$  = 36.21 \$/SMH

Method 2: Hourly Machine Cost/PMH (5)

Hourly Machine Cost/PMH = (FC + OC)/PMH/yr

Hourly Machine Cost/PMH =  $\frac{30,964.00 + 12,483.78}{1,180 \text{ PMH/yr}}$  = 36.82 \$/PMH

**B.5 Production and Cost Estimates for Unit 4**

**B.5 Production and Cost Estimates for Unit 4 - B47G3 Helicopter -  
options 1, 2, and 3**

139

**Client:** SFI  
**Unit:** Unit 4  
**Material:** Calcium

Helicopter: Bell 47G3 Ave. Acceleration Rate= 3.5 ft/sec<sup>2</sup>  
Cost = \$426 /flight hour  
Max. Payload: 1000 lbs  
Max. Ferry Speed = 45 mph  
Ave. Applic. Speed = 45 mph  
Swath Width = 45 feet  
One-way Ferry Distance 0.2 mile  
Ave. Reload Time = 5 seconds

Application Potential: 45 ft (swath) X 45 mph X 0.002 = 4.05 acres/minute

Target Application Rate of Material (lbs/ac): 2000 lbs/acre

Bucket Rate: 435 lbs/acre

Dump Time per load = 34.1 secs per 1000 lb payload

Estimated cycle time per maximum payload = 1.5 minutes

Estimated production/flight hour = 20.0 tons/flight hour

Unadjusted production/PMH (1) = 20.0 tons/PMH

**Cost Per Ton of Applied Material:**

Application = \$9.24 per ton (includes loading and application)

Ferry = \$12.03 per ton (based on round trip ferry distance, accel. & decel.)

**Cost/Ton For Unit = \$21.26 per ton**

(1) No allowance for refueling

**B.5 Production and Cost Estimates for Unit 4 - B47G3 Helicopter -  
options 1, 2, and 3**

140

**Bell 47G3**

Acceleration = 3.5 ft/sec<sup>2</sup>

Velocity Conversions: Ferry Distance = 0.2 mile

mph	ft/sec	Max. Ferry Speed =	45 mph
20	29.3		
25	36.7	Application Speed =	45 mph
30	44.0		
35	51.3		
40	58.7		
45	66.0		
50	73.3		
55	80.7		
60	88.0		
65	95.3		
70	102.7		

Acceleration to Ferry:

Time = 18.9 seconds Distance = 622 feet

Deceleration to Apply:

Time = 0.0 seconds Distance = 0 feet

FD = Total distance - (Distance to Accelerate + Distance to Decelerate)

FD = 434 feet

Ferry Time:

Time = 6.6 seconds

One-Way Time:

Time = 25.4 seconds

**Two-Way Time:**

**Time = 50.9 seconds**

Application Time:

Potential: 45 ft swath x 45 mph x 0.002 = 4.05 ac/min

Payload = 1000 lbs Ap. Rate = 2000 lbs

Rate/pass= 435 lbs/acre

**Time to apply = 34.1 seconds to dump payload**

**Reload Bucket = 5 seconds**

**Total Estimated Cycle Time = 89.9 seconds = 1.5 minutes**

**B.5 Production and Cost Estimates for Unit 4 - B47G3 Helicopter -  
options 1, 2, and 3**

141

a = 3.5 ft/sec <sup>2</sup>						
max. ferry speed mph	ft/sec	time to max tmax (secs)	dist to max ferry speed sa (feet)	mile	minimum distance* sa + sd (ft)	mile
20	29.3	8.4	123	0.02	246	0.05
25	36.7	10.5	192	0.04	384	0.07
30	44.0	12.6	277	0.05	553	0.10
35	51.3	14.7	376	0.07	753	0.14
40	58.7	16.8	492	0.09	983	0.19
45	66.0	18.9	622	0.12	1245	0.24
50	73.3	21.0	768	0.15	1537	0.29
55	80.7	23.0	930	0.18	1859	0.35
60	88.0	25.1	1106	0.21	2213	0.42
65	95.3	27.2	1298	0.25	2597	0.49
70	102.7	29.3	1506	0.29	3012	0.57
75	110.0	31.4	1729	0.33	3457	0.65
80	117.3	33.5	1967	0.37	3933	0.74
85	124.7	35.6	2220	0.42	4441	0.84
90	132.0	37.7	2489	0.47	4978	0.94

\*minimum distance to accelerate/decelerate to reach maximum ferry speed

**B.5 Truck Costs Based on Potential Helicopter Production Rates -  
unit 4, option 1**

142

Basis:			Helicopter:	
	Truck & Driver	36.21 \$/SMH	60	Actual Flight Time/SMH (minutes/SMH) (1)
Total Cost/SMH =		36.21 \$/SMH	50%	%Utilization(Helo)/SMH
			5	Est. Flight Hours/Day (2)

Truck:  
 # Trucks/Drivers = 1  
 SMH = 1200 hours/yr  
 PMH = 1180 hours/yr  
 SMH/Day = 10 SMH/Day

Estimated Total Cost/Day/Truck = 362.06 \$/Day/Truck

Potential Production of Helicopter:

PPH = 20.0 Tons/PMH

PPH/Day(3) 100.1 Tons/Day

Estimated Cost/Ton = (\$/Day/Truck \* #Trucks )/ (PPH/Day) = \$/ton

**Estimated Cost/Ton = 3.62 \$/ton**

- (1) No allowance for refueling
- (2) Estimated flight hours = 50% of SMH for truck
- (3) Maximum 120 tons/day from historical records

**B47G3 Application With Truck Transport**

<b>Transport Segment:</b>	R2-R3	TS1-R2	4A - 4
<b>Miles (one way):</b>	0.8	2.1	0
<b>Heliport(s) Serviced:</b>	4A	4A	4A
<b>Unit:</b>	Unit 4 - option 1		
<b>Material:</b>	Calcium	Calcium	Calcium
<b>Tonnage:</b>	12	12	12

**Fixed Road Costs (1):**

## Improvement:

Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0

## Construction:

Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0

<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>0</b>
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**Fixed Heliport Costs (2):**

## Improvement:

Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0

## Construction:

Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0

Move-In	0	0	250
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<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>250</b>
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**Road Maintenance (3):**

## Surfacing:

Rock	0.087 \$/ton-mile	0.087	0
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<b>Subtotal</b>	<b>0.07 \$/ton</b>	<b>0.18</b>	<b>0</b>
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Grading	0.00 \$/mile	300.00	0.00
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<b>Subtotal</b>	<b>0.00 \$</b>	<b>1260.00</b>	<b>0.00</b>
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Total =	0 \$	1,260	250
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<b>Variable =</b>	<b>0.25 \$/ton</b>
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<b>Fixed =</b>	<b>1510.00 \$</b>
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(1) Est lump sum costs of improve/const

(2) Est lump sum costs of improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25 cy/5778 tons-mile \*\$20.00/cy (del. rock price)

\* #miles (one way) = \$0.087/ton-mile

**B.5 Primary Haul Costs - unit 4, option 1  
(Delivered to Transfer Site)**

144

<b>Total Tons =</b>	238 tons	<b>Tons/trip =</b>	60
<b>Source:</b>	Portland	<b>#Trips =</b>	4
<b>Destination:</b>	Tangent		
<b>Miles (one-way):</b>	75 miles		
<b>Cost/Mile:</b>	0.50 \$/mile		

<b>Subtotal =</b>	150.00 \$	0.63 \$/ton
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<b>Source:</b>	Tangent	<b>Tons/trip =</b>	30
<b>Destination:</b>	Transfer #1	<b>#Trips =</b>	8
<b>Miles (one-way):</b>	45 miles		
<b>Cost/Mile</b>	1.40 \$/mile		

<b>Subtotal =</b>	504.00 \$	2.12 \$/ton
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<b>Total Cost =</b>	<b>654.00 \$</b>
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Table 11: Estimated costs for transporation and application of materials - unit 4, option 1

<b>Client:</b>		SFI					
<b>Unit:</b>		Unit 4					
<b>Material:</b>		Calcium					
<b>Tonnage:</b>		12 tons					
<b>Heliport(s) Serviced:</b>		4A					
<b>Apply with B47G3, 1 ag truck, bulk, no aerial ferry</b>							
<b>Links</b>	<b>P-T</b>	<b>T-TS1</b>	<b>TS1-R2</b>	<b>R2-R3</b>	<b>R3-4A</b>	<b>4A-4</b>	<b>Subtotals</b>
<b>Roads/move-in</b>							
<b>(\$/ton) Fixed</b>			1260.00			250.00	1510.00
<b>(\$/ton) Variable</b>			0.18	0.07			0.25
<b>Helicopter</b>							
<b>(\$/ton) 47G3</b>						21.26	21.26
<b>(\$/ton) 205A1</b>							0.00
<b>Ag Trucks</b>							
<b>(\$/ton)</b>						3.62	3.62
<b>Primary Transport</b>							
<b>(\$/ton)</b>	0.63	2.12					2.75
<b>Base Cost Material</b>							
<b>(\$/ton)</b>	140.00						140.00
<b>Subtotal Fixed Costs</b>	0.00	0.00	1260.00	0.00		250.00	
<b>Subtotal Variable Costs</b>	140.63	2.12	0.18	0.07	0.00	24.88	
<b>Total Estimated Cost:</b>							
	<b>All Costs</b>		<b>Without Primary Transport &amp; Base</b>				
<b>Fixed</b>	1510.00	\$	1510.00	\$			
<b>Variable</b>	167.88	\$/ton	25.13	\$/ton			
<b>Total Cost =</b>	3,524.54	\$	1,811.57	\$			
<b>Cost/ton =</b>	293.71	\$/ton	150.96	\$/ton			

**B.5 Production and Cost Estimates for Unit 4 - B205A1 Helicopter -  
options 4 and 5**

146

**Client:** SFI  
**Unit:** Unit 4  
**Material:** Calcium

Helicopter: Bell 205A1 Ave. Acceleration Rate= 2.5 ft/sec<sup>2</sup>  
Cost = \$1,134 /flight hour  
Max. Payload: 3200 lbs  
Max. Ferry Speed = 70 mph  
Ave. Applic. Speed = 50 mph  
Swath Width = 45 feet  
One-way Ferry Distance 0.9 mile  
Ave. Reload Time = 7 seconds

Application Potential: 45 ft (swath) X 50 mph X 0.002 = 4.5 acres/minute

Target Application Rate of Material (lbs/ac): 2000 lbs/acre

Bucket Rate: 444 lbs/acre

Dump Time per load = 96.1 secs per 3200 lb payload

Estimated cycle time per maximum payload = 4.0 minutes

Estimated production/flight hour = 24.0 tons/flight hour

Unadjusted production/SMH (1) = 24.0 tons/SMH

**Cost Per Ton of Applied Material:**

Application = \$20.29 per ton (includes loading and application)

Ferry = \$26.96 per ton (based on round trip ferry distance, accel. & decel.)

**Cost/Ton For Unit = \$47.25 per ton**

(1) No allowance for refueling

**B.5 Production and Cost Estimates for Unit 4 - B205A1 Helicopter -  
options 4 and 5**

147

**Bell 205A1**

Acceleration = 2.5 ft/sec<sup>2</sup>

Velocity Conversions: Ferry Distance = 0.9 mile

mph	ft/sec	Max. Ferry Speed =	70 mph
20	29.3		
25	36.7	Application Speed =	50 mph
30	44.0		
35	51.3		
40	58.7		
45	66.0		
50	73.3		
55	80.7		
60	88.0		
65	95.3		
70	102.7		

Acceleration to Ferry:

Time = 41.1 seconds Distance = 2108 feet

Deceleration to Apply:

Time = 11.7 seconds Distance = 1033 feet

FD = Total distance - (Distance to Accelerate + Distance to Decelerate)

FD = 1611 feet

Ferry Time:

Time = 15.7 seconds

One-Way Time:

Time = 68.5 seconds

Two-Way Time:

Time = 137.0 seconds

Application Time:

Potential: 45 ft swath x 50 mph x 0.002 = 4.5 ac/min

Payload = 3200 lbs Ap. Rate = 2000 lbs

Rate/pass= 444 lbs/acre

Time to apply = 96.1 seconds to dump payload

Reload Bucket = 7 seconds

Total Estimated Cycle Time = 240.1 seconds = 4.0 minutes

**B.5 Production and Cost Estimates for Unit 4 - B205A1 Helicopter -  
options 4 and 5**

148

a = 2.5 ft/sec <sup>2</sup>						
max. ferry speed		time to max	dist to max ferry speed		minimum distance*	
mph	ft/sec	tmax (secs)	sa (feet)	mile	sa + sd (ft)	mile
20	29.3	11.7	172	0.03	344	0.07
25	36.7	14.7	269	0.05	538	0.10
30	44.0	17.6	387	0.07	774	0.15
35	51.3	20.5	527	0.10	1054	0.20
40	58.7	23.5	688	0.13	1377	0.26
45	66.0	26.4	871	0.17	1742	0.33
50	73.3	29.3	1076	0.20	2151	0.41
55	80.7	32.3	1301	0.25	2603	0.49
60	88.0	35.2	1549	0.29	3098	0.59
65	95.3	38.1	1818	0.34	3635	0.69
70	102.7	41.1	2108	0.40	4216	0.80
75	110.0	44.0	2420	0.46	4840	0.92
80	117.3	46.9	2753	0.52	5507	1.04
85	124.7	49.9	3108	0.59	6217	1.18
90	132.0	52.8	3485	0.66	6970	1.32

\*minimum distance to accelerate/decelerate to reach maximum ferry speed

**B.5 Production Rate Estimates - Helicopter  
Ferry Only - B205A1 - unit 4, options 2 and 3**

149

**Bell 205A1**

Acceleration = 2.5 ft/sec<sup>2</sup>      Max. Payload = 3200 lbs

Ferry Distance (one-way) 0.9 mile

Max. Ferry Speed = 70 mph

Airspeed Load/Unload = 0 mph

Time to Hook/Unhook = 5 seconds

Acceleration to Ferry Speed:

Time = 41.1 seconds      Distance = 2108 feet

Deceleration to Unload:

Time = 41.1 seconds      Distance = 2108 feet

FD = Total distance - (Distance to Accelerate + Distance to Decelerate)

FD = 536 feet

Ferry Time:

Time = 5.2 seconds

One-Way Time:

Time = 87.4 seconds

**Two-Way Time:**

Time = 174.7 seconds

H/U = 5.0 seconds

**Total Estimated Cycle Time = 179.7 seconds = 3.0 minutes**

Estimated production/flight hour (1),(2)= 30.0 tons/flight hour

**Cost Per Ton of Applied Material:**

**Cost/Ton for Unit = \$37.73 per ton**

(1) No allowance for refueling

(2) Adjustment for 1000 lb payload increments

**B.5 Production Rate Estimates - Helicopter  
Ferry Only - B205A1 - unit 4, options 2 and 3**

150

a = 2.5 ft/sec<sup>2</sup>

max. ferry speed		time to max	dist to max ferry speed		minimum distance*	
mph	ft/sec	tmax (secs)	sa (feet)	mile	sa + sd (ft)	mile
20	29.3	11.7	172	0.03	344	0.07
25	36.7	14.7	269	0.05	538	0.10
30	44.0	17.6	387	0.07	774	0.15
35	51.3	20.5	527	0.10	1054	0.20
40	58.7	23.5	688	0.13	1377	0.26
45	66.0	26.4	871	0.17	1742	0.33
50	73.3	29.3	1076	0.20	2151	0.41
55	80.7	32.3	1301	0.25	2603	0.49
60	88.0	35.2	1549	0.29	3098	0.59
65	95.3	38.1	1818	0.34	3635	0.69
70	102.7	41.1	2108	0.40	4216	0.80
75	110.0	44.0	2420	0.46	4840	0.92
80	117.3	46.9	2753	0.52	5507	1.04
85	124.7	49.9	3108	0.59	6217	1.18
90	132.0	52.8	3485	0.66	6970	1.32

\*minimum distance to accelerate/decelerate to reach maximum ferry speed

## B.5 Estimated Truck Costs Based on Potential Helicopter Production Rates - 151

### unit 4, options 2 and 3

Basis:		Helicopter:		
	Truck & Driver	36.21	\$/SMH	60 Actual Flight Time/SMH (minutes/SMH) (1)
Total Cost/SMH =		36.21	\$/SMH	50% %Utilization(Helo)/SMH
				5 Est. Flight Hours/Day (2)

Truck:

# Trucks/Drivers =	1	Ferry with 205A; apply with 47G3
SMH =	1200 hours/yr	
PMH =	1180 hours/yr	
SMH/Day =	10 SMH/Day	

Estimated Total Cost/Day/Truck = 362.06 \$/Day/Truck

Potential Production of Helicopter:

PPH = 20.0 Tons/PMH (based on lowest production/PMH)

PPH/Day(3) 100.1 Tons/Day

Estimated Cost/Ton = (\$/Day/Truck \* #Trucks) / (PPH/Day) = \$/ton

**Estimated Cost/Ton = 3.62 \$/ton**

- (1) No allowance for refueling
- (2) Estimated flight hours = 50% of SMH for truck
- (3) Maximum 150 tons/day from historical records

Table 12: Estimated improvement and maintenance costs - unit 4, option 2

<b>Transport Segment:</b>	TS1- SLBL	SLBL-FBR2	FBR2-FBR3	4A - 4
<b>Miles (one way):</b>	0	0	0	0
<b>Heliport(s) Serviced:</b>	4A	4A	4A	4A
<b>Unit:</b>		unit 4 - option 2		
<b>Material: (Bulk)</b>	Calcium	Calcium	Calcium	Calcium
<b>Tonnage:</b>	12	12	12	12
<b>Ferry to HP with 205A-apply with 47G3</b>				
<b>Fixed Road Costs (1):</b>				
Improvement:				
Grading	0	0	0	0
Brushing	0	0	0	0
Rocking	0	0	0	0
Construction:				
Construction	0	0	0	0
Grading	0	0	0	0
Rocking	0	0	0	0
<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>				
Improvement:				
Grading	0	0	0	0
Brushing	0	0	0	0
Rocking	0	0	0	0
Construction:				
Construction	0	0	0	0
Grading	0	0	0	0
Rocking	0	0	0	0
Move-In	1500	0	0	250
<b>Subtotal</b>	<b>1500 \$</b>	<b>0</b>	<b>0</b>	<b>250</b>
<b>Road Maintenance (3):</b>				
Surfacing:				
Rock	0.087 \$/ton-mile	0.087	0.087	0
<b>Subtotal</b>	<b>0.00 \$/ton</b>	<b>0.00</b>	<b>0.00</b>	<b>0</b>
Grading	0.00 \$/mile	0.00	0.00	0.00
<b>Subtotal</b>	<b>0.00 \$</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>
Total =	1,500 \$	0	0	250
<b>Variable =</b>				<b>0.00 \$/ton</b>
<b>Fixed =</b>				<b>1750.00 \$</b>

(1) Est lump sum cost improve/const

(2) Est lump sum cost improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile = 25cy/5778 tons-mile\*\$20.00/cy (del. rock price)

