AN ABSTRACT OF THE THESIS OF

James E. Ammeson for the degree of Master of Forestry in Forest Engineering presented on May 7, 1984.

Title: A Production Study of the Pendulum Balloon Logging System

Abstract approved: Eldon D. Olsen
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The purpose of this paper is to compare the estimated production of the pendulum swing logging system to the production of a conventional balloon logging system.

Cycle Time is established for the conventional system by time study techniques. A combination approach is used to model the pendulum system. A computer model simulates the mechanics of the inhaul and outhaul elements. The time study data from the conventional system is used to estimate the remainder of the cycle time for the pendulum system. Net payloads are calculated for both systems by a static analysis.

The calculations show the pendulum system to be more productive when yarding distances are less than 1200 feet. The production calculations show the conventional system to be more productive when yarding distances exceed 1200 feet.

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Typed by Mary Ann (Sadie) Airth for James E. Ammeson

A Production Study of the Pendulum Balloon Logging System

by

James E. Ammeson

in partial fulfillment of
the requirements for the
degree of

Master of Forestry

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I would like to express my personal appreciation to those who helped me with my project. Brian Tuor assisted with the field work and provided counsel when needed. Faye Stewart and everyone at Flying Scottsman Inc. were courteous and helpful during my time study of their operation. I am further indebted to the members of my graduate committee, Professor John O'Leary, Professor Robert Phelps, and Dr. Tom West for their support and expertise. Lastly, I would particularly like to thank my major professor, Dr. Eldon Olsen, whose help was invaluable.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In 1974, Mr. John Bell proposed and patented a new logging system which he named "The Aerial Load Lifting and Transportation Method and System" (US Patent Number 3807577). Mr. Bell also coined the name pendulum swing for his proposal. The pendulum swing refers to a primary operational feature of the system.

The pendulum system uses a tethered balloon to generate lift. In a logging application, a turn of logs could be fully suspended by the lift provided by the balloon. The log turn would be directed to the landing in much the same fashion as is done in traditional high lead logging.

Mr. Bell has hypothesized that this system has significant advantages over the long reach systems currently in use. Mr. Bell provided funds for the Forest Engineering Department at Oregon State University to investigate the feasibility of the pendulum system.

This study is the last of four studies designed to determine the effectiveness of the pendulum swing concept (Tour 1984, Beary 1983, Avery 1984). The results of this study have been integrated into a report authored by Dr. Eldon Olsen of Oregon State which summarizes the technical and economic feasibility of the pendulum system (Olsen, 1984).

STATEMENT OF OBJECTIVE

The study was set up with the following objectives:

1. Establish mathematical relationships to describe conventional balloon logging productivity.
2. Develop a model which will describe the operational characteristics of the pendulum system. This includes predicting average turn time and system payload.
3. Compare the productivity of the pendulum configuration to the conventional system.
4. Evaluate the pendulum swing system as a harvesting tool. Suggest limitations and possible improvements.

The foundation of this study is the contention that the pendulum swing system must be competitive with conventional balloon yarding. That is, the pendulum system must be superior to conventional technology in certain field conditions to merit further development.

SCOPE

The conventional balloon logging production data was gathered on an operation in southwestern Oregon. The results of this study are limited to the yarding configuration and field conditions observed.

Several assumptions are made to facilitate modeling the pendulum system.

1. Groundslope is a constant 60%.
2. Full log suspension is required.
3. Harvest method is clearcut.
4. Yarding is downhill to a single haul road.

A computer simulation model is developed to evaluate the pendulum system. The program simulates a Thunderbird TMY-70 yarder rigged in the pendulum swing configuration. The TMY-70 yarder was chosen because of its high horsepower and fast linespeeds. Appendix A has a more complete machine description. The results from the model are only applicable to the machine and configuration described. The engineering mechanics approach used to develop the model could, however, be tailored to fit other conditions.

LITERATURE REVIEW

Initial research on the pendulum concept began soon after the system was proposed in 1973. The Pacific Northwest Experiment Station (PNW) of the U.S. Forest Service worked on sizing equipment needs and estimating theoretical payload capabilities. The PNW engineers concluded the system had potential for both success and problems. It was felt that further testing was needed. The Forest Service Logging systems group at Oregon State University made a more through examination of theoretical payloads and line forces. The study revealed that the work to date had oversimplified the static conditions associated with the pendulum system.

Avery (1984) developed a computer model which calculates potential balloon lift for any load point given the geometry of the setup. The model uses an iterative procedure to solve for a system in static equilibrium. Catenary equations are used to model line tensions. The model does not include operating lines such as the mainline or haulback in determining the force balance.

Beary (1984) developed a relationship which quantified the expected centrifugal force on the pendulum line during the swing operation. The relationship illustrates that pendulum line tension could increase a maximum of 60% during a free swing. If a controlled swing is assumed so that the yarder provides positive control of the log turn at all times, swing velocity would be limited to about 1/4 of the potential free swing velocity. Centrifugal acceleration is proportional to the square of the velocity. The additional pendulum line tension for the controlled swing case is about 1/16 of the maximum calculated for the free swing. The controlled swing is assumed in my analysis so centrifugal force will be neglected.

Tuor (1984) conducted field tests of the pendulum swing configuration. A 37,000 cubic foot balloon was used. Static tests were made to measure line tensions as the balloon was rigged in various configurations.

Olsen (1984) authored two reports which summarized the engineering and economic feasibility of the pendulum swing concept. Olsen synthesized information from Avery (1984), Beary (1984), Tuor (1984), and this report. Additional research is reported concerning the effects of weather, system cost and delay time for both the pendulum and conventional balloon systems.