\*#miles (one way) = \$0.087/ton-mile



Table 13: Estimated improvement and maintenance costs - unit 4, option 3

153

<b>Transport Segment:</b>	TS2- SLBA	SLBA-FR2	FR2-FR3	4A - 4
<b>Miles (one way):</b>	0	0	0	0
<b>Heliport(s) Serviced:</b>	4A	4A	4A	4A
<b>Unit:</b>		unit 4 - option 3		
<b>Material: (Bags)</b>	Calcium	Calcium	Calcium	Calcium
<b>Tonnage:</b>	12	12	12	12
<b>Ferry to HP with 205A-apply with 47G3</b>				
<b>Fixed Road Costs (1):</b>				
Improvement:				
Grading	0	0	0	0
Brushing	0	0	0	0
Rocking	0	0	0	0
Construction:				
Construction	0	0	0	0
Grading	0	0	0	0
Rocking	0	0	0	0
<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>				
Improvement:				
Grading	0	0	0	0
Brushing	0	0	0	0
Rocking	0	0	0	0
Construction:				
Construction	0	0	0	0
Grading	0	0	0	0
Rocking	0	0	0	0
Move-In	1500	0	0	250
<b>Subtotal</b>	<b>1500 \$</b>	<b>0</b>	<b>0</b>	<b>250</b>
<b>Road Maintenance (3):</b>				
Surfacing:				
Rock	0.087 \$/ton-mile	0.087	0.087	0
<b>Subtotal</b>	<b>0.00 \$/ton</b>	<b>0.00</b>	<b>0.00</b>	<b>0</b>
Grading	0.00 \$/mile	0.00	0.00	0.00
<b>Subtotal</b>	<b>0.00 \$</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>
Total =	1,500 \$	0	0	250
<b>Variable =</b>				<b>0.00 \$/ton</b>
<b>Fixed =</b>				<b>1750.00 \$</b>

(1) Est lump sum cost improve/const

(2) Est lump sum cost improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25cy/5778 tons-mile\*\$20.00/cy (del. rock price)

\*#miles (one way) = \$0.087/ton-mile

Table 14: Estimated improvement and maintenance costs - unit 4, option 4

<b>Transport Segment:</b>	TS1- SLBL	SLBL-SLBLD4	SLBLD4-4
<b>Miles (one way):</b>	0	0	0
<b>Heliport(s) Serviced:</b>	4A	4A	4A
<b>Unit:</b>	unit 4 - option 4		
<b>Material: (Bulk)</b>	Calcium	Calcium	Calcium
<b>Tonnage:</b>	12	12	12
<b>Direct apply 205A - bulk</b>			
<b>Fixed Road Costs (1):</b>			
Improvement:			
Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>			
Improvement:			
Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
Move-In	1500	0	0
<b>Subtotal</b>	<b>1500 \$</b>	<b>0</b>	<b>0</b>
<b>Road Maintenance (3):</b>			
Surfacing:			
Rock	0.087 \$/ton-mile	0.087	0.087
<b>Subtotal</b>	<b>0.00 \$/ton</b>	<b>0.00</b>	<b>0.00</b>
Grading	0.00 \$/mile	0.00	0.00
<b>Subtotal</b>	<b>0.00 \$</b>	<b>0.00</b>	<b>0.00</b>
Total =	1,500 \$	0	0
<b>Variable =</b>		<b>0.00 \$/ton</b>	
<b>Fixed =</b>		<b>1500.00 \$</b>	

(1) Est lump sum costs of improve/const

(2) Est lump sum costs of improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25 cy/5778 tons-mile \* \$20.00/cy (del rock price)

\* # miles (one-way) = \$0.087/ton-mile

Table 15: Estimated improvement and maintenance costs - unit 4, option 5

<b>Transport Segment:</b>	TS2- SLBA	SLBA-SLBAD4	SLBAD4-4
<b>Miles (one way):</b>	0	0	0
<b>Heliport(s) Serviced:</b>	4A	4A	4A
<b>Unit:</b>	unit 4 - option 5		
<b>Material: (Bags)</b>	Calcium	Calcium	Calcium
<b>Tonnage:</b>	12	12	12
<b>Direct apply 205A - bags</b>			
<b>Fixed Road Costs (1):</b>			
Improvement:			
Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>			
Improvement:			
Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
Move-In	1500	0	0
<b>Subtotal</b>	<b>1500 \$</b>	<b>0</b>	<b>0</b>
<b>Road Maintenance (3):</b>			
Surfacing:			
Rock	0.087 \$/ton-mile	0.087	0.087
<b>Subtotal</b>	<b>0.00 \$/ton</b>	<b>0.00</b>	<b>0.00</b>
Grading	0.00 \$/mile	0.00	0.00
<b>Subtotal</b>	<b>0.00 \$</b>	<b>0.00</b>	<b>0.00</b>
Total =	1,500 \$	0	0
		<b>Variable =</b>	<b>0.00 \$/ton</b>
		<b>Fixed =</b>	<b>1500.00 \$</b>

(1) Est lump sum costs of improve/const

(2) Est lump sum costs of improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25 cy/5778 tons-mile \* \$20.00/cy (del rock price)

\* # miles (one-way) = \$0.087/ton-mile

**B.5 Primary Haul Costs - unit 4, options 2, 3, 4 and 5**  
**(Delivered to Transfer Site)**

156

**Bulk Delivery**

<b>Total Tons =</b>	238 tons	<b>Tons/trip =</b>	60
<b>Source:</b>	Portland	<b>#Trips =</b>	4
<b>Destination:</b>	Tangent		
<b>Miles (one-way):</b>	75 miles		
<b>Cost/Mile:</b>	0.50 \$/mile		

**Subtotal =** 150.00 \$ 0.63 \$/ton

<b>Source:</b>	Tangent	<b>Tons/trip =</b>	30
<b>Destination:</b>	Transfer #1	<b>#Trips =</b>	8
<b>Miles (one-way):</b>	45 miles		
<b>Cost/Mile</b>	1.40 \$/mile		

**Subtotal =** 504.00 \$ 2.12 \$/ton

**Total Cost =** 654.00 \$

**Bag Delivery**

<b>Source:</b>	Portland	<b>Tons/trip =</b>	60
<b>Destination:</b>	Transfer #2	<b>#Trips =</b>	4
<b>Miles (one-way):</b>	120 miles		
<b>Cost/Mile:</b>	0.80 \$/mile		

**Subtotal =** 384.00 \$ 1.61 \$/ton

Table 16: Estimated costs for transportation and application of materials - unit 4, option 2

<b>Client:</b>		SFI						
<b>Unit:</b>		unit 4 - option 2						
<b>Material:</b>		Calcium						
<b>Tonnage:</b>		12 tons						
<b>Heliport(s) Serviced:</b>		4A						
<b>Ferry With 205A - Apply With 47G3 - bulk</b>								
<b>Links</b>	<b>P-T</b>	<b>T-TS1</b>	<b>TS1-SLBL</b>	<b>SLBL-FBR2</b>	<b>FBR2-FBR3</b>	<b>FBR3-FB4A</b>	<b>FB4A-4</b>	<b>Subtotals</b>
<b>Roads/move-in</b>								
<b>(\$/ton) Fixed</b>			1500.00				250.00	1750.00
<b>(\$/ton) Variable</b>								0.00
<b>Helicopter</b>								
<b>(\$/ton) 47G3</b>							21.26	21.26
<b>(\$/ton) 205A1</b>							37.73	37.73
<b>Ag Trucks</b>								
<b>(\$/ton)</b>							3.62	3.62
<b>Primary Transport</b>								
<b>(\$)</b>	0.63	2.12						2.75
<b>Base Cost Material</b>								
<b>(\$/ton)</b>	140.00							140.00
<b>Subtotal Fixed Costs</b>	0.00	0.00	1500.00	0.00	0.00	0.00	250.00	1750.00
<b>Subtotal Variable Costs</b>	140.63	2.12	0.00	0.00	0.00	0.00	62.61	205.35
<b>Total Estimated Cost:</b>			Without Primary Transport & Base					
<b>Fixed</b>	1750.00	\$	1750.00	\$				
<b>Variable</b>	205.35	\$/ton	62.61	\$/ton				
<b>Total Cost =</b>	4,214.25	\$	2,501.27	\$				
<b>Cost/ton =</b>	351.19	\$/ton	208.44	\$/ton				

Table 17: Estimated costs for transportation and application of materials - unit 4, option 3

<b>Client:</b>		SFI					
<b>Unit:</b>		unit 4 - option 3					
<b>Material:</b>		Calcium					
<b>Tonnage:</b>		12 tons					
<b>Heliport(s) Serviced:</b>		4A					
<b>Ferry With 205A1 - Apply With 47G3 -BAGS</b>							
<b>Links</b>	<b>P - TS2</b>	<b>TS2 - SLBA</b>	<b>SLBA - FR2</b>	<b>FR2-FR3</b>	<b>FR3-F4A</b>	<b>F4A-4</b>	<b>Subtotals</b>
<b>Roads/move-in</b>							
<b>(\$/ton) Fixed</b>		1500.00				250.00	1750.00
<b>(\$/ton) Variable</b>							0.00
<b>Helicopter</b>							
<b>(\$/ton) 47G3</b>						21.26	21.26
<b>(\$/ton) 205A1</b>						37.73	37.73
<b>Ag Trucks</b>							
<b>(\$/ton)</b>						3.62	3.62
<b>Primary Transport</b>							
<b>(\$)</b>	1.61						1.61
<b>Base Cost Material</b>							
<b>(\$/ton)</b>	130.00						130.00
<b>Subtotal Fixed Costs</b>	0.00	1500.00	0.00	0.00	0.00	250.00	1750.00
<b>Subtotal Variable Costs</b>	131.61	0.00	0.00	0.00	0.00	62.61	194.22
<b>Total Estimated Cost:</b>			Without Primary Transport & Base				
<b>Fixed</b>	1750.00	\$	1750.00	\$			
<b>Variable</b>	194.22	\$/ton	62.61	\$/ton			
<b>Total Cost =</b>	4,080.63	\$	2,501.27	\$			
<b>Cost/ton =</b>	340.05	\$/ton	208.44	\$/ton			

Table 18: Estimated costs for transportation and application of materials - unit 4, option 4

<b>Client:</b>		SFI						
<b>Unit:</b>		unit 4 - option 4						
<b>Material:</b>		Calcium						
<b>Tonnage:</b>		12 tons						
<b>Heliport(s) Serviced:</b>		4A						
<b>Direct Apply With 205A1 - bulk</b>								
<b>Links</b>	<b>P-T</b>	<b>T-TS1</b>	<b>TS1-SLBL</b>	<b>SLBL-SLBLD4</b>	<b>SLBLD4-4</b>			<b>Subtotals</b>
<b>Roads/move-in</b>								
<b>(\$/ton) Fixed</b>			1500.00					1500.00
<b>(\$/ton) Variable</b>								0.00
<b>Helicopter</b>								
<b>(\$/ton) 47G3</b>								0.00
<b>(\$/ton) 205A1</b>					47.25			47.25
<b>Ag Trucks</b>								
<b>(\$/ton)</b>								0.00
<b>Primary Transport</b>								
<b>(\$/ton)</b>	0.63	2.12						2.75
<b>Base Cost Material</b>								
<b>(\$/ton)</b>	140.00							140.00
Subtotal Fixed Costs	0.00	0.00	1500.00	0.00	0.00	0.00	0.00	1500.00
Subtotal Variable Costs	140.63	2.12	0.00	0.00	47.25	0.00	0.00	190.00
<b>Total Estimated Cost:</b>			Without Primary Transport & Base					
Fixed	1500.00	\$	1500.00	\$				
Variable	190.00	\$/ton	47.25	\$/ton				
<b>Total Cost =</b>	3,780.02	\$	2,067.05	\$				
<b>Cost/ton =</b>	315.00	\$/ton	172.25	\$/ton				

Table 19: Estimated costs for transportation and application of materials - unit 4, option 5

<b>Client:</b>		SFI						
<b>Unit:</b>		unit 4 - option 5						
<b>Material:</b>		Calcium						
<b>Tonnage:</b>		12 tons						
<b>Heliport(s) Serviced:</b>		4A						
<b>Direct Apply With 205A1 - BAGS</b>								
<b>Links</b>	<b>P-TS2</b>	<b>TS2-SLBA</b>	<b>SLBA-SLBAD4</b>	<b>SLBAD4-4</b>	<b>Subtotals</b>			
<b>Roads/move-in</b>								
<b>(\$/ton) Fixed</b>		1500.00			1500.00			
<b>(\$/ton) Variable</b>					0.00			
<b>Helicopter</b>								
<b>(\$/ton) 47G3</b>					0.00			
<b>(\$/ton) 205A1</b>				47.25	47.25			
<b>Ag Trucks</b>								
<b>(\$/ton)</b>					0.00			
<b>Primary Transport</b>								
<b>(\$)</b>	1.61				1.61			
<b>Base Cost Material</b>								
<b>(\$/ton)</b>	130.00				130.00			
<b>Subtotal Fixed Costs</b>	0.00	1500.00	0.00	0.00	1500.00			
<b>Subtotal Variable Costs</b>	131.61	0.00	0.00	47.25	178.87			
<b>Total Estimated Cost:</b>			Without Primary Transport & Base					
<b>Fixed</b>	1500.00	\$	1500.00	\$				
<b>Variable</b>	178.87	\$/ton	47.25	\$/ton				
<b>Total Cost =</b>	3,646.41	\$	2,067.05	\$				
<b>Cost/ton =</b>	303.87	\$/ton	172.25	\$/ton				



**B.6 Production and Cost Estimates for Unit 5**

**B.6 Production and Cost Estimates for Unit 5, HP 5A - B47G3 Helicopter -  
options 1, 2 and 3**

162

**Client:** SFI  
**Unit:** Unit 5 - HP 5A  
**Material:** Calcium

Helicopter: Bell 47G3 Ave. Acceleration Rate= 3.5 ft/sec<sup>2</sup>  
Cost = \$426 /flight hour  
Max. Payload: 1000 lbs  
Max. Ferry Speed = 60 mph  
Ave. Applic. Speed = 45 mph  
Swath Width = 45 feet  
One-way Ferry Distance 1 mile  
Ave. Reload Time = 5 seconds

Application Potential: 45 ft (swath) X 45 mph X 0.002 = 4.05 acres/minute

Target Application Rate of Material (lbs/ac): 2000 lbs/acre

Bucket Rate: 435 lbs/acre

Dump Time per load = 34.1 secs per 1000 lb payload

Estimated cycle time per maximum payload = 3.1 minutes

Estimated production/flight hour = 9.7 tons/flight hour

Unadjusted production/PMH (1) = 9.7 tons/PMH

**Cost Per Ton of Applied Material:**

Application = \$9.24 per ton (includes loading and application)

Ferry = \$34.69 per ton (based on round trip ferry distance, accel. & decel.)

**Cost/Ton For Unit = \$43.93 per ton**

(1) No allowance for refueling

**B.6 Production and Cost Estimates for Unit 5, HP 5A - B47G3 Helicopter -  
options 1, 2 and 3**

163

**Bell 47G3**

Acceleration = 3.5 ft/sec<sup>2</sup>

Velocity Conversions: Ferry Distance = 1.0 mile

mph	ft/sec	Max. Ferry Speed =	60 mph
20	29.3		
25	36.7	Application Speed =	45 mph
30	44.0		
35	51.3		
40	58.7		
45	66.0		
50	73.3		
55	80.7		
60	88.0		
65	95.3		
70	102.7		

Acceleration to Ferry:

Time = 25.1 seconds Distance = 1106 feet

Deceleration to Apply:

Time = 6.3 seconds Distance = 484 feet

FD = Total distance - (Distance to Accelerate + Distance to Decelerate)

FD = 3690 feet

Ferry Time:

Time = 41.9 seconds

One-Way Time:

Time = 73.4 seconds

Two-Way Time:

Time = 146.7 seconds

Application Time:

Potential: 45 ft swath x 45 mph x 0.002 = 4.05 ac/min

Payload = 1000 lbs Ap. Rate = 2000 lbs

Rate/pass = 435 lbs/acre

Time to apply = 34.1 seconds to dump payload

Reload Bucket = 5 seconds

Total Estimated Cycle Time = 185.8 seconds = 3.1 minutes

**B.6 Production and Cost Estimates for Unit 5, HP 5A - B47G3 Helicopter -  
options 1, 2 and 3**

164

a = 3.5 ft/sec<sup>2</sup>

max. ferry speed		time to max	dist to max ferry speed		minimum distance*	
mph	ft/sec	tmax (secs)	sa (feet)	mile	sa + sd (ft)	mile
20	29.3	8.4	123	0.02	246	0.05
25	36.7	10.5	192	0.04	384	0.07
30	44.0	12.6	277	0.05	553	0.10
35	51.3	14.7	376	0.07	753	0.14
40	58.7	16.8	492	0.09	983	0.19
45	66.0	18.9	622	0.12	1245	0.24
50	73.3	21.0	768	0.15	1537	0.29
55	80.7	23.0	930	0.18	1859	0.35
60	88.0	25.1	1106	0.21	2213	0.42
65	95.3	27.2	1298	0.25	2597	0.49
70	102.7	29.3	1506	0.29	3012	0.57
75	110.0	31.4	1729	0.33	3457	0.65
80	117.3	33.5	1967	0.37	3933	0.74
85	124.7	35.6	2220	0.42	4441	0.84
90	132.0	37.7	2489	0.47	4978	0.94

\*minimum distance to accelerate/decelerate to reach maximum ferry speed

**B.6 Truck Costs Based on Potential Helicopter Production Rates -  
unit 5, HP 5A, options 1, 2 and 3**

165

Basis:			Helicopter:	
	Truck & Driver	36.21 \$/SMH	60	Actual Flight Time/SMH (minutes/SMH) (1)
Total Cost/SMH =		36.21 \$/SMH	50%	%Utilization(Helo)/SMH
			5	Est. Flight Hours/Day (2)

Truck:  
 # Trucks/Drivers = 3  
 SMH = 1200 hours/yr  
 PMH = 1180 hours/yr  
 SMH/Day = 10 SMH/Day

Estimated Total Cost/Day/Truck = 362.06 \$/Day/Truck

Potential Production of Helicopter:

PPH = 9.7 Tons/PMH

PPH/Day(3) 48.4 Tons/Day

Estimated Cost/Ton = (\$/Day/Truck \* #Trucks) / (PPH/Day) = \$/ton

**Estimated Cost/Ton = 22.42 \$/ton**

- (1) No allowance for refueling
- (2) Estimated flight hours = 50% of SMH for truck
- (3) Maximum 120 tons/day from historical records

Table 20: Estimated improvement and maintenance costs - unit 5, HP 5A - option 1 166

<b>Transport Segment:</b>	R2-R4	R4-R5	5A - 5
<b>Miles (one way):</b>	2.9	0.7	0
<b>Heliport(s) Serviced:</b>	5A	5A	5A
<b>Unit:</b>	Unit 5	Unit 5	Unit 5
<b>Material:</b>	Calcium	Calcium	Calcium
<b>Tonnage:</b>	172.5	172.5	172.5
<b>Fixed Road Costs (1):</b>			
Improvement:			
Grading	95	0	0
Brushing	0	0	0
Rocking	1679	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
<b>Subtotal</b>	<b>1774 \$</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>			
Improvement:			
Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
Move-In	0	0	250
<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>250</b>
<b>Road Maintenance (3):</b>			
Surfacing:			
Rock	0.087 \$/ton-mile	0.087	0
<b>Subtotal</b>	<b>0.25 \$/ton</b>	<b>0.06</b>	<b>0</b>
Grading	150.00 \$/mile	300.00	0.00
<b>Subtotal</b>	<b>870.00 \$</b>	<b>420.00</b>	<b>0.00</b>
<b>Total =</b>	<b>2,644 \$</b>	<b>420</b>	<b>250</b>
<b>Variable =</b>		<b>0.31 \$/ton</b>	
<b>Fixed =</b>		<b>3314.00 \$</b>	

(1) Est lump sum costs of improve/const

(2) Est lump sum costs of improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25 cy/5778 tons-mile \* \$20.00/cy (del. rock price)

\* #miles (one way) = \$0.087/ton-mile

**B.6 Primary Haul Costs - unit 5, HP 5A/5B, option 1**  
**(Delivered to Transfer Site)**

167

<b>Total Tons =</b>	238 tons	<b>Tons/trip =</b>	60
<b>Source:</b>	Portland	<b>#Trips =</b>	4
<b>Destination:</b>	Tangent		
<b>Miles (one-way):</b>	75 miles		
<b>Cost/Mile:</b>	0.50 \$/mile		

<b>Subtotal =</b>	150.00 \$	0.63 \$/ton
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<b>Source:</b>	Tangent	<b>Tons/trip =</b>	30
<b>Destination:</b>	Transfer #1	<b>#Trips =</b>	8
<b>Miles (one-way):</b>	45 miles		
<b>Cost/Mile</b>	1.40 \$/mile		

<b>Subtotal =</b>	504.00 \$	2.12 \$/ton
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<b>Total Cost =</b>	<b>654.00 \$</b>
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Table 21: Estimated costs for transportation and application of materials - unit 5, HP 5A - option 1

<b>Client:</b>		SFI						
<b>Unit:</b>		Unit 5						
<b>Material:</b>		Calcium						
<b>Tonnage:</b>		172.5 tons						
<b>Heliport(s) Serviced:</b>		5A						
<b>Apply with B47G3, 3 ag trucks, bulk, no aerial ferry</b>								
<b>Links</b>	<b>P-T</b>	<b>T-TS1</b>	<b>TS1-R2*</b>	<b>R2-R4</b>	<b>R4-R5</b>	<b>R5-5A</b>	<b>5A-5</b>	<b>Subtotals</b>
<b>Roads/move-in</b>								
<b>(\$/ton) Fixed</b>			1260.00	2644.00	420		250.00	4574.00
<b>(\$/ton) Variable</b>			0.18	0.25	0.06			0.50
<b>Helicopter</b>								
<b>(\$/ton) 47G3</b>							43.93	43.93
<b>(\$/ton) 205A1</b>								0.00
<b>Ag Trucks</b>								
<b>(\$/ton)</b>							22.42	22.42
<b>Primary Transport</b>								
<b>(\$/ton)</b>	0.63	2.12						2.75
<b>Base Cost Material</b>								
<b>(\$/ton)</b>	140.00							140.00
<b>Total Estimated Cost:</b>								
	All Costs		Without Primary Transport & Base					
Fixed	4574.00	\$	4574.00	\$	*Mtc costs accounted for in Religion unit costs			
Variable	209.59	\$/ton	66.84	\$/ton				
<b>Total Cost =</b>	40,728.64	\$	16,104.63	\$				
<b>Cost/ton =</b>	236.11	\$/ton	93.36	\$/ton				



**B.6 Production and Cost Estimates for Unit 5, HP 5B - B47G3 Helicopter -  
options 1, 2 and 3**

169

**Client:** SFI  
**Unit:** Unit 5 - HP 5B  
**Material:** Calcium

Helicopter: Bell 47G3 Ave. Acceleration Rate= 2 ft/sec<sup>2</sup>  
Cost = \$426 /flight hour  
Max. Payload: 800 lbs  
Max. Ferry Speed = 45 mph  
Ave. Applic. Speed = 45 mph  
Swath Width = 45 feet  
One-way Ferry Distance 0.2 mile  
Ave. Reload Time = 5 seconds

Application Potential: 45 ft (swath) X 45 mph X 0.002 = 4.05 acres/minute

Target Application Rate of Material (lbs/ac): 2000 lbs/acre

Bucket Rate: 435 lbs/acre

Dump Time per load = 27.2 secs per 800 lb payload

Estimated cycle time per maximum payload = 1.6 minutes

Estimated production/flight hour = 14.8 tons/flight hour

Unadjusted production/PMH = 14.8 tons/PMH

**Cost Per Ton of Applied Material:**

Application = \$9.53 per ton (includes loading and application)

Ferry = \$19.21 per ton (based on round trip ferry distance, accel. & decel.)

**Cost/Ton For Unit = \$28.74 per ton**

**B.6 Production and Cost Estimates for Unit 5, HP 5B - B47G3 Helicopter -  
options 1, 2 and 3**

170

**Bell 47G3**

Acceleration = 2 ft/sec<sup>2</sup>

Velocity Conversions: Ferry Distance = 0.2 mile

mph	ft/sec	Max. Ferry Speed =	45 mph
20	29.3		
25	36.7	Application Speed =	45 mph
30	44.0		
35	51.3		
40	58.7		
45	66.0		
50	73.3		
55	80.7		
60	88.0		
65	95.3		
70	102.7		

Acceleration to Ferry:

Time = 33.0 seconds Distance = 1089 feet

Deceleration to Apply:

Time = 0.0 seconds Distance = 0 feet

FD = Total distance - (Distance to Accelerate + Distance to Decelerate)

FD = 0 feet

Ferry Time:

Time = 0.0 seconds

One-Way Time:

Time = 32.5 seconds

Two-Way Time:

Time = 65.0 seconds

Application Time:

Potential: 45 ft swath x 45 mph x 0.002 = 4.05 ac/min

Payload = 800 lbs Ap. Rate = 2000 lbs

Rate/pass= 435 lbs/acre

Time to apply = 27.2 seconds to dump payload

Reload Bucket = 5 seconds

Total Estimated Cycle Time = 97.2 seconds = 1.6 minutes

**B.6 Production and Cost Estimates for Unit 5, HP 5B - B47G3 Helicopter -  
options 1, 2 and 3**

171

a = 2 ft/sec <sup>2</sup>						
max. ferry speed mph	ft/sec	time to max tmax (secs)	dist to max sa (feet)	ferry speed mile	minimum distance*	
					sa + sd (ft)	mile
20	29.3	14.7	215	0.04	430	0.08
25	36.7	18.3	336	0.06	672	0.13
30	44.0	22.0	484	0.09	968	0.18
35	51.3	25.7	659	0.12	1318	0.25
40	58.7	29.3	860	0.16	1721	0.33
45	66.0	33.0	1089	0.21	2178	0.41
50	73.3	36.7	1344	0.25	2689	0.51
55	80.7	40.3	1627	0.31	3254	0.62
60	88.0	44.0	1936	0.37	3872	0.73
65	95.3	47.7	2272	0.43	4544	0.86
70	102.7	51.3	2635	0.50	5270	1.00
75	110.0	55.0	3025	0.57	6050	1.15
80	117.3	58.7	3442	0.65	6884	1.30
85	124.7	62.3	3885	0.74	7771	1.47
90	132.0	66.0	4356	0.83	8712	1.65

\*minimum distance to accelerate/decelerate to reach maximum ferry speed

**B.6 Truck Costs Based on Potential Helicopter Production Rates -  
unit 5, HP 5B, options 1, 2 and 3**

172

Basis:			Helicopter:	
	Truck & Driver	36.21 \$/SMH	60	Actual Flight Time/SMH (minutes/SMH) (1)
Total Cost/SMH =		36.21 \$/SMH	50%	%Utilization(Helo)/SMH
			5	Est. Flight Hours/Day (2)

Truck:  
 # Trucks/Drivers = 3  
 SMH = 1200 hours/yr  
 PMH = 1180 hours/yr  
 SMH/Day = 10 SMH/Day

Estimated Total Cost/Day/Truck = 362.06 \$/Day/Truck

Potential Production of Helicopter:

PPH = 14.8 Tons/PMH

PPH/Day(3) 74.0 Tons/Day

Estimated Cost/Ton = (\$/Day/Truck \* #Trucks )/ (PPH/Day) = \$/ton

**Estimated Cost/Ton = 14.67 \$/ton**

- (1) No allowance for refueling
- (2) Estimated flight hours = 50% of SMH for truck
- (3) Maximum 120 tons/day from historical records

Table 22: Estimated improvement and maintenance costs - unit 5, HP 5B - option 1 173

<b>Transport Segment:</b>	<b>R4-R6</b>	<b>5B - 5</b>
<b>Miles (one way):</b>	<b>1.5</b>	<b>0</b>
<b>Heliport(s) Serviced:</b>	<b>5B</b>	<b>5A</b>
<b>Unit:</b>	<b>Unit 5</b>	<b>Unit 5</b>
<b>Material:</b>	<b>Calcium</b>	<b>Calcium</b>
<b>Tonnage:</b>	<b>172.5</b>	<b>172.5</b>

**Fixed Road Costs (1):**

Improvement:

Grading	475	0
Brushing	0	0
Rocking	5550	0

Construction:

Construction	0	0
Grading	0	0
Rocking	0	0

<b>Subtotal</b>	<b>6025 \$</b>	<b>0</b>
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**Fixed Heliport Costs (2):**

Improvement:

Grading	0	0
Brushing	0	0
Rocking	0	0

Construction:

Construction	0	0
Grading	0	0
Rocking	0	0

Move-In	0	250
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<b>Subtotal</b>	<b>0 \$</b>	<b>250</b>
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**Road Maintenance (3):**

Surfacing:

Rock	0.087 \$/ton-mile hauled	0.087
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<b>Subtotal</b>	<b>0.13 \$/ton</b>	<b>0</b>
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Grading	150.00 \$/mile	0.00
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<b>Subtotal</b>	<b>450.00 \$</b>	<b>0.00</b>
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Total =	6,475 \$	0	250
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Variable = 0.13 \$/ton

Fixed = 6725.00 \$

(1) Est lump sum costs of improve/const

(2) Est lump sum costs of improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25 cy/5778 tons-mile \*\$20.00/cy (del. rock price)

\* #miles (one way) = \$0.087/ton-mile

Table 23: Estimated costs for transportation and application of materials - unit 5, HP 5B - option 1

<b>Client:</b>		SFI						
<b>Unit:</b>		Unit 5						
<b>Material:</b>		Calcium						
<b>Tonnage:</b>		172.5 tons						
<b>Heliport(s) Serviced:</b>		5B						
<b>Apply with B47G3, 3 ag trucks, bulk, no aerial ferry</b>								
<b>Links</b>	<b>P-T</b>	<b>T-TS1</b>	<b>TS1-R2*</b>	<b>R2-R4**</b>	<b>R4-R6</b>	<b>R6-5B</b>	<b>5B-5</b>	<b>Subtotals</b>
<b>Roads/move-in</b>								
<b>(\$/ton) Fixed</b>			1260.00	2644.00	6,475		250.00	10629.00
<b>(\$/ton) Variable</b>			0.18	0.25	0.13			0.57
<b>Helicopter</b>								
<b>(\$/ton) 47G3</b>							28.74	28.74
<b>(\$/ton) 205A1</b>								0.00
<b>Ag Trucks</b>								
<b>(\$/ton)</b>							14.67	14.67
<b>Primary Transport</b>								
<b>(\$/ton)</b>	0.63	2.12						2.75
<b>Base Cost Material</b>								
<b>(\$/ton)</b>	140.00							140.00
<b>Total Estimated Cost:</b>								
	All Costs		Without Primary Transport & Base					
<b>Fixed</b>	10629.00	\$	10629.00	\$	*Mtc costs accounted for in Unit 4 costs			
<b>Variable</b>	186.72	\$/ton	43.98	\$/ton	**Mtc costs accounted for in Unit 5, HP 5A costs			
<b>Total Cost =</b>	42,838.91	\$	18,214.90	\$				
<b>Cost/ton =</b>	248.34	\$/ton	105.59	\$/ton				

**B.6 Production and Cost Estimates for Unit 5 - B205A1 Helicopter -  
options 4 and 5**

175

**Client:** SFI  
**Unit:** Unit 5  
**Material:** Calcium

Helicopter: Bell 205A1 Ave. Acceleration Rate= 2.5 ft/sec<sup>2</sup>  
Cost = \$1,134 /flight hour  
Max. Payload: 3200 lbs  
Max. Ferry Speed = 90 mph  
Ave. Applic. Speed = 50 mph  
Swath Width = 45 feet  
One-way Ferry Distance 2.6 mile  
Ave. Reload Time = 7 seconds

Application Potential: 45 ft (swath) X 50 mph X 0.002 = 4.5 acres/minute

Target Application Rate of Material (lbs/ac): 2000 lbs/acre

Bucket Rate: 444 lbs/acre

Dump Time per load = 96.1 secs per 3200 lb payload

Estimated cycle time per maximum payload = 6.2 minutes

Estimated production/flight hour = 15.4 tons/flight hour

Unadjusted production/SMH (1) = 15.4 tons/SMH

**Cost Per Ton of Applied Material:**

Application = \$20.29 per ton (includes loading and application)

Ferry = \$53.38 per ton (based on round trip ferry distance, accel. & decel.)

**Cost/Ton For Unit = \$73.67 per ton**

(1) No allowance for refueling

**B.6 Production and Cost Estimates for Unit 5 - B205A1 Helicopter -  
options 4 and 5**

176

**Bell 205A1**

Acceleration = 2.5 ft/sec<sup>2</sup>

Velocity Conversions: Ferry Distance = 2.6 mile

mph	ft/sec	Max. Ferry Speed =	90 mph
20	29.3		
25	36.7	Application Speed =	50 mph
30	44.0		
35	51.3		
40	58.7		
45	66.0		
50	73.3		
55	80.7		
60	88.0		
65	95.3		
70	102.7		

Acceleration to Ferry:

Time = 52.8 seconds Distance = 3485 feet

Deceleration to Apply:

Time = 23.5 seconds Distance = 2409 feet

FD = Total distance - (Distance to Accelerate + Distance to Decelerate)

FD = 7834 feet

Ferry Time:

Time = 59.3 seconds

One-Way Time:

Time = 135.6 seconds

Two-Way Time:

Time = 271.2 seconds

Application Time:

Potential: 45 ft swath x 50 mph x 0.002 = 4.5 ac/min

Payload = 3200 lbs Ap. Rate = 2000 lbs

Rate/pass= 444 lbs/acre

Time to apply = 96.1 seconds to dump payload

Reload Bucket = 7 seconds

Total Estimated Cycle Time = 374.3 seconds = 6.2 minutes



**B.6 Production and Cost Estimates for Unit 5 - B205A1 Helicopter -  
options 4 and 5**

177

a = 2.5 ft/sec<sup>2</sup>

max. ferry speed		time to max	dist to max ferry speed		minimum distance*	
mph	ft/sec	tmax (secs)	sa (feet)	mile	sa + sd (ft)	mile
20	29.3	11.7	172	0.03	344	0.07
25	36.7	14.7	269	0.05	538	0.10
30	44.0	17.6	387	0.07	774	0.15
35	51.3	20.5	527	0.10	1054	0.20
40	58.7	23.5	688	0.13	1377	0.26
45	66.0	26.4	871	0.17	1742	0.33
50	73.3	29.3	1076	0.20	2151	0.41
55	80.7	32.3	1301	0.25	2603	0.49
60	88.0	35.2	1549	0.29	3098	0.59
65	95.3	38.1	1818	0.34	3635	0.69
70	102.7	41.1	2108	0.40	4216	0.80
75	110.0	44.0	2420	0.46	4840	0.92
80	117.3	46.9	2753	0.52	5507	1.04
85	124.7	49.9	3108	0.59	6217	1.18
90	132.0	52.8	3485	0.66	6970	1.32

\*minimum distance to accelerate/decelerate to reach maximum ferry speed

**B.6 Production Rate Estimates - Helicopter  
Ferry Only - B205A1 - unit 5, HP 5A, options 2 and 3**

178

**Bell 205A1**

Acceleration = 2.5 ft/sec<sup>2</sup>      Max. Payload = 3200 lbs

Ferry Distance (one-way) 2.3 mile

Max. Ferry Speed = 90 mph

Airspeed Load/Unload = 0 mph

Time to Hook/Unhook = 5 seconds

Acceleration to Ferry Speed:

Time = 52.8 seconds      Distance = 3485 feet

Deceleration to Unload:

Time = 52.8 seconds      Distance = 3485 feet

FD = Total distance - (Distance to Accelerate + Distance to Decelerate)

FD = 5174 feet

Ferry Time:

Time = 39.2 seconds

One-Way Time:

Time = 144.8 seconds

**Two-Way Time:**

Time = 289.6 seconds

H/U = 5.0 seconds

**Total Estimated Cycle Time = 294.6 seconds = 4.9 minutes**

Estimated production/flight hour (1),(2)= 18.3 tons/flight hour

**Cost Per Ton of Applied Material:**

**Cost/Ton for Unit = \$61.85 per ton**

(1) No allowance for refueling

(2) Adjustment for 1000 lb payload increments

**B.6 Production Rate Estimates - Helicopter**  
**Ferry Only - B205A1 - unit 5, HP 5A, options 2 and 3**

179

a = 2.5 ft/sec<sup>2</sup>

max. ferry speed		time to max	dist to max ferry speed		minimum distance*	
mph	ft/sec	tmax (secs)	sa (feet)	mile	sa + sd (ft)	mile
20	29.3	11.7	172	0.03	344	0.07
25	36.7	14.7	269	0.05	538	0.10
30	44.0	17.6	387	0.07	774	0.15
35	51.3	20.5	527	0.10	1054	0.20
40	58.7	23.5	688	0.13	1377	0.26
45	66.0	26.4	871	0.17	1742	0.33
50	73.3	29.3	1076	0.20	2151	0.41
55	80.7	32.3	1301	0.25	2603	0.49
60	88.0	35.2	1549	0.29	3098	0.59
65	95.3	38.1	1818	0.34	3635	0.69
70	102.7	41.1	2108	0.40	4216	0.80
75	110.0	44.0	2420	0.46	4840	0.92
80	117.3	46.9	2753	0.52	5507	1.04
85	124.7	49.9	3108	0.59	6217	1.18
90	132.0	52.8	3485	0.66	6970	1.32

\*minimum distance to accelerate/decelerate to reach maximum ferry speed

**B.6 Production Rate Estimates - Helicopter  
Ferry Only - B205A1 unit 5, HP 5B, options 2 and 3**

180

**Bell 205A1**

Acceleration = 2.5 ft/sec<sup>2</sup>      Max. Payload = 3200 lbs

Ferry Distance (one-way) 2.6 mile

Max. Ferry Speed = 90 mph

Airspeed Load/Unload = 0 mph

Time to Hook/Unhook = 5 seconds

Acceleration to Ferry Speed:

Time = 52.8 seconds      Distance = 3485 feet

Deceleration to Unload:

Time = 52.8 seconds      Distance = 3485 feet

FD = Total distance - (Distance to Accelerate + Distance to Decelerate)

FD = 6758 feet

Ferry Time:

Time = 51.2 seconds

One-Way Time:

Time = 156.8 seconds

Two-Way Time:

Time = 313.6 seconds

H/U = 5.0 seconds

**Total Estimated Cycle Time = 318.6 seconds = 5.3 minutes**

Estimated production/flight hour (1),(2)= 16.9 tons/flight hour

**Cost Per Ton of Applied Material:**

**Cost/Ton for Unit = \$66.89 per ton**

(1) No allowance for refueling

(2) Adjustment for 1000 lb payload increments

**B.6 Production Rate Estimates - Helicopter**  
**Ferry Only - B205A1 unit 5, HP 5B, options 2 and 3**

181

a = 2.5 ft/sec<sup>2</sup>

max. ferry speed		time to max	dist to max ferry speed		minimum distance*	
mph	ft/sec	tmax (secs)	sa (feet)	mile	sa + sd (ft)	mile
20	29.3	11.7	172	0.03	344	0.07
25	36.7	14.7	269	0.05	538	0.10
30	44.0	17.6	387	0.07	774	0.15
35	51.3	20.5	527	0.10	1054	0.20
40	58.7	23.5	688	0.13	1377	0.26
45	66.0	26.4	871	0.17	1742	0.33
50	73.3	29.3	1076	0.20	2151	0.41
55	80.7	32.3	1301	0.25	2603	0.49
60	88.0	35.2	1549	0.29	3098	0.59
65	95.3	38.1	1818	0.34	3635	0.69
70	102.7	41.1	2108	0.40	4216	0.80
75	110.0	44.0	2420	0.46	4840	0.92
80	117.3	46.9	2753	0.52	5507	1.04
85	124.7	49.9	3108	0.59	6217	1.18
90	132.0	52.8	3485	0.66	6970	1.32

\*minimum distance to accelerate/decelerate to reach maximum ferry speed

**B.6 Estimated Truck Costs Based on Potential Helicopter Production Rates - 182**  
**B205A1 Ferry - unit 5, HP 5A/5B, options 2 and 3**

Basis:			Helicopter:	
	Truck & Driver	36.21 \$/SMH	60	Actual Flight Time/SMH (minutes/SMH) (1)
Total Cost/SMH =		36.21 \$/SMH	50%	%Utilization(Helo)/SMH
			5	Est. Flight Hours/Day (2)

Truck:  
# Trucks/Drivers = 2 Ferry with 205A; apply with 47G3  
SMH = 1200 hours/yr  
PMH = 1180 hours/yr  
SMH/Day = 10 SMH/Day

Estimated Total Cost/Day/Truck = 362.06 \$/Day/Truck

Potential Production of Helicopter:

**HP 5A**

PPH = 9.7 Tons/PMH (based on lowest production/PMH)

PPH/Day(3) 48.4 Tons/Day

Estimated Cost/Ton = (\$/Day/Truck \* #Trucks) / (PPH/Day) = \$/ton

**Estimated Cost/Ton = 14.95 \$/ton**

**HP 5B**

PPH = 14.8 Tons/PMH (based on lowest production/PMH)

PPH/Day(3) 74.0 Tons/Day

Estimated Cost/Ton = (\$/Day/Truck \* #Trucks) / (PPH/Day) = \$/ton

**Estimated Cost/Ton = 9.78 \$/ton**

- (1) No allowance for refueling
- (2) Estimated flight hours = 50% of SMH for truck
- (3) Maximum 150 tons/day from historical records

Table 24: Estimated improvement and maintenance costs - unit 5, HP 5A - option 2 183

<b>Transport Segment:</b>	TS1- SLBL	SLBL-FBR2	FBR2-FBR4	FBR4-FBR5	FB5A - 5
<b>Miles (one way):</b>	0	0	0	0	0
<b>Heliport(s) Serviced:</b>	5A	5A	5A	5A	5A
<b>Unit:</b>	Unit 5	Unit 5	Unit 5	Unit 5	Unit 5
<b>Material: (Bulk)</b>	Calcium	Calcium	Calcium	Calcium	Calcium
<b>Tonnage:</b>	172.5	172.5	172.5	172.5	172.5
<b>Ferry to HP with 205A-apply with 47G3</b>					
<b>Fixed Road Costs (1):</b>					
Improvement:					
Grading	0	0	500	0	0
Brushing	0	0	0	0	0
Rocking	0	0	0	0	0
Construction:					
Construction	0	0	0	0	0
Grading	0	0	0	0	0
Rocking	0	0	0	0	0
<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>500</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>					
Improvement:					
Grading	0	0	0	0	0
Brushing	0	0	0	0	0
Rocking	0	0	0	0	0
Construction:					
Construction	0	0	0	0	0
Grading	0	0	0	0	0
Rocking	0	0	0	0	0
Move-In	1500	0	0	0	250
<b>Subtotal</b>	<b>1500 \$</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>250</b>
<b>Road Maintenance (3):</b>					
Surfacing:					
Rock	0.087 \$/ton-mile	0.087	0.087	0.087	0.087
<b>Subtotal</b>	<b>0.00 \$/ton</b>	<b>0.00</b>	<b>0.00</b>	<b>0</b>	<b>0</b>
Grading	0.00 \$/mile	0.00	0.00	0.00	0.00
<b>Subtotal</b>	<b>0.00 \$</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>
Total =	1,500 \$	0	500	0	250
<b>Variable =</b>				<b>0.00 \$/ton</b>	
<b>Fixed =</b>				<b>2250.00 \$</b>	

(1) Est lump sum cost improve/const

(2) Est lump sum cost improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25cy/5778 tons-mile\*\$20.00/cy (del. rock price)

\*#miles (one way) = \$0.087/ton-mile

Table 25: Estimated improvement and maintenance costs - unit 5, HP 5A - option 3 184

<b>Transport Segment:</b>	TS2- SLBA	SLBA-FR2	FR2-FR4	FR4-FR5	F5A - 5
<b>Miles (one way):</b>	0	0	0	0	0
<b>Heliport(s) Serviced:</b>	5A	5A	5A	5A	5A
<b>Unit:</b>	Unit 5	Unit 5	Unit 5	Unit 5	Unit 5
<b>Material: (Bags)</b>	Calcium	Calcium	Calcium	Calcium	Calcium
<b>Tonnage:</b>	172.5	172.5	172.5	172.5	172.5
<b>Ferry to HP with 205A-apply with 47G3</b>					
<b>Fixed Road Costs (1):</b>					
Improvement:					
Grading	0	0	500	0	0
Brushing	0	0	0	0	0
Rocking	0	0	0	0	0
Construction:					
Construction	0	0	0	0	0
Grading	0	0	0	0	0
Rocking	0	0	0	0	0
<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>500</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>					
Improvement:					
Grading	0	0	0	0	0
Brushing	0	0	0	0	0
Rocking	0	0	0	0	0
Construction:					
Construction	0	0	0	0	0
Grading	0	0	0	0	0
Rocking	0	0	0	0	0
Move-In	1500	0	0	0	250
<b>Subtotal</b>	<b>1500 \$</b>	<b>0</b>	<b>0</b>	<b>0</b>	<b>250</b>
<b>Road Maintenance (3):</b>					
Surfacing:					
Rock	0.087 \$/ton-mile	0.087	0.087	0.087	0.087
<b>Subtotal</b>	<b>0.00 \$/ton</b>	<b>0.00</b>	<b>0.00</b>	<b>0</b>	<b>0</b>
Grading	0.00 \$/mile	0.00	0.00	0.00	0.00
<b>Subtotal</b>	<b>0.00 \$</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>	<b>0.00</b>
Total =	1,500 \$	0	500	0	250
<b>Variable =</b>				<b>0.00 \$/ton</b>	
<b>Fixed =</b>				<b>2250.00 \$</b>	

(1) Est lump sum cost improve/const

(2) Est lump sum cost improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25cy/5778 tons-mile\*\$20.00/cy (del. rock price)

\*#miles (one way) = \$0.087/ton-mile



Table 26: Estimated improvement and maintenance costs - unit 5, HP 5B - option 2 185

<b>Transport Segment:</b>	FBR4-FBR6	FBR6-FB5B	FB5B - 5
<b>Miles (one way):</b>	0	0	1
<b>Heliport(s) Serviced:</b>	5B	5B	5B
<b>Unit:</b>	Unit 5	Unit 5	Unit 5
<b>Material: (Bulk)</b>	Calcium	Calcium	Calcium
<b>Tonnage:</b>	172.5	172.5	172.5
<b>Ferry to HP with 205A-apply with 47G3</b>			
<b>Fixed Road Costs (1):</b>			
Improvement:			
Grading	500	0	0
Brushing	0	0	0
Rocking	500	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
<b>Subtotal</b>	<b>1000 \$</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>			
Improvement:			
Grading	0	500	0
Brushing	0	0	0
Rocking	0	500	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
Move-In	0	0	250
<b>Subtotal</b>	<b>0 \$</b>	<b>1000</b>	<b>250</b>
<b>Road Maintenance (3):</b>			
Surfacing:			
Rock	0.087 \$/ton-mile	0.087	
<b>Subtotal</b>	<b>0 \$/ton</b>	<b>0</b>	
Grading	0.00 \$/mile	0.00	
<b>Subtotal</b>	<b>0.00 \$</b>	<b>0.00</b>	
<b>Total =</b>	<b>1,000 \$</b>	<b>1,000</b>	<b>250</b>
		<b>Variable =</b>	<b>0.00 \$/ton</b>
		<b>Fixed =</b>	<b>2250.00 \$</b>

(1) Est lump sum cost improve/const

(2) Est lump sum cost improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25cy/5778 tons-mile\*\$20.00/cy (del. rock price)

\*#miles (one way) = \$0.087/ton-mile

Table 27: Estimated improvement and maintenance costs - unit 5, HP 5B - option 3 186

<b>Transport Segment:</b>	FR4-FR6	FR6-FR5B	FR5B - 5
<b>Miles (one way):</b>	0	0	0
<b>Heliport(s) Serviced:</b>	5B	5B	5B
<b>Unit:</b>	Unit 5	Unit 5	Unit 5
<b>Material: (Bags)</b>	Calcium	Calcium	Calcium
<b>Tonnage:</b>	172.5	172.5	172.5
<b>Ferry to HP with 205A-apply with 47G3</b>			
<b>Fixed Road Costs (1):</b>			
Improvement:			
Grading	500	0	0
Brushing	0	0	0
Rocking	500	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
<b>Subtotal</b>	<b>1000 \$</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>			
Improvement:			
Grading	0	500	0
Brushing	0	0	0
Rocking	0	500	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
Move-In	0	0	250
<b>Subtotal</b>	<b>0 \$</b>	<b>1000</b>	<b>250</b>
<b>Road Maintenance (3):</b>			
Surfacing:			
Rock	0.087 \$/ton-mile	0.087	0.087
<b>Subtotal</b>	<b>0 \$/ton</b>	<b>0</b>	<b>0</b>
Grading	0.00 \$/mile	0.00	0.00
<b>Subtotal</b>	<b>0.00 \$</b>	<b>0.00</b>	<b>0.00</b>
Total =	1,000 \$	1,000	250
		<b>Variable =</b>	<b>0.00 \$/ton</b>
		<b>Fixed =</b>	<b>2250.00 \$</b>

(1) Est lump sum cost improve/const

(2) Est lump sum cost improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25cy/5778 tons-mile\*\$20.00/cy (del. rock price)

\*#miles (one way) = \$0.087/ton-mile

Table 28: Estimated improvement and maintenance costs - unit 5, option 4

<b>Transport Segment:</b>	TS1- SLBL	SLBL-SLBLD5	SLBLD5-5
<b>Miles (one way):</b>	0	0	0
<b>Heliport(s) Serviced:</b>	5A/5B	5A/5B	5A/5B
<b>Unit:</b>	Unit 5	Unit 5	Unit 5
<b>Material: (Bulk)</b>	Calcium	Calcium	Calcium
<b>Tonnage:</b>	172.5	172.5	172.5
<b>Direct apply 205A - bulk</b>			
<b>Fixed Road Costs (1):</b>			
Improvement:			
Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>			
Improvement:			
Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
Move-In	1500	0	0
<b>Subtotal</b>	<b>1500 \$</b>	<b>0</b>	<b>0</b>
<b>Road Maintenance (3):</b>			
Surfacing:			
Rock	0.087 \$/ton-mile	0.087	0.087
<b>Subtotal</b>	<b>0.00 \$/ton</b>	<b>0.00</b>	<b>0.00</b>
Grading	0.00 \$/mile	0.00	0.00
<b>Subtotal</b>	<b>0.00 \$</b>	<b>0.00</b>	<b>0.00</b>
Total =	1,500 \$	0	0
<b>Variable =</b>		<b>0.00 \$/ton</b>	
<b>Fixed =</b>		<b>1500.00 \$</b>	

(1) Est lump sum costs of improve/const

(2) Est lump sum costs of improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25 cy/5778 tons-mile \* \$20.00/cy (del rock price)

\* # miles (one-way) = \$0.087/ton-mile

Table 29: Estimated improvement and maintenance costs - unit 5, option 5

188

<b>Transport Segment:</b>	TS2- SLBA	SLBA-SLBAD5	SLBAD5-5
<b>Miles (one way):</b>	0	0	0
<b>Heliport(s) Serviced:</b>	5A/5B	5A/5B	5A/5B
<b>Unit:</b>	Unit 5	Unit 5	Unit 5
<b>Material: (Bags)</b>	Calcium	Calcium	Calcium
<b>Tonnage:</b>	172.5	172.5	172.5
<b>Direct apply 205A - bags</b>			
<b>Fixed Road Costs (1):</b>			
Improvement:			
Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
<b>Subtotal</b>	<b>0 \$</b>	<b>0</b>	<b>0</b>
<b>Fixed Heliport Costs (2):</b>			
Improvement:			
Grading	0	0	0
Brushing	0	0	0
Rocking	0	0	0
Construction:			
Construction	0	0	0
Grading	0	0	0
Rocking	0	0	0
Move-In	1500	0	0
<b>Subtotal</b>	<b>1500 \$</b>	<b>0</b>	<b>0</b>
<b>Road Maintenance (3):</b>			
Surfacing:			
Rock	0.087 \$/ton-mile	0.087	0.087
<b>Subtotal</b>	<b>0.00 \$/ton</b>	<b>0.00</b>	<b>0.00</b>
Grading	0.00 \$/mile	0.00	0.00
<b>Subtotal</b>	<b>0.00 \$</b>	<b>0.00</b>	<b>0.00</b>
Total =	1,500 \$	0	0
		<b>Variable =</b>	<b>0.00 \$/ton</b>
		<b>Fixed =</b>	<b>1500.00 \$</b>

(1) Est lump sum costs of improve/const

(2) Est lump sum costs of improve/const

(3) Rock wear basis: log hauling: 25 cy/MMBF-mile =  
25 cy/5778 tons-mile \* \$20.00/cy (del rock price)

\* # miles (one-way) = \$0.087/ton-mile

**B.6 Primary Haul Costs - unit 5, options 2, 3, 4 and 5  
(Delivered to Transfer Site)**

189

**Bulk Delivery**

<b>Total Tons =</b>	238 tons	<b>Tons/trip =</b>	60
<b>Source:</b>	Portland	<b>#Trips =</b>	4
<b>Destination:</b>	Tangent		
<b>Miles (one-way):</b>	75 miles		
<b>Cost/Mile:</b>	0.50 \$/mile		

<b>Subtotal =</b>	150.00 \$	0.63 \$/ton
-------------------	-----------	-------------

<b>Source:</b>	Tangent	<b>Tons/trip =</b>	30
<b>Destination:</b>	Transfer #1	<b>#Trips =</b>	8
<b>Miles (one-way):</b>	45 miles		
<b>Cost/Mile</b>	1.40 \$/mile		

<b>Subtotal =</b>	504.00 \$	2.12 \$/ton
-------------------	-----------	-------------

<b>Total Cost =</b>	<b>654.00 \$</b>
---------------------	------------------

**Bag Delivery**

<b>Source:</b>	Portland	<b>Tons/trip =</b>	60
<b>Destination:</b>	Transfer #2	<b>#Trips =</b>	4
<b>Miles (one-way):</b>	120 miles		
<b>Cost/Mile:</b>	0.80 \$/mile		

<b>Subtotal =</b>	384.00 \$	1.61 \$/ton
-------------------	-----------	-------------

Table 30: Estimated costs for transportation and application of materials - unit 5, HP 5A, option 2

Client:		SFI							
Unit:		Unit 5							
Material:		Calcium							
Tonnage:		172.5 tons							
Heliport(s) Serviced:		5A							
Ferry With 205A - Apply With 47G3 - bulk									
Links	P-T	T-TS1	TS1-SLBL	SLBL-FBR2	FBR2-FBR4	FBR4-FBR5	FBR5-FB5A	FB5A-5	Subtotals
Roads/move-in									
(\$/ton) Fixed			1500.00		500.00			250	2250.00
(\$/ton) Variable									0.00
Helicopter									
(\$/ton) 47G3								43.93	43.93
(\$/ton) 205A1								61.85	61.85
Ag Trucks									
(\$/ton)								14.95	14.95
Primary Transport									
(\$/ton)	0.63	2.12							2.75
Base Cost Material									
(\$/ton)	140.00								140.00
Total Estimated Cost:									
			Without Primary Transport & Base						
Fixed	2250.00	\$	2250.00	\$					
Variable	263.47	\$/ton	120.72	\$/ton					
Total Cost =	47,698.85	\$	23,074.84	\$					
Cost/ton =	276.52	\$/ton	133.77	\$/ton					

Table 31: Estimated costs for transportation and application of materials - unit 5, HP 5A, option 3

<b>Client:</b>		SFI							
<b>Unit:</b>		Unit 5							
<b>Material:</b>		Calcium							
<b>Tonnage:</b>		172.5 tons							
<b>Heliport(s) Serviced:</b>		5A							
<b>Ferry With 205A1 - Apply With 47G3 -BAGS</b>									
<b>Links</b>	<b>P - TS2</b>	<b>TS2 - SLBA</b>	<b>SLBA - FR2</b>	<b>FR2-FR4</b>	<b>FR4-FR5</b>	<b>FR5-F5A</b>	<b>F5A-5</b>	<b>Subtotals</b>	
<b>Roads/move-in</b>									
<b>(\$/ton) Fixed</b>		1500.00		500.00			250.00	2250.00	
<b>(\$/ton) Variable</b>								0.00	
<b>Helicopter</b>									
<b>(\$/ton) 47G3</b>							43.93	43.93	
<b>(\$/ton) 205A1</b>							61.85	61.85	
<b>Ag Trucks</b>									
<b>(\$/ton)</b>							14.95	14.95	
<b>Primary Transport</b>									
<b>(\$/ton)</b>	1.61							1.61	
<b>Base Cost Material</b>									
<b>(\$/ton)</b>	130.00							130.00	
<b>Total Estimated Cost:</b>									
			Without Primary Transport & Base						
Fixed	2250.00	\$	2250.00	\$					
Variable	252.34	\$/ton	120.72	\$/ton					
Total Cost =	45,778.16	\$	23,074.84	\$					
Cost/ton =	265.38	\$/ton	133.77	\$/ton					

Table 32: Estimated costs for transportation and application of materials - unit 5, HP 5B, option 2

Client:		SFI							
Unit:		Unit 5							
Material:		Calcium							
Tonnage:		172.5 tons							
Heliport(s) Serviced:		5B							
Ferry With 205A - Apply With 47G3 - bulk									
Links	P-T	T-TS1	TS1-SLBL	SLBL-FBR2	FBR2-FBR4	FBR4-FBR6	FBR6-FB5B	FB5B-5	Subtotals
Roads/move-in									
(\$/ton) Fixed			1500.00	0.00	500.00	1000.00	1000.00	250.00	4250.00
(\$/ton) Variable									0.00
Helicopter									
(\$/ton) 47G3								28.74	28.74
(\$/ton) 205A1								66.89	66.89
Ag Trucks									
(\$/ton)								9.78	9.78
Primary Transport									
(\$/ton)	0.63	2.12							2.75
Base Cost Material									
(\$/ton)	140.00								140.00
Total Estimated Cost:									
			Without Primary Transport & Base						
Fixed	4250.00	\$	4250.00	\$					
Variable	248.16	\$/ton	105.41	\$/ton					
Total Cost =	47,056.96	\$	22,432.95	\$					
Cost/ton =	272.79	\$/ton	130.05	\$/ton					



Table 33: Estimated costs for transportation and application of materials - unit 5, HP 5B, option 3

Client:		SFI						
Unit:		Unit 5						
Material:		Calcium						
Tonnage:		172.5 tons						
Heliport(s) Serviced:		5B						
Ferry With 205A1 - Apply With 47G3 -BAGS								
Links	P - TS2	TS2 - SLBA	SLBA - FR2	FR2-FR4	FR4-FR6	FR6-FR5B	FR5B-5	Subtotals
Roads/move-in								
(\$/ton) Fixed		1500.00	0.00	500.00	1000.00	1000.00	250.00	4250.00
(\$/ton) Variable								0.00
Helicopter								
(\$/ton) 47G3							28.74	28.74
(\$/ton) 205A1							66.89	66.89
Ag Trucks								
(\$/ton)							9.78	9.78
Primary Transport								
(\$/ton)	1.61							1.61
Base Cost Material								
(\$/ton)	130.00							130.00
Total Estimated Cost:								
			Without Primary Transport & Base					
Fixed	4250.00	\$	4250.00	\$				
Variable	237.02	\$/ton	105.41	\$/ton				
Total Cost =	45,136.27	\$	22,432.95	\$				
Cost/ton =	261.66	\$/ton	130.05	\$/ton				



Table 35: Estimated costs for transportation and application of materials - unit 5, option 5

Client:		SFI							
Unit:		Unit 5							
Material:		Calcium							
Tonnage:		172.5 tons							
Heliport(s) Serviced:		5A/5B							
Direct Apply With 205A1 - BAGS									
Links	P-TS2	TS2-SLBA	SLBA-SLBAD5	SLBAD5-5	Subtotals				
Roads/move-in									
(\$/ton) Fixed		1500.00			1500.00				
(\$/ton) Variable					0.00				
Helicopter									
(\$/ton) 47G3					0.00				
(\$/ton) 205A1				73.67	73.67				
Ag Trucks									
(\$/ton)					0.00				
Primary Transport									
(\$/ton)	1.61				1.61				
Base Cost Material									
(\$/ton)	130.00				130.00				
Total Estimated Cost: Without Primary Transport & Base									
Fixed	1500.00	\$	1500.00	\$					
Variable	205.29	\$/ton	73.67	\$/ton					
Total Cost =	36,912.25	\$	14,208.93	\$					
Cost/ton =	213.98	\$/ton	82.37	\$/ton					

**Appendix C: Input for Mixed-Integer Linear Programming Models**

C.1	Input for Hyper LINDO <sup>®</sup> 6.1.....	197
C.2	Input for What'sBest! <sup>®</sup> .....	200

**Objective Function:**

MIN 1260 Y3 + 2644 Y4 + 420 Y5 + 250 Y7 + 6475 Y8 + 250 Y10  
 + 1500 Y11 + 500 Y15 + 250 Y18 + 1000 Y19 + 1000 Y20 + 250 Y21  
 + 1500 Y23 + 500 Y27 + 250 Y30 + 1000 Y31 + 1000 Y32 + 250 Y33  
 + 250 Y36 + 250 Y42 + 250 Y48 + 140.63 X1 + 2.12 X2 + 0.18 X3  
 + 0.25 X4 + 0.06 X5 + 66.34 X7 + 0.13 X8 + 43.41 X10 + 73.67 X13  
 + 120.73 X18 + 110.58 X21 + 131.61 X22 + 73.67 X25 + 120.73 X30  
 + 105.41 X33 + 0.07 X34 + 24.88 X36 + 47.25 X38 + 62.61 X42  
 + 47.25 X44 + 62.61 X48

**Constraints:****SUBJECT TO**

- 2) 500 Y1 - X1  $\geq$  0
- 3) 500 Y2 - X2  $\geq$  0
- 4) 500 Y3 - X3  $\geq$  0
- 5) 500 Y4 - X4  $\geq$  0
- 6) 500 Y5 - X5  $\geq$  0
- 7) 500 Y6 - X6  $\geq$  0
- 8) 500 Y7 - X7  $\geq$  0
- 9) 500 Y8 - X8  $\geq$  0
- 10) 500 Y9 - X9  $\geq$  0
- 11) 500 Y10 - X10  $\geq$  0
- 12) 500 Y11 - X11  $\geq$  0
- 13) 500 Y12 - X12  $\geq$  0
- 14) 500 Y13 - X13  $\geq$  0
- 15) 500 Y14 - X14  $\geq$  0
- 16) 500 Y15 - X15  $\geq$  0
- 17) 500 Y16 - X16  $\geq$  0
- 18) 500 Y17 - X17  $\geq$  0
- 19) 500 Y18 - X18  $\geq$  0
- 20) 500 Y19 - X19  $\geq$  0
- 21) 500 Y20 - X20  $\geq$  0
- 22) 500 Y21 - X21  $\geq$  0
- 23) 500 Y22 - X22  $\geq$  0
- 24) 500 Y23 - X23  $\geq$  0
- 25) 500 Y24 - X24  $\geq$  0
- 26) 500 Y25 - X25  $\geq$  0
- 27) 500 Y26 - X26  $\geq$  0
- 28) 500 Y27 - X27  $\geq$  0
- 29) 500 Y28 - X28  $\geq$  0
- 30) 500 Y29 - X29  $\geq$  0
- 31) 500 Y30 - X30  $\geq$  0
- 32) 500 Y31 - X31  $\geq$  0
- 33) 500 Y32 - X32  $\geq$  0
- 34) 500 Y33 - X33  $\geq$  0
- 35) 500 Y34 - X34  $\geq$  0
- 36) 500 Y35 - X35  $\geq$  0
- 37) 500 Y36 - X36  $\geq$  0
- 38) 500 Y37 - X37  $\geq$  0

```

39) 500 Y38 - X38 >= 0
40) 500 Y40 - X40 >= 0
41) 500 Y41 - X41 >= 0
42) 500 Y42 - X42 >= 0
43) 500 Y43 - X43 >= 0
44) 500 Y44 - X44 >= 0
45) 500 Y46 - X46 >= 0
46) 500 Y47 - X47 >= 0
47) 500 Y48 - X48 >= 0
48) X1 + X22 = 184.5
49) X1 - X2 = 0
50) X2 - X3 - X11 = 0
51) X3 - X4 - X34 = 0
52) X4 - X5 - X8 = 0
53) X5 - X6 = 0
54) -X7 + X6 = 0
55) X7 + X10 + X13 + X18 + X21 + X25 + X30 + X33 = 172.5
56) X8 - X9 = 0
57) -X10 + X9 = 0
58) X11 - X12 - X14 - X37 = 0
59) -X13 + X12 = 0
60) X14 - X15 - X40 = 0
61) X15 - X16 - X19 = 0
62) X16 - X17 = 0
63) -X18 + X17 = 0
64) X19 - X20 = 0
65) -X21 + X20 = 0
66) X22 - X23 = 0
67) X23 - X24 - X26 - X43 = 0
68) -X25 + X24 = 0
69) X26 - X27 - X46 = 0
70) X27 - X28 - X31 = 0
71) X28 - X29 = 0
72) -X30 + X29 = 0
73) X31 - X32 = 0
74) -X33 + X32 = 0
75) X34 - X35 = 0
76) -X36 + X35 = 0
77) X36 + X38 + X42 + X44 + X48 = 12
78) -X38 + X37 = 0
79) X40 - X41 = 0
80) -X42 + X41 = 0
81) -X44 + X43 = 0
82) X46 - X47 = 0
83) -X48 + X47 = 0
END
INTE Y1
INTE Y2
INTE Y3
INTE Y4
INTE Y5

```

```
INTE  Y6
INTE  Y7
INTE  Y8
INTE  Y9
INTE  Y10
INTE  Y11
INTE  Y12
INTE  Y13
INTE  Y14
INTE  Y15
INTE  Y16
INTE  Y17
INTE  Y18
INTE  Y19
INTE  Y20
INTE  Y21
INTE  Y22
INTE  Y23
INTE  Y24
INTE  Y25
INTE  Y26
INTE  Y27
INTE  Y28
INTE  Y29
INTE  Y30
INTE  Y31
INTE  Y32
INTE  Y33
INTE  Y34
INTE  Y35
INTE  Y36
INTE  Y37
INTE  Y38
INTE  Y40
INTE  Y41
INTE  Y42
INTE  Y43
INTE  Y44
INTE  Y46
INTE  Y47
INTE  Y48
```

## C.2 Input for What'sBest!®

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Decision Variables	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19
2		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3																				
4	Constraints	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19
5	Consv. Flow Node 1	1																		
6	2	1	-1																	
7	3		1	-1								-1								
8	4			1	-1															
9	5				1	-1			-1											
10	6					1	-1													
11	7						1	-1												
12	8							1			1			1					1	
13	9								1	-1										
14	10									1	-1									
15	11											1	-1		-1					
16	12												1	-1						
17	13														1	-1				
18	14															1	-1			-1
19	15																1	-1		
20	16																	1	-1	
21	17																			1
22	18																			
23	19																			
24	20																			
25	21																			
26	22																			
27	23																			
28	24																			
29	25																			
30	26																			
31	27																			
32	28																			
33	29																			
34	30																			
35	31																			
36	32																			
37	33																			
38	34																			
39	35																			
40	36																			
41	Triggers Y1+Y22≤1																			
42	Y11+Y3≤1																			
43	Y14+Y37≤1																			
44	Y14+Y12≤1																			
45	Y43+Y26≤1																			
46	Y26+Y24≤1																			
47	Y5+Y8≤1																			
48	Y16+Y19≤1																			
49	Y28+Y31≤1																			
50	500Y1-X1≥0	-1																		
51	500Y2-X2≥0		-1																	
52	500Y3-X3≥0			-1																



## C.2 Input for What'sBest!<sup>®</sup>

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
53	500Y4-X4>0				-1															
54	500Y5-X5>0					-1														
55	500Y6-X6>0						-1													
56	500Y7-X7>0							-1												
57	500Y8-X8>0								-1											
58	500Y9-X9>0									-1										
59	500Y10-X10>0										-1									
60	500Y11-X11>0											-1								
61	500Y12-X12>0												-1							
62	500Y13-X13>0													-1						
63	500Y14-X14>0														-1					
64	500Y15-X15>0															-1				
65	500Y16-X16>0																-1			
66	500Y17-X17>0																	-1		
67	500Y18-X18>0																		-1	
68	500Y19-X19>0																			-1
69	500Y20-X20>0																			
70	500Y21-X21>0																			
71	500Y22-X22>0																			
72	500Y23-X23>0																			
73	500Y24-X24>0																			
74	500Y25-X25>0																			
75	500Y26-X26>0																			
76	500Y27-X27>0																			
77	500Y28-X28>0																			
78	500Y29-X29>0																			
79	500Y30-X30>0																			
80	500Y31-X31>0																			
81	500Y32-X32>0																			
82	500Y33-X33>0																			
83	500Y34-X34>0																			
84	500Y35-X35>0																			
85	500Y36-X36>0																			
86	500Y37-X37>0																			
87	500Y38-X38>0																			
88	500Y40-X40>0																			
89	500Y41-X41>0																			
90	500Y42-X42>0																			
91	500Y43-X43>0																			
92	500Y44-X44>0																			
93	500Y46-X46>0																			
94	500Y47-X47>0																			
95	500Y48-X48>0																			
96																				
97		x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19
98	Costs	140.63	2.12	0.18	0.25	0.06	0	66.34	0.13	0	43.41	0	0	73.67	0	0	0	0	120.73	0
99																				

# C.2 Input for What'sBest!<sup>®</sup>

	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
1	x20	x21	x22	x23	x24	x25	x26	x27	x28	x29	x30	x31	x32	x33	x34	x35	x36	x37	x38	x40	x41	x42
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3																						
4	x20	x21	x22	x23	x24	x25	x26	x27	x28	x29	x30	x31	x32	x33	x34	x35	x36	x37	x38	x40	x41	x42
5			1																			
6																						
7																						
8																						
9															-1							
10																						
11																						
12		1				1					1			1								
13																						
14																						
15																		-1				
16																						
17																				-1		
18																						
19																						
20																						
21	-1																					
22	1	-1																				
23			1	-1																		
24				1	-1		-1															
25					1	-1																
26							1	-1														
27								1	-1			-1										
28									1	-1												
29										1	-1											
30												1	-1									
31													1	-1								
32															1	-1						
33																1	-1					
34																	1		1			1
35																		1	-1			
36																				1	-1	
37																					1	-1
38																						
39																						
40																						
41																						
42																						
43																						
44																						
45																						
46																						
47																						
48																						
49																						
50																						
51																						
52																						

## C.2 Input for What'sBest!®

	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
53																						
54																						
55																						
56																						
57																						
58																						
59																						
60																						
61																						
62																						
63																						
64																						
65																						
66																						
67																						
68																						
69	-1																					
70		-1																				
71			-1																			
72				-1																		
73					-1																	
74						-1																
75							-1															
76								-1														
77									-1													
78										-1												
79											-1											
80												-1										
81													-1									
82														-1								
83															-1							
84																-1						
85																	-1					
86																		-1				
87																			-1			
88																				-1		
89																					-1	
90																						-1
91																						
92																						
93																						
94																						
95																						
96																						
97	x20	x21	x22	x23	x24	x25	x26	x27	x28	x29	x30	x31	x32	x33	x34	x35	x36	x37	x38	x40	x41	x42
98	0	105.41	131.61	0	0	73.67	0	0	0	0	120.73	0	0	105.41	0.07	0	24.88	0	47.25	0	0	62.61
99																						

## C.2 Input for What'sBest!®

	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL
1	x43	x44	x46	x47	x48	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10	y11	y12	y13	y14	y15	y16	y17
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3																						
4	x43	x44	x46	x47	x48	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10	y11	y12	y13	y14	y15	y16	y17
5																						
6																						
7																						
8																						
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14																						
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20																						
21																						
22																						
23																						
24	-1																					
25																						
26			-1																			
27																						
28																						
29																						
30																						
31																						
32																						
33																						
34		1			1																	
35																						
36																						
37																						
38	1	-1																				
39			1	-1																		
40				1	-1																	
41						1																
42								1								1						
43																			1			
44																	1		1			
45																						
46																						
47										1			1									
48																					1	
49																						
50						500																
51							500															
52								500														

## C.2 Input for What'sBest!<sup>®</sup>

	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL
53									500													
54										500												
55											500											
56												500										
57													500									
58														500								
59															500							
60																500						
61																	500					
62																		500				
63																			500			
64																				500		
65																					500	
66																						500
67																						
68																						
69																						
70																						
71																						
72																						
73																						
74																						
75																						
76																						
77																						
78																						
79																						
80																						
81																						
82																						
83																						
84																						
85																						
86																						
87																						
88																						
89																						
90																						
91	-1																					
92		-1																				
93			-1																			
94				-1																		
95					-1																	
96																						
97	x1	x2	x3	x4	x5	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10	y11	y12	y13	y14	y15	y16	y17
98	0	47.25	0	0	62.61	0	0	1260	2644	420	0	250	6475	0	250	1500	0	0	0	500	0	0
99																						

# C.2 Input for What'sBest!®

	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH
1	y18	y19	y20	y21	y22	y23	y24	y25	y26	y27	y28	y29	y30	y31	y32	y33	y34	y35	y36	y37	y38	y40
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3																						
4	y18	y19	y20	y21	y22	y23	y24	y25	y26	y27	y28	y29	y30	y31	y32	y33	y34	y35	y36	y37	y38	y40
5																						
6																						
7																						
8																						
9																						
10																						
11																						
12																						
13																						
14																						
15																						
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22																						
23																						
24																						
25																						
26																						
27																						
28																						
29																						
30																						
31																						
32																						
33																						
34																						
35																						
36																						
37																						
38																						
39																						
40																						
41					1																	
42																						
43																			1			
44																						
45									1													
46							1		1													
47																						
48		1																				
49											1			1								
50																						
51																						
52																						

## C.2 Input for What'sBest!®

	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH
53																						
54																						
55																						
56																						
57																						
58																						
59																						
60																						
61																						
62																						
63																						
64																						
65																						
66																						
67	500																					
68		500																				
69			500																			
70				500																		
71					500																	
72						500																
73							500															
74								500														
75									500													
76										500												
77											500											
78												500										
79													500									
80														500								
81															500							
82																500						
83																	500					
84																		500				
85																			500			
86																				500		
87																					500	
88																						500
89																						
90																						
91																						
92																						
93																						
94																						
95																						
96																						
97	y18	y19	y20	y21	y22	y23	y24	y25	y26	y27	y28	y29	y30	y31	y32	y33	y34	y35	y36	y37	y38	y40
98	250	1000	1000	250	0	1500	0	0	0	500	0	0	250	1000	1000	250	0	0	250	0	0	0
99																						

# C.2 Input for What'sBest!<sup>®</sup>

	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW
1	y41	y42	y43	y44	y46	y47	y48								
2	1	1	1	1	1	1	1								
3															
4	y41	y42	y43	y44	y46	y47	y48					SUM	DIR	RHS	Units
5												2	Not =	184.5	tons
6												0	=	0	tons
7												-1	Not =	0	tons
8												0	=	0	tons
9												-2	Not =	0	tons
10												0	=	0	tons
11												0	=	0	tons
12												8	Not =	172.5	tons
13												0	=	0	tons
14												0	=	0	tons
15												-2	Not =	0	tons
16												0	=	0	tons
17												-1	Not =	0	tons
18												-1	Not =	0	tons
19												0	=	0	tons
20												0	=	0	tons
21												0	=	0	tons
22												0	=	0	tons
23												0	=	0	tons
24												-2	Not =	0	tons
25												0	=	0	tons
26												-1	Not =	0	tons
27												-1	Not =	0	tons
28												0	=	0	tons
29												0	=	0	tons
30												0	=	0	tons
31												0	=	0	tons
32												0	=	0	tons
33												0	=	0	tons
34												5	Not =	12	tons
35												0	=	0	tons
36												0	=	0	tons
37												0	=	0	tons
38												0	=	0	tons
39												0	=	0	tons
40												0	=	0	tons
41												2	Not <=	1	\$
42												2	Not <=	1	\$
43												2	Not <=	1	\$
44												2	Not <=	1	\$
45			1									2	Not <=	1	\$
46												2	Not <=	1	\$
47												2	Not <=	1	\$
48												2	Not <=	1	\$
49												2	Not <=	1	\$
50												499	>=	0	\$
51												499	>=	0	\$
52												499	>=	0	\$



## C.2 Input for What'sBest!<sup>®</sup>

	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW
53												499 >=		0 \$	
54												499 >=		0 \$	
55												499 >=		0 \$	
56												499 >=		0 \$	
57												499 >=		0 \$	
58												499 >=		0 \$	
59												499 >=		0 \$	
60												499 >=		0 \$	
61												499 >=		0 \$	
62												499 >=		0 \$	
63												499 >=		0 \$	
64												499 >=		0 \$	
65												499 >=		0 \$	
66												499 >=		0 \$	
67												499 >=		0 \$	
68												499 >=		0 \$	
69												499 >=		0 \$	
70												499 >=		0 \$	
71												499 >=		0 \$	
72												499 >=		0 \$	
73												499 >=		0 \$	
74												499 >=		0 \$	
75												499 >=		0 \$	
76												499 >=		0 \$	
77												499 >=		0 \$	
78												499 >=		0 \$	
79												499 >=		0 \$	
80												499 >=		0 \$	
81												499 >=		0 \$	
82												499 >=		0 \$	
83												499 >=		0 \$	
84												499 >=		0 \$	
85												499 >=		0 \$	
86												499 >=		0 \$	
87												499 >=		0 \$	
88												499 >=		0 \$	
89	500											499 >=		0 \$	
90		500										499 >=		0 \$	
91			500									499 >=		0 \$	
92				500								499 >=		0 \$	
93					500							499 >=		0 \$	
94						500						499 >=		0 \$	
95							500					499 >=		0 \$	
96															
97	y41	y42	y43	y44	y45	y46	y47	y48							
98	0	250	0	0	0	0	250					22278			
99															

**Appendix D: Input for NETWORK 2000**

From Node	To Node	Variable Cost	Fixed Cost	X	Y
P	T	140.63	0.00	1	1
T	TS1	2.12	0.00	2	2
TS1	R2	0.18	1260.00	3	3
R2	R4	0.25	2644.00	4	4
R4	R5	0.06	420.00	5	5
R5	5A	0.00	0.00	6	6
5A	5	66.34	250.00	7	7
R4	R6	0.13	6475.00	8	8
R6	5B	0.00	0.00	9	9
5B	5	43.41	250.00	10	10
TS1	SLBL	0.00	1500.00	11	11
SLBL	SLBLD5	0.00	0.00	12	12
SLBLD5	5	73.67	0.00	13	13
SLBL	FBR2	0.00	0.00	14	14
FBR2	FBR4	0.00	500.00	15	15
FBR4	FBR5	0.00	0.00	16	16
FBR5	FB5A	0.00	0.00	17	17
FB5A	5	120.73	250.00	18	18
FBR4	FBR6	0.00	1000.00	19	19
FBR6	FB5B	0.00	1000.00	20	20
FB5B	5	105.41	250.00	21	21
P	TS2	131.61	0.00	22	22
TS2	SLBA	0.00	1500.00	23	23
SLBA	SLBAD5	0.00	0.00	24	24
SLBAD5	5	73.67	0.00	25	25

SLBA	FR2	0.00	0.00	26	26
FR2	FR4	0.00	500.00	27	27
FR4	FR5	0.00	0.00	28	28
FR5	F5A	0.00	0.00	29	29
F5A	5	120.73	250.00	30	30
FR4	FR6	0.00	1000.00	31	31
FR6	FR5B	0.00	1000.00	32	32
FR5B	5	105.41	250.00	33	33
R2	R3	0.07	0.00	34	34
R3	4A	0.00	0.00	35	35
4A	4	24.88	250.00	36	36
SLBL	SLBLD4	0.00	0.00	37	37
SLBLD4	4	47.25	0.00	38	38
SLBL	FBR2			14	14
FBR2	FBR3	0.00	0.00	40	40
FBR3	FB4A	0.00	0.00	41	41
FB4A	4	62.61	250.00	42	42
SLBA	SLBAD4	0.00	0.00	43	43
SLBAD4	4	47.25	0.00	44	44
SLBA	FR2			26	26
FR2	FR3	0.00	0.00	46	46
FR3	F4A	0.00	0.00	47	47
F4A	4	62.61	250.00	48	48

Source and Destination Links					
<u>Line #</u>	<u>Source</u>	<u>Destination</u>	<u>Volume</u>	<u>Year</u>	
2	P	4	12	0.00	
3	P	5	172.5	0.00	

**Appendix E: Output for Mixed-Integer Programming Models**

E.1	Output for Hyper LINDO® 6.1.....	215
E.2	Output for What'sBest!® .....	220

NEW INTEGER SOLUTION OF 39057.1200 AT BRANCH 25 PIVOT 208

## OBJECTIVE FUNCTION VALUE

1) 39057.1200

VARIABLE	VALUE	REDUCED COST
Y1	.000000	.000000
Y2	.000000	.000000
Y3	.000000	-3980.000000
Y4	.000000	.000000
Y5	.000000	420.000000
Y6	.000000	.000000
Y7	.000000	250.000000
Y8	.000000	5329.004000
Y9	.000000	.000000
Y10	.000000	.000000
Y11	.000000	1500.000000
Y12	.000000	.000000
Y13	.000000	.000000
Y14	.000000	.000000
Y15	.000000	500.000000
Y16	.000000	.000000
Y17	.000000	.000000
Y18	.000000	250.000000
Y19	.000000	1000.000000
Y20	.000000	1000.000000
Y21	.000000	250.000000
Y22	1.000000	.000000
Y23	1.000000	1500.000000
Y24	1.000000	.000000
Y25	1.000000	.000000
Y26	.000000	.000000
Y27	.000000	500.000000
Y28	.000000	.000000
Y29	.000000	.000000
Y30	.000000	250.000000
Y31	.000000	1000.000000
Y32	.000000	1000.000000
Y33	.000000	250.000000
Y34	.000000	.000000
Y35	.000000	.000000
Y36	.000000	.000000
Y37	.000000	.000000
Y38	.000000	.000000
Y40	.000000	.000000

Y41	.000000	.000000
Y42	.000000	250.000000
Y43	1.000000	.000000
Y44	1.000000	.000000
Y46	.000000	.000000
Y47	.000000	.000000
Y48	.000000	250.000000
X1	.000000	.000000
X2	.000000	.000000
X3	.000000	.000000
X4	.000000	.000000
X5	.000000	.000000
X7	.000000	.000000
X8	.000000	.000000
X10	.000000	.000000
X13	.000000	.000000
X18	.000000	.000000
X21	.000000	.000000
X22	184.500000	.000000
X25	172.500000	.000000
X30	.000000	.000000
X33	.000000	.000000
X34	.000000	.000000
X36	.000000	.000000
X38	.000000	.000000
X42	.000000	.000000
X44	12.000000	.000000
X48	.000000	.000000
X6	.000000	20.068000
X9	.000000	.000000
X11	.000000	.000000
X12	.000000	11.140000
X14	.000000	.000000
X15	.000000	.000000
X16	.000000	.000000
X17	.000000	70.560000
X19	.000000	.000000
X20	.000000	61.420000
X23	184.500000	.000000
X24	172.500000	.000000
X26	.000000	.000000
X27	.000000	.000000
X28	.000000	.000000
X29	.000000	59.420000
X31	.000000	.000000
X32	.000000	45.120000



X35	.000000	.000000
X37	.000000	11.140000
X40	.000000	.000000
X41	.000000	34.040000
X43	12.000000	.000000
X46	.000000	.000000
X47	.000000	22.900000

ROW	SLACK OR SURPLUS	DUAL PRICES
-----	------------------	-------------

2)	.000000	.000000
3)	.000000	.000000
4)	.000000	-10.480000
5)	.000000	-5.288000
6)	.000000	.000000
7)	.000000	.000000
8)	.000000	.000000
9)	.000000	-2.291992
10)	.000000	.000000
11)	.000000	-.500000
12)	.000000	.000000
13)	.000000	.000000
14)	.000000	.000000
15)	.000000	.000000
16)	.000000	.000000
17)	.000000	.000000
18)	.000000	.000000
19)	.000000	.000000
20)	.000000	.000000
21)	.000000	.000000
22)	.000000	.000000
23)	315.500000	.000000
24)	315.500000	.000000
25)	327.500000	.000000
26)	327.500000	.000000
27)	.000000	.000000
28)	.000000	.000000
29)	.000000	.000000
30)	.000000	.000000
31)	.000000	.000000
32)	.000000	.000000
33)	.000000	.000000
34)	.000000	.000000
35)	.000000	.000000
36)	.000000	.000000
37)	.000000	-.500000

38)	.000000	.000000
39)	.000000	.000000
40)	.000000	.000000
41)	.000000	.000000
42)	.000000	.000000
43)	488.000000	.000000
44)	488.000000	.000000
45)	.000000	.000000
46)	.000000	.000000
47)	.000000	.000000
48)	.000000	-205.280000
49)	.000000	64.649990
50)	.000000	62.529990
51)	.000000	51.870000
52)	.000000	46.331990
53)	.000000	46.271990
54)	.000000	66.340000
55)	.000000	.000000
56)	.000000	43.910000
57)	.000000	43.910000
58)	.000000	62.529990
59)	.000000	73.670000
60)	.000000	62.529990
61)	.000000	62.529990
62)	.000000	62.529990
63)	.000000	133.090000
64)	.000000	62.529990
65)	.000000	123.950000
66)	.000000	73.670000
67)	.000000	73.670000
68)	.000000	73.670000
69)	.000000	73.670000
70)	.000000	73.670000
71)	.000000	73.670000
72)	.000000	133.090000
73)	.000000	73.670000
74)	.000000	118.790000
75)	.000000	51.800000
76)	.000000	51.800000
77)	.000000	26.420000
78)	.000000	73.670000
79)	.000000	62.529990
80)	.000000	96.570000
81)	.000000	73.670000
82)	.000000	73.670000
83)	.000000	96.570000

NO. ITERATIONS= 208  
BRANCHES= 25 DETERM.= -39.063E 20  
BOUND ON OPTIMUM: 39057.12  
DELETE Y43 AT LEVEL 8  
DELETE Y44 AT LEVEL 7  
DELETE Y25 AT LEVEL 6  
DELETE Y24 AT LEVEL 5  
DELETE Y22 AT LEVEL 4  
DELETE Y3 AT LEVEL 3  
DELETE Y23 AT LEVEL 2  
DELETE Y8 AT LEVEL 1  
ENUMERATION COMPLETE. BRANCHES= 25 PIVOTS= 208  
  
LAST INTEGER SOLUTION IS THE BEST FOUND  
RE-INSTALLING BEST SOLUTION...

What'sBest! 5.0 Status Report

8/4/02 3:54 PM

Solver memory allocated: 16384

Model Type: LINEAR / INTEGER

The smallest and largest coefficients in the model were:

0.60000000E-01      6475.0000

The smallest coefficient occurred in constraint cell: Sheet1!F98  
on optimizable cell: Sheet1!F2

The largest coefficient occurred in constraint cell: Sheet1!BC98  
on optimizable cell: Sheet1!BC2

CLASSIFICATION STATISTICS      Current /    Maximum

Numeric	8865 /	10000
Adjustable	92 /	300
Constraints	91 /	150
Integers	30 /	30
Optimizable	569	
Nonlinear	0 /	30
Coefficients	1107	

Best integer value: 39057.12 @ 164 tries. Theoretical limit: 39057.12

Solution Status: GLOBALLY OPTIMAL.

Solution Time: 0 Hours 0 Minutes 1 Seconds

End of report.

(Corrected helicopter production estimates)

Output for What'sBest!®

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Decision Variables	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19
2		()	()	()	()	()	()	()	()	()	()	()	()	()	()	()	()	()	()	()
3																				
4	Constraints	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19
5	Consv. Flow Node 1	0																		
6	2	0	0																	
7	3		0	0								0								
8	4			0	0															
9	5				0	0			0											
10	6					0	0													
11	7						0	0												
12	8							0			0			0					0	
13	9								0	0										
14	10									0	0									
15	11											0	0		0					
16	12												0	0						
17	13														0					
18	14															0	0			0
19	15																0	0	0	
20	16																	0	0	
21	17																			0
22	18																			
23	19																			
24	20																			
25	21																			
26	22																			
27	23																			
28	24																			
29	25																			
30	26																			
31	27																			
32	28																			
33	29																			
34	30																			
35	31																			
36	32																			
37	33																			
38	34																			
39	35																			
40	36																			
41	Triggers Y1+Y22<1																			
42	Y11+Y3<1																			
43	Y14+Y37<1																			
44	Y14+Y12<1																			
45	Y43+Y26<1																			
46	Y26+Y24<1																			
47	Y5+Y8<1																			
48	Y16+Y19<1																			
49	Y28+Y31<1																			
50	500Y1-X1≥0	0																		
51	500Y2-X2≥0		0																	
52	500Y3-X3≥0			0																
53	500Y4-X4≥0				0															
54	500Y5-X5≥0					0														
55	500Y6-X6≥0						0													
56	500Y7-X7≥0							0												

Output for What'sBest!<sup>R</sup>

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
57	500Y8-X8≥0								0											
58	500Y9-X9≥0									0										
59	500Y10-X10≥0										0									
60	500Y11-X11≥0											0								
61	500Y12-X12≥0												0							
62	500Y13-X13≥0													0						
63	500Y14-X14≥0														0					
64	500Y15-X15≥0															0				
65	500Y16-X16≥0																0			
66	500Y17-X17≥0																	0		
67	500Y18-X18≥0																		0	
68	500Y19-X19≥0																			0
69	500Y20-X20≥0																			
70	500Y21-X21≥0																			
71	500Y22-X22≥0																			
72	500Y23-X23≥0																			
73	500Y24-X24≥0																			
74	500Y25-X25≥0																			
75	500Y26-X26≥0																			
76	500Y27-X27≥0																			
77	500Y28-X28≥0																			
78	500Y29-X29≥0																			
79	500Y30-X30≥0																			
80	500Y31-X31≥0																			
81	500Y32-X32≥0																			
82	500Y33-X33≥0																			
83	500Y34-X34≥0																			
84	500Y35-X35≥0																			
85	500Y36-X36≥0																			
86	500Y37-X37≥0																			
87	500Y38-X38≥0																			
88	500Y40-X40≥0																			
89	500Y41-X41≥0																			
90	500Y42-X42≥0																			
91	500Y43-X43≥0																			
92	500Y44-X44≥0																			
93	500Y46-X46≥0																			
94	500Y47-X47≥0																			
95	500Y48-X48≥0																			
96																				
97		x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19
98	Costs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
99																				

Output for What'sBest!<sup>®</sup>

	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
1	x20	x21	x22	x23	x24	x25	x26	x27	x28	x29	x30	x31	x32	x33	x34	x35	x36	x37	x38	x40	x41	x42
2	0	0	184.5	184.5	172.5	172.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3																						
4	x20	x21	x22	x23	x24	x25	x26	x27	x28	x29	x30	x31	x32	x33	x34	x35	x36	x37	x38	x40	x41	x42
5			184.5																			
6																						
7																						
8																						
9															0							
10																						
11																						
12		0				172.5					0			0								
13																						
14																						
15																		0				
16																						
17																				0		
18																						
19																						
20																						
21	0																					
22	0	0																				
23			184.5	-184.5																		
24				184.5	-172.5		0															
25					172.5	-172.5																
26							0	0														
27								0	0			0										
28									0	0												
29										0	0											
30												0	0									
31													0	0								
32														0	0							
33															0	0						
34																0	0					0
35																	0	0				
36																		0	0			
37																				0	0	0
38																					0	0
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53																						
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55																						
56																						

Output for What'sBest!<sup>R</sup>

	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
57																						
58																						
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60																						
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64																						
65																						
66																						
67																						
68																						
69	0																					
70		0																				
71			-184.5																			
72				-184.5																		
73					-172.5																	
74						-172.5																
75							0															
76								0														
77									0													
78										0												
79											0											
80												0										
81													0									
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85																	0					
86																		0				
87																			0			
88																				0		
89																					0	
90																						0
91																						
92																						
93																						
94																						
95																						
96																						
97	x0	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10	x11	x12	x13	x14	x15	x16	x17	x18	x19	x20	x21
98	0	0	24282.05	0	0	12708.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
99																						



Output for What'sBest!<sup>®</sup>

	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL
1	x43	x44	x46	x47	x48	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10	y11	y12	y13	y14	y15	y16	y17
2	12	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3																						
4	x43	x44	x46	x47	x48	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10	y11	y12	y13	y14	y15	y16	y17
5																						
6																						
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19																						
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21																						
22																						
23																						
24	-12																					
25																						
26			0																			
27																						
28																						
29																						
30																						
31																						
32																						
33																						
34		12			0																	
35																						
36																						
37																						
38	12	-12																				
39			0	0																		
40				0	0																	
41						0																
42								0								0						
43																			0			
44																	0		0			
45																						
46																						
47										0			0									
48																					0	
49																						
50						0																
51							0															
52								0														
53									0													
54										0												
55											0											
56												0										

Output for What'sBest!<sup>R</sup>

	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ	BK	BL
57													0									
58														0								
59															0							
60																0						
61																	0					
62																		0				
63																			0			
64																				0		
65																					0	
66																						0
67																						
68																						
69																						
70																						
71																						
72																						
73																						
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85																						
86																						
87																						
88																						
89																						
90																						
91	-12																					
92		-12																				
93			0																			
94				0																		
95					0																	
96																						
97	x43	x44	x45	x47	x48	y1	y2	y3	y4	y5	y6	y7	y8	y9	y10	y11	y12	y13	y14	y15	y16	y17
98	0	567	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
99																						

Output for What'sBest!<sup>®</sup>

	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH
1	y18	y19	y20	y21	y22	y23	y24	y25	y26	y27	y28	y29	y30	y31	y32	y33	y34	y35	y36	y37	y38	y40
2	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3																						
4	y18	y19	y20	y21	y22	y23	y24	y25	y26	y27	y28	y29	y30	y31	y32	y33	y34	y35	y36	y37	y38	y40
5																						
6																						
7																						
8																						
9																						
10																						
11																						
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14																						
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29																						
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31																						
32																						
33																						
34																						
35																						
36																						
37																						
38																						
39																						
40																						
41					1																	
42																						
43																			0			
44																						
45									0													
46							1		0													
47																						
48		0																				
49											0			0								
50																						
51																						
52																						
53																						
54																						
55																						
56																						

Output for What'sBest!®

	BM	BN	BO	BP	BQ	BR	BS	BT	BU	BV	BW	BX	BY	BZ	CA	CB	CC	CD	CE	CF	CG	CH
57																						
58																						
59																						
60																						
61																						
62																						
63																						
64																						
65																						
66																						
67	0																					
68		0																				
69			0																			
70				0																		
71					500																	
72						500																
73							500															
74								500														
75									0													
76										0												
77											0											
78												0										
79													0									
80														0								
81															0							
82																0						
83																	0					
84																		0				
85																			0			
86																				0		
87																					0	
88																						0
89																						
90																						
91																						
92																						
93																						
94																						
95																						
96																						
97	y1	y2	y3	y4	y22	y23	y24	y25	y26	y27	y28	y29	y30	y31	y32	y33	y34	y35	y36	y37	y38	y40
98	0	0	0	0	0	1500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
99																						

Output for What'sBest!<sup>®</sup>

	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW
1	y41	y42	y43	y44	y46	y47	y48								
2	0	0	1	1	0	0	0								
3															
4	y41	y42	y43	y44	y46	y47	y48					SUM	DIR	RHS	Units
5												184.5	#REF!	184.5	tons
6												0	#REF!	0	tons
7												0	#REF!	0	tons
8												0	#REF!	0	tons
9												0	#REF!	0	tons
10												0	#REF!	0	tons
11												0	#REF!	0	tons
12												172.5	#REF!	172.5	tons
13												0	#REF!	0	tons
14												0	#REF!	0	tons
15												0	#REF!	0	tons
16												0	#REF!	0	tons
17												0	#REF!	0	tons
18												0	#REF!	0	tons
19												0	#REF!	0	tons
20												0	#REF!	0	tons
21												0	#REF!	0	tons
22												0	#REF!	0	tons
23												0	#REF!	0	tons
24												0	#REF!	0	tons
25												0	#REF!	0	tons
26												0	#REF!	0	tons
27												0	#REF!	0	tons
28												0	#REF!	0	tons
29												0	#REF!	0	tons
30												0	#REF!	0	tons
31												0	#REF!	0	tons
32												0	#REF!	0	tons
33												0	#REF!	0	tons
34												12	#REF!	12	tons
35												0	#REF!	0	tons
36												0	#REF!	0	tons
37												0	#REF!	0	tons
38												0	#REF!	0	tons
39												0	#REF!	0	tons
40												0	#REF!	0	tons
41												1	#REF!	1	\$
42												0	#REF!	1	\$
43												0	#REF!	1	\$
44												0	#REF!	1	\$
45			1									1	#REF!	1	\$
46												1	#REF!	1	\$
47												0	#REF!	1	\$
48												0	#REF!	1	\$
49												0	#REF!	1	\$
50												0	#REF!	0	\$
51												0	#REF!	0	\$
52												0	#REF!	0	\$
53												0	#REF!	0	\$
54												0	#REF!	0	\$
55												0	#REF!	0	\$
56												0	#REF!	0	\$

Output for What'sBest!<sup>®</sup>

	CI	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW
57												0	#REF!	0 \$	
58												0	#REF!	0 \$	
59												0	#REF!	0 \$	
60												0	#REF!	0 \$	
61												0	#REF!	0 \$	
62												0	#REF!	0 \$	
63												0	#REF!	0 \$	
64												0	#REF!	0 \$	
65												0	#REF!	0 \$	
66												0	#REF!	0 \$	
67												0	#REF!	0 \$	
68												0	#REF!	0 \$	
69												0	#REF!	0 \$	
70												0	#REF!	0 \$	
71												315.5	#REF!	0 \$	
72												315.5	#REF!	0 \$	
73												327.5	#REF!	0 \$	
74												327.5	#REF!	0 \$	
75												0	#REF!	0 \$	
76												0	#REF!	0 \$	
77												0	#REF!	0 \$	
78												0	#REF!	0 \$	
79												0	#REF!	0 \$	
80												0	#REF!	0 \$	
81												0	#REF!	0 \$	
82												0	#REF!	0 \$	
83												0	#REF!	0 \$	
84												0	#REF!	0 \$	
85												0	#REF!	0 \$	
86												0	#REF!	0 \$	
87												0	#REF!	0 \$	
88												0	#REF!	0 \$	
89	0											0	#REF!	0 \$	
90		0										0	#REF!	0 \$	
91			500									488	#REF!	0 \$	
92				500								488	#REF!	0 \$	
93					0							0	#REF!	0 \$	
94						0						0	#REF!	0 \$	
95							0					0	#REF!	0 \$	
96															
97	y41	y42	y43	y44	y45	y46	y47	y48							
98	0	0	0	0	0	0	0	0				39057.12			
99															

**Appendix F: Output for NETWORK 2000 Model**

**Network 2000 - Best Routes**

The best solution has been found at 2 iteration of the shortest path algorithm.

The best routes found are:

<u>Sale #</u>	<u>Volume</u>	<u>Route</u>			
1	172.5	P -> TS2 -> SLBA -> SLBAD5 -> 5			
2	12.0	P -> TS2 -> SLBA -> SLBAD4 -> 4			
Total discounted variable cost			:	37557.12	( 203.56 \$/unit )
Total discounted fixed cost			:	1500.00	( 8.13 \$/unit )
Total discounted variable and fixed cost			:	39057.12	( 211.69 \$/unit )



Network 2000 - Link Report

Below list shows the links to be used in your project.

<u>From node</u>	<u>To node</u>	<u>Volume passed</u>	<u>Variable cost</u>	<u>Fixed cost</u>	<u>Lower limit</u>	<u>Upper limit</u>	<u>Open year</u>
P	TS2	184.5	131.6	0.0	0.	0.0	0
SLBA	SLBAD4	12.0	0.0	0.0	0.	0.0	0
SLBA	SLBAD5	172.5	0.0	0.0	0.	0.0	0
SLBAD4	4	12.0	47.3	0.0	0.	0.0	0
SLBAD5	5	172.5	73.7	0.0	0.	0.0	0
TS2	SLBA	184.5	0.0	1500.0	0.	0.0	0

## Network 2000 - Sale Report

## Detailed Sale Report :

## Sale Number : 1

* Route	:	P -> TS2 -> SLBA -> SLBAD5 -> 5
* Volume	:	172.50
* Year	:	0
* Variable cost	:	35410.80 ( 205.28 \$/unit )
* Fixed cost	:	1500.00 ( 8.70 \$/unit )
* Total cost	:	36910.80 ( 213.98 \$/unit )

## Sale Number : 2

* Route	:	P -> TS2 -> SLBA -> SLBAD4 -> 4
* Volume	:	12.00
* Year	:	0
* Variable cost	:	2146.32 ( 178.86 \$/unit )
* Fixed cost	:	0.00 ( 0.00 \$/unit )
* Total cost	:	2146.32 ( 178.86 \$/unit )

Total discounted variable cost	:	37557.12 ( 203.56 \$/unit )
Total discounted fixed cost	:	1500.00 ( 8.13 \$/unit )
Total discounted variable and fixed cost	:	39057.12 ( 211.69 \$/unit )

## Network 2000 - Year Report

## Year Report :

Discount rate : 0.00 %

Year : 0

<u>Sale No.</u>	<u>Volume</u>	<u>New links that should be opened in the current year</u>
1	172.50	P -> TS2, SLBA -> SLBAD5, SLBAD5 -> 5, TS2 -> SLBA
2	12.00	SLBA -> SLBAD4, SLBAD4 -> 4
Sub-total :	Volume	:
		184.50
	Discounted variable cost	:
		37557.12 ( 203.56 \$/unit )
	Discounted fixed cost	:
		1500.00 ( 8.13 \$/unit )
	Discounted variable and fixed cost	:
		39057.12 ( 211.69 \$/unit )

<b>Total Costs :</b>	Total discounted variable cost	:	37557.12 ( 203.56 \$/unit )
	Total discounted fixed cost	:	1500.00 ( 8.13 \$/unit )
	Total discounted variable and fixed cost	:	39057.12 ( 211.69 \$/unit )

**Appendix G: Time Study Forms**











## **AERIAL NUTRITION PRODUCTION STUDY**

### **Helicopter Non-Productive Time Elements**

#### **Element Codes:**

##### **Non-flight:**

- PF** = pre-flight prep and inspection
- W/C** = warm-up/cool down
- PT** = personal time/breaks
- MBG** = mobilization - drive to/from project area
- REF** = landed and refueling
- DEL** = delays
  - NH** = mechanical/repairs helicopter
  - NS** = mechanical/repairs support equipment
  - NB** = mechanical/repairs bucket/application equipment
  - NW** = waiting for support equipment/personnel to reach next set-up
  - NM** = waiting for delivery of materials
  - NT** = other

##### **Flight:**

- MBF** = mobilization - fly to/from project area from helibase
- TRU** = travel to next unit
- TRH** = travel to next heliport
- REG** = reconnaissance - general
- REU** = reconnaissance - unit boundary mapping, etc.
- CAL** = calibration
- ABR** = aborted delivery of load
- DEL** = delays
  - FS** = mechanical/repairs support equipment
  - FB** = mechanical/repairs bucket/application equipment
  - FW** = waiting for support equipment/personnel to reach next set-up
  - FM** = waiting for delivery of materials
  - FT** = other

**Appendix H: Ag-Nav<sup>®</sup> 2 Unit Maps**

16/1/2003

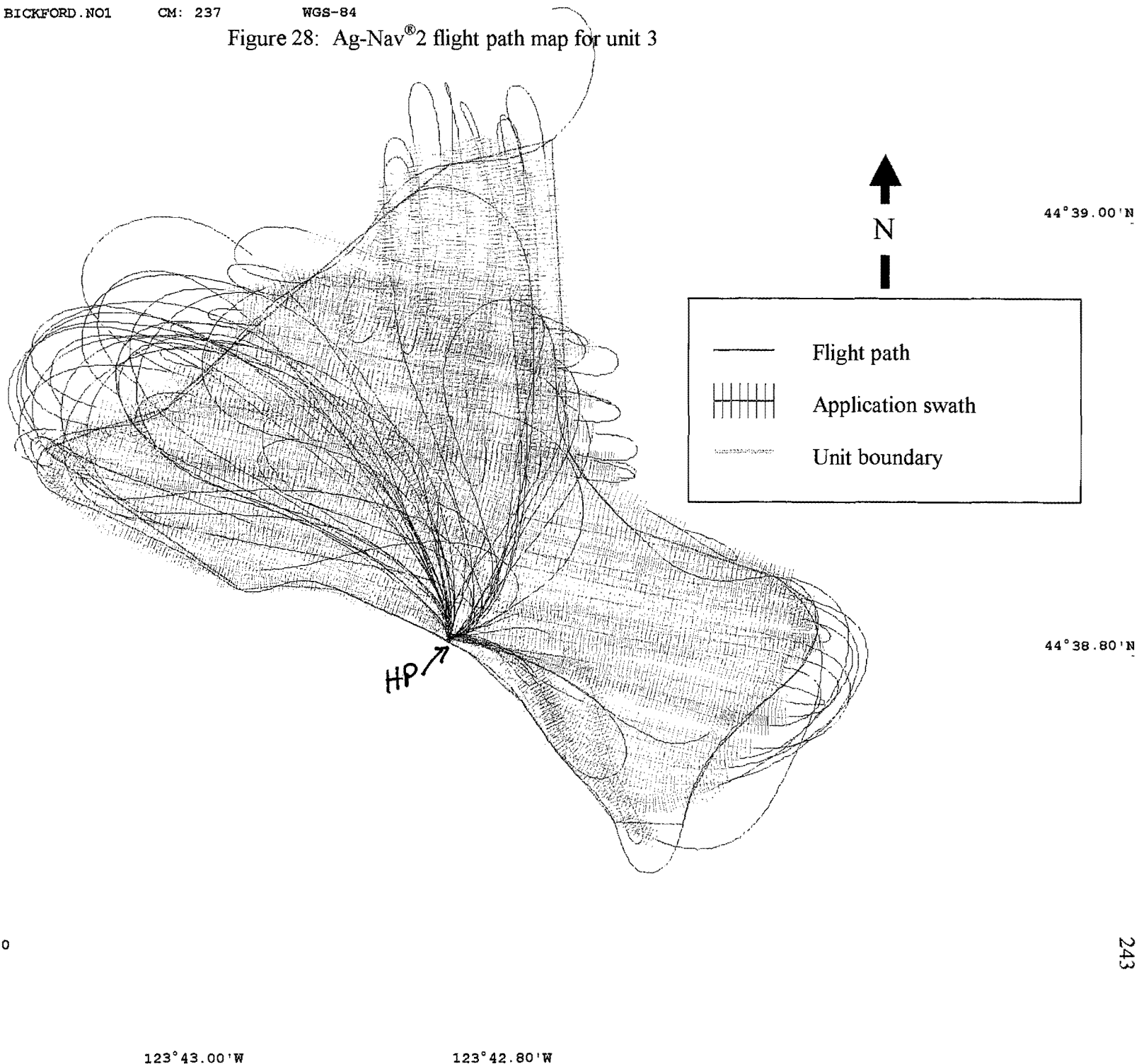
Area Name: BICKFORD.NO1

CM: 237

WGS-84

Figure 28: Ag-Nav<sup>®</sup> 2 flight path map for unit 3

Time Local 13:47:20.4  
Latitude 44°38.827'N  
Longitude 123°42.848'  
X\_UTM 443370  
Y\_UTM 4943999  
Altitude 1053 ft  
Area 38.3acrs  
AreaSprayIn 69.3acrs  
AreaSprayTot 76.4acrs  
SwathWidth 44.9 ft



16/1/2003

Area Name: NORTON.NO1

CM: 237

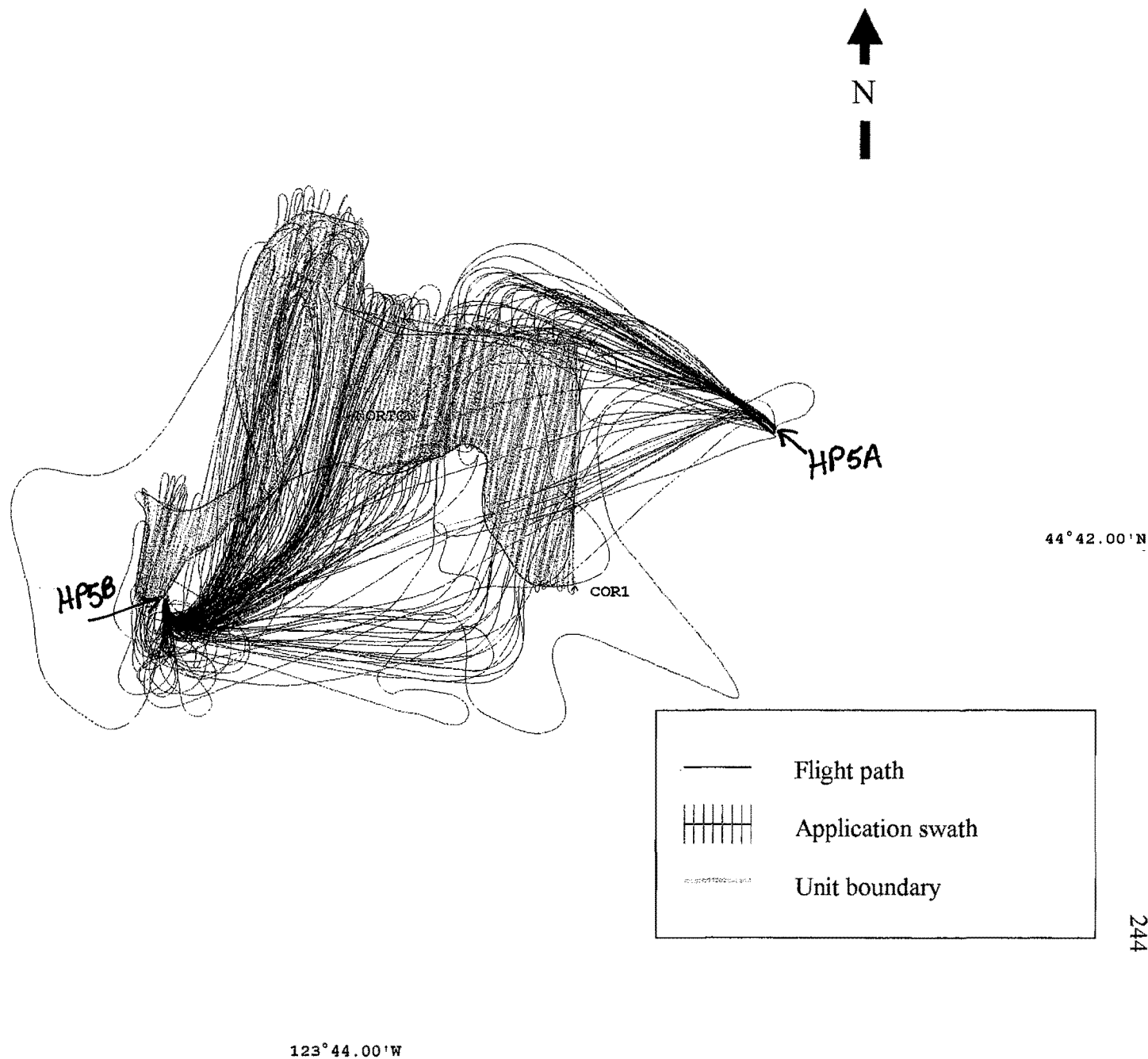
WGS-84

Counter 92222  
 Time Local 19:57:12.2  
 Time GPS 86232.20  
 Latitude 44°41.910'N  
 Longitude 123°44.533'  
 X\_UTM 441196  
 Y\_UTM 4949727  
 Altitude 1211 ft  
 Speed 38.4 mph  
 XTrack -1175 ft  
 TrackAngle 194  
 LockedLine 69  
 HDOP (Std) 1  
 Sats/TSLDU 8 / 6  
 Area/min 0.0acr/m  
 FlowRateApp 0.0gal/m  
 FlowRateReq 0.0gal/m  
 Sensitivity 0  
 Boom Pressure 0.0psi

Area 168.8acrs  
 AreaSprayIn 235.5acrs  
 AreaSprayTot 250.4acrs  
 SwathWidth 44.9 ft  
 AvgSprSpeed 42.6 mph  
 Rpm 0

Figure 29: Ag-Nav® 2 flight path map for unit 5

44°43.00'N



## **Appendix I: Flight Data Analyses**

I.1	Empirical Model Estimate Versus DGPS Data for Unit 3 and Unit 4.....	246
I.2	DGPS Flight Data With Acceleration/Deceleration for Unit 3.....	249
I.3	Visual Inspection of 50-cycle Data Sample Plots to Meet Regression Assumptions.....	251
I.4	50-cycle Sample Regression: Extra Sum-of-Squares F-test.....	255

## **I.1 Empirical Model Estimate Versus DGPS Data for Unit 3 and Unit 4**

Figure 30: Empirical model estimate and flight data for unit 3

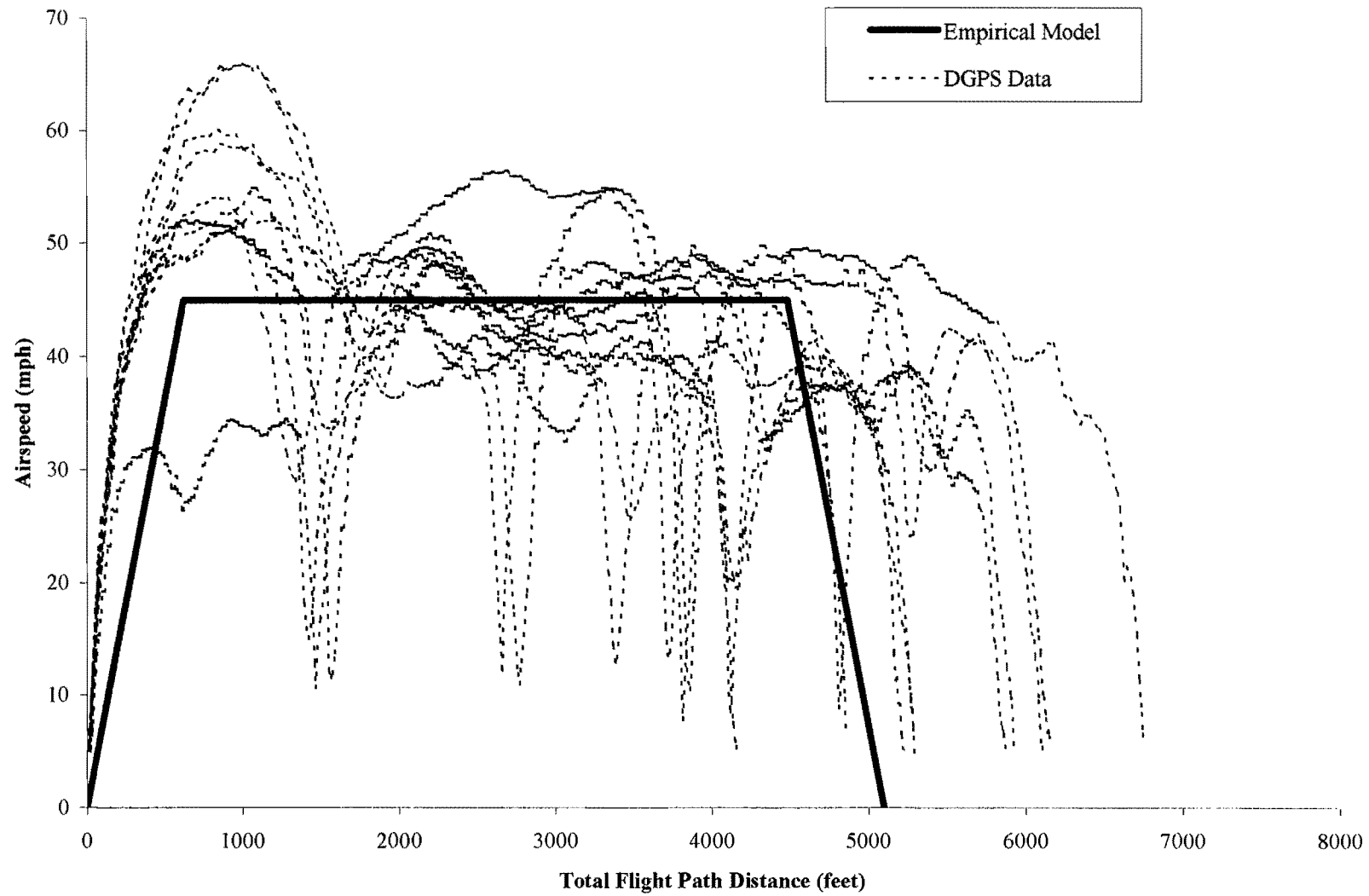
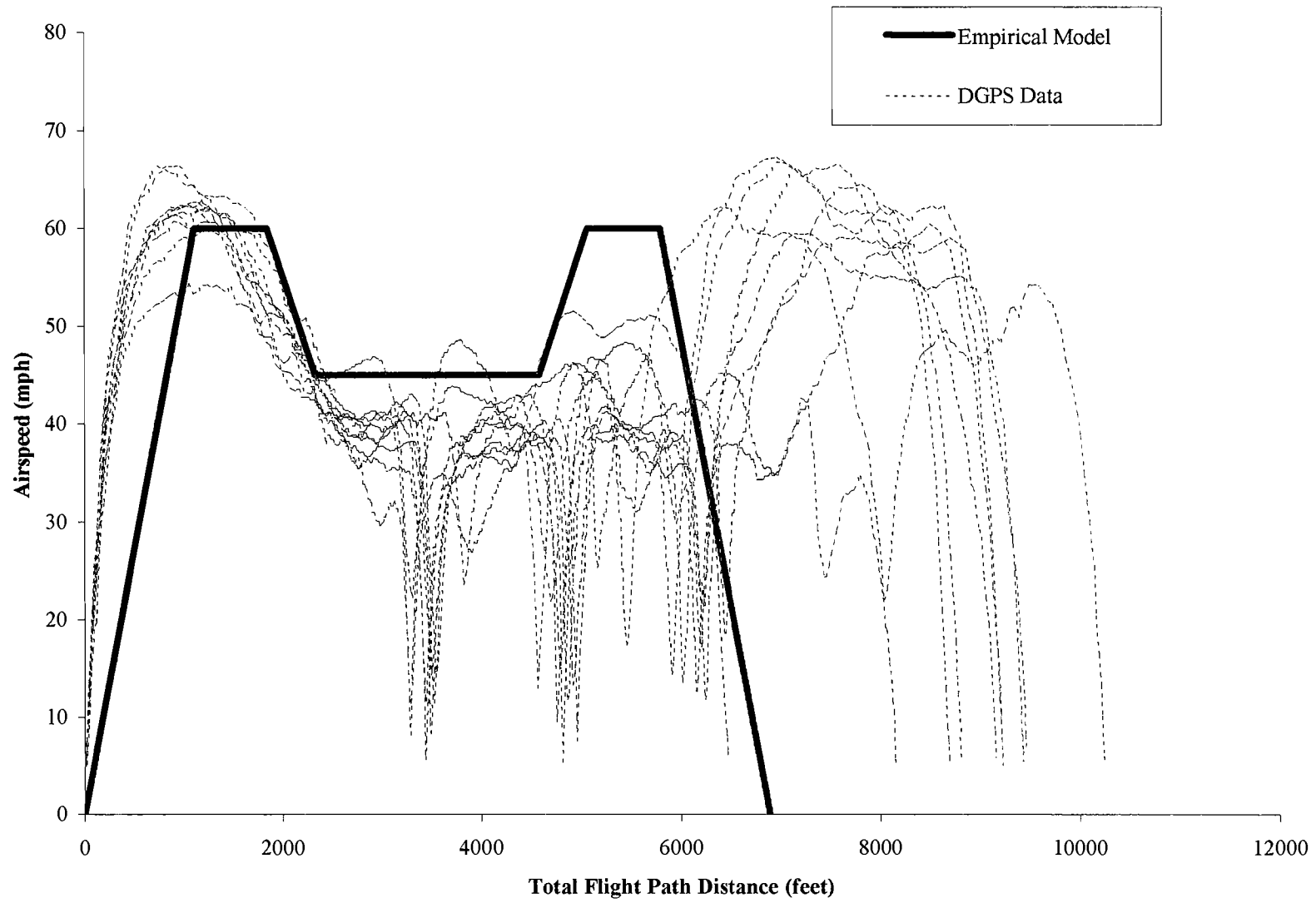


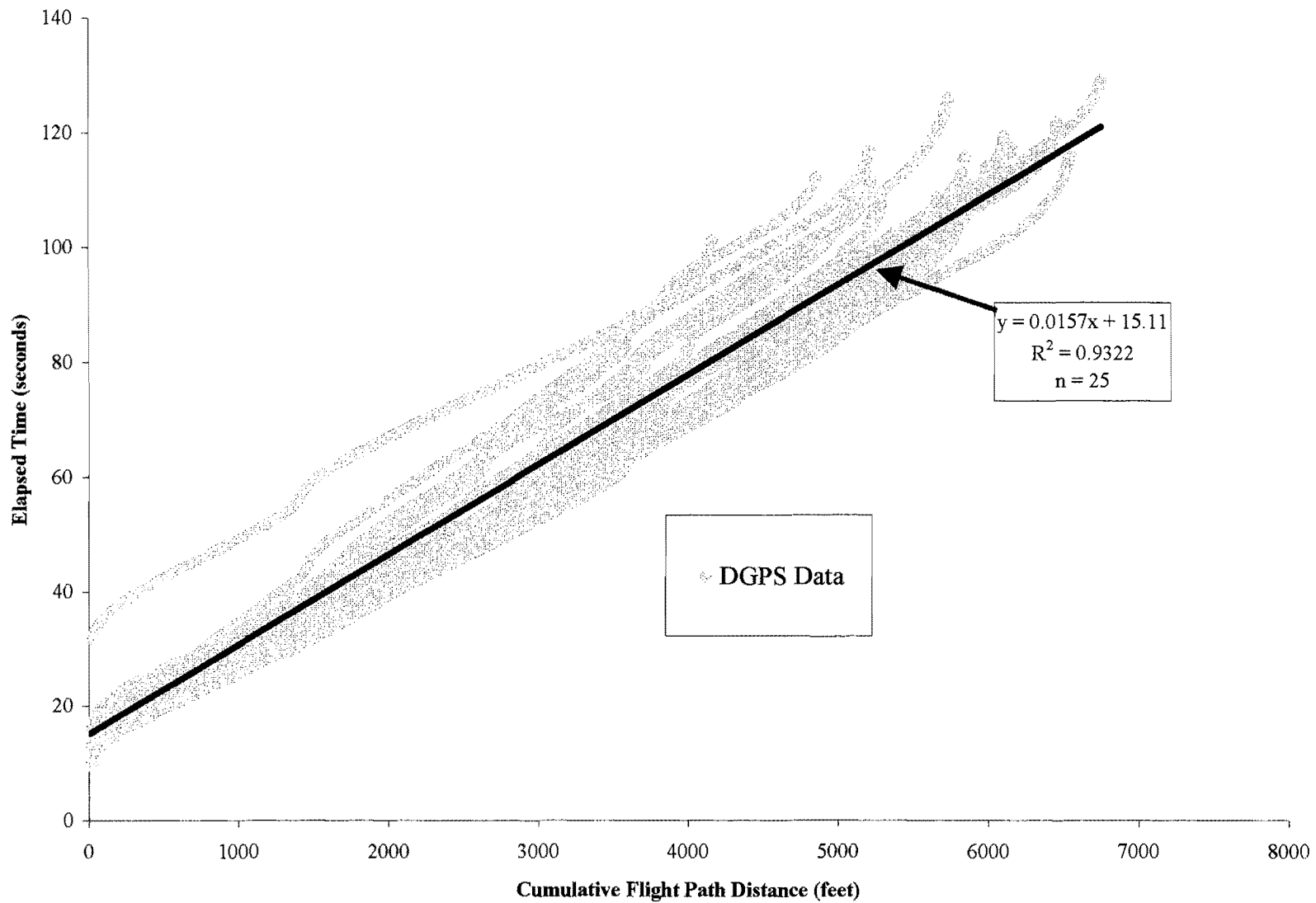
Figure 31: Empirical model estimate and flight data for unit 4





**I.2 DGPS Flight Data With Acceleration/Deceleration for Unit 3**

Figure 32: DGPS flight data with acceleration/deceleration components included in elapsed cycle time for unit 3



### **I.3 Visual Inspection of 50-Cycle Data Sample Plots to Meet Regression Assumptions**

Figure 33: Box plots of 50-cycle data samples

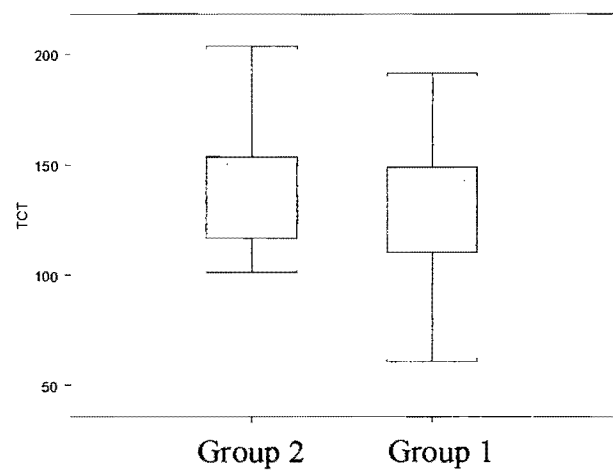


Figure 34: Matrix of scatterplots for full regression model

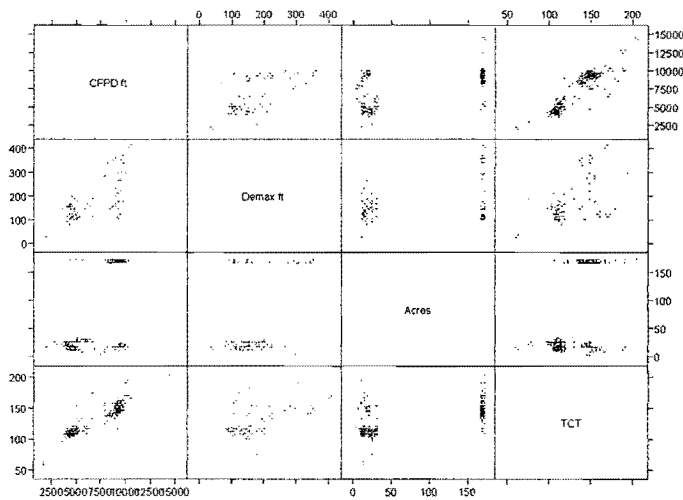


Figure 35: Residuals plot for 50-cycle data sample (Group 1)

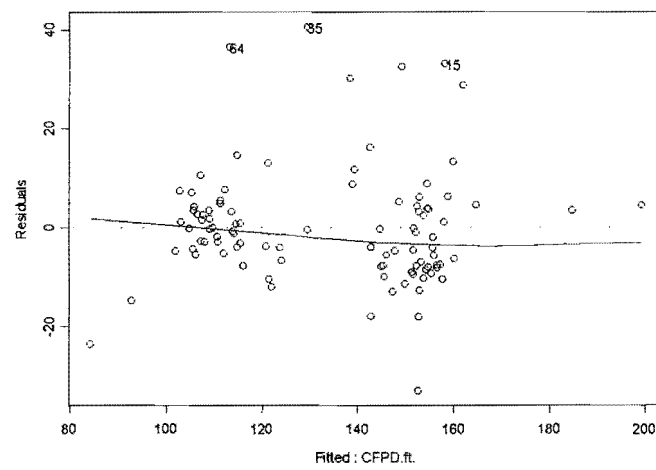


Figure 36: Normal QQ plot for 50-cycle data sample (Group 1)

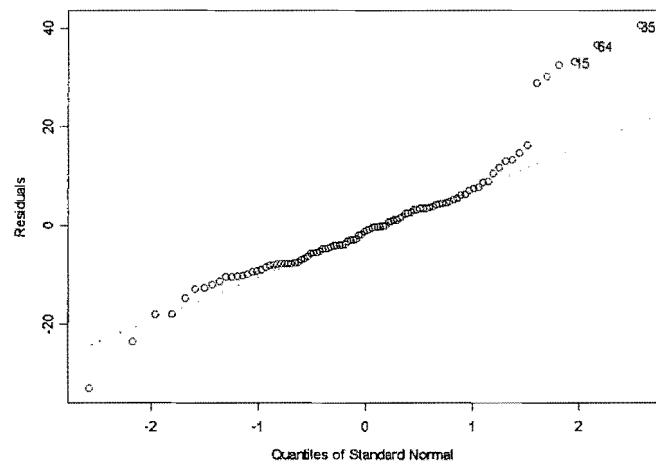
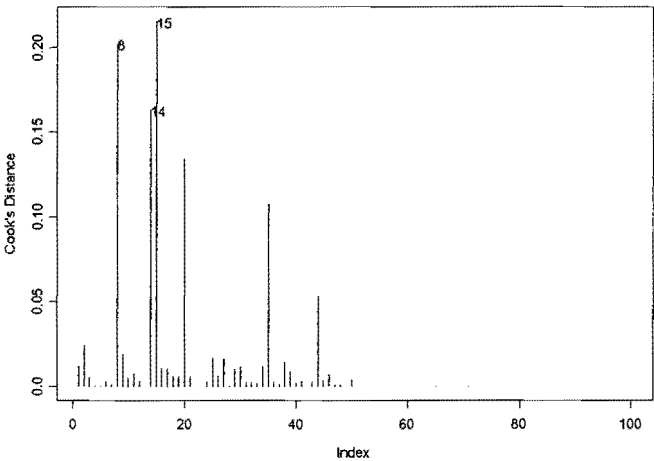


Figure 37: Cook's distance plot of 50-cycle data sample (Group 1)



#### I.4 50-Cycle Sample Regression: Extra Sum-of-Squares F-test

From Ramsey and Schafer (1997):

The  $F$ -statistic is the extra sum of squares per extra degree of freedom, scaled by the best estimate of variance. The extra sum of squares is the single number that summarizes the difference in sizes of the residuals from the full and reduced models.

$$\text{F-statistic} = \frac{(\text{Extra sum of squares})/(\text{Extra degrees of freedom})}{\text{est } \sigma_{\text{full}}^2}$$

or

$$\text{F-statistic} = [(RSS - FSS)/(df_R - df_F)]/(FSS/df_F)$$

where:

$\text{est } \sigma_{\text{full}}^2$  = estimate of residual standard error of full model

RSS = residual sum of squares from reduced model

FSS = residual sum of squares from full model

$df_R$  = degrees of freedom of reduced model

$df_F$  = degrees of freedom of full model

Full model = linear regression with 3 variables: cumulative flight path distance, maximum difference in elevation on flight path, acres

Reduced model = linear regression with 1 variable: total flight path distance

From S-Plus®2000 output:

$$RSS = 7666.54$$

$$FSS = 7545.10$$

$$df_R = 48$$

$$df_F = 46$$

then:

$$\text{F-statistic} = [(7666.54 - 7545.10)/(48-46)]/(7545.10/46) = 0.370198 = F_{2,46}$$

From S-Plus<sup>®</sup>2000:

The p-value for  $F_{2,46} \geq 0.370198$  is  $= 1 - 0.3073638 = 0.6926362$

Therefore:

The high p-value ( $> 0.05$ ) indicates the reduced model should be accepted over the full model.