Swan and Danler (1984) completed a preliminary feasibility study for fitting computer controls to the pendulum swing system. The computer control system would coordinate the movement of the mainline, haulback line, and lifting line to maximize efficiency. The authors conclude that a computer control system appears feasible although additional research is needed. My analysis assumes efficient coordination of the operating lines whether control is achieved by an operator or a computer system.

SYSTEM DESCRIPTION

The Pendulum Swing System

The pendulum balloon system is illustrated in Figure 1. Major components of the system are a 1.1 million cubic foot natural shaped balloon, three or more kevlar guylines, and a conventional 4 drum yarder. A more complete list of equipment is in Appendix A.

The helium filled balloon is held in a relatively fixed position 1000-1500 feet above the ground by the guylines. One guyline is attached to a portable winch capable of spooling the entire length of guyline to facilitate repositioning and retrieving the balloon. The remaining guylines are anchored to stumps or other suitable anchoring devices.

An inverted tyler system (Olsen, 1984) is used to transfer lift from the balloon to the load and as a means of yarding. See Figure 2 for a detailed view of the inverted tyler system.

Downhill yarding is preferred. Uphill yarding is feasible but the intrinsic values of the pendulum swing are minimized.

A typical yarding cycle begins with the outhaul of the carriage. The carriage is pulled out to the hook site by inhauling the haulback line. The lifting line is used to control carriage clearance during the outhaul operation. The carriage has chokers attached and the hooking operation is essentially the same as for high lead logging. When the logs are hooked, lift is generated by tensioning the lifting

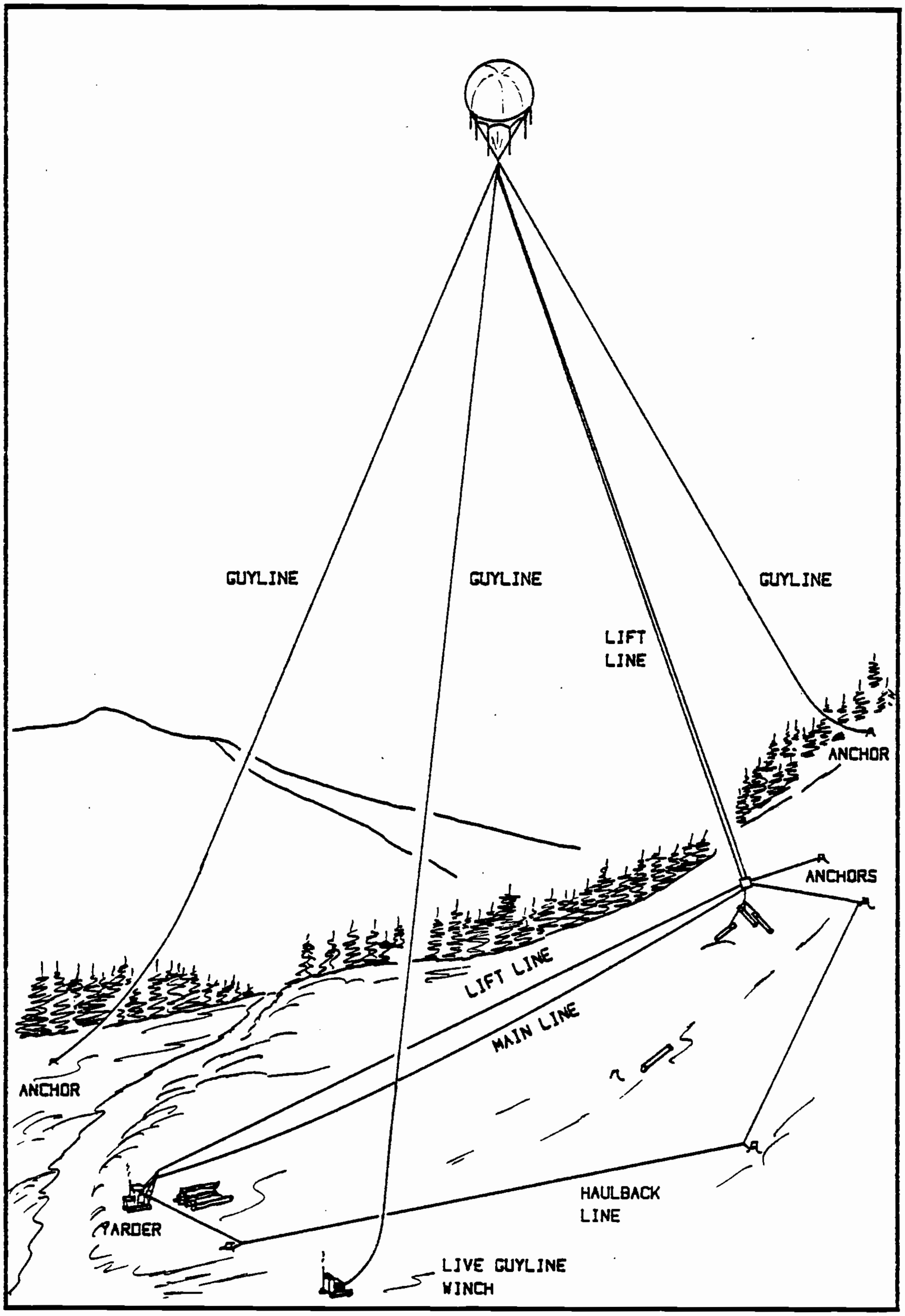


Figure 1

Pendulum Swing Balloon Logging System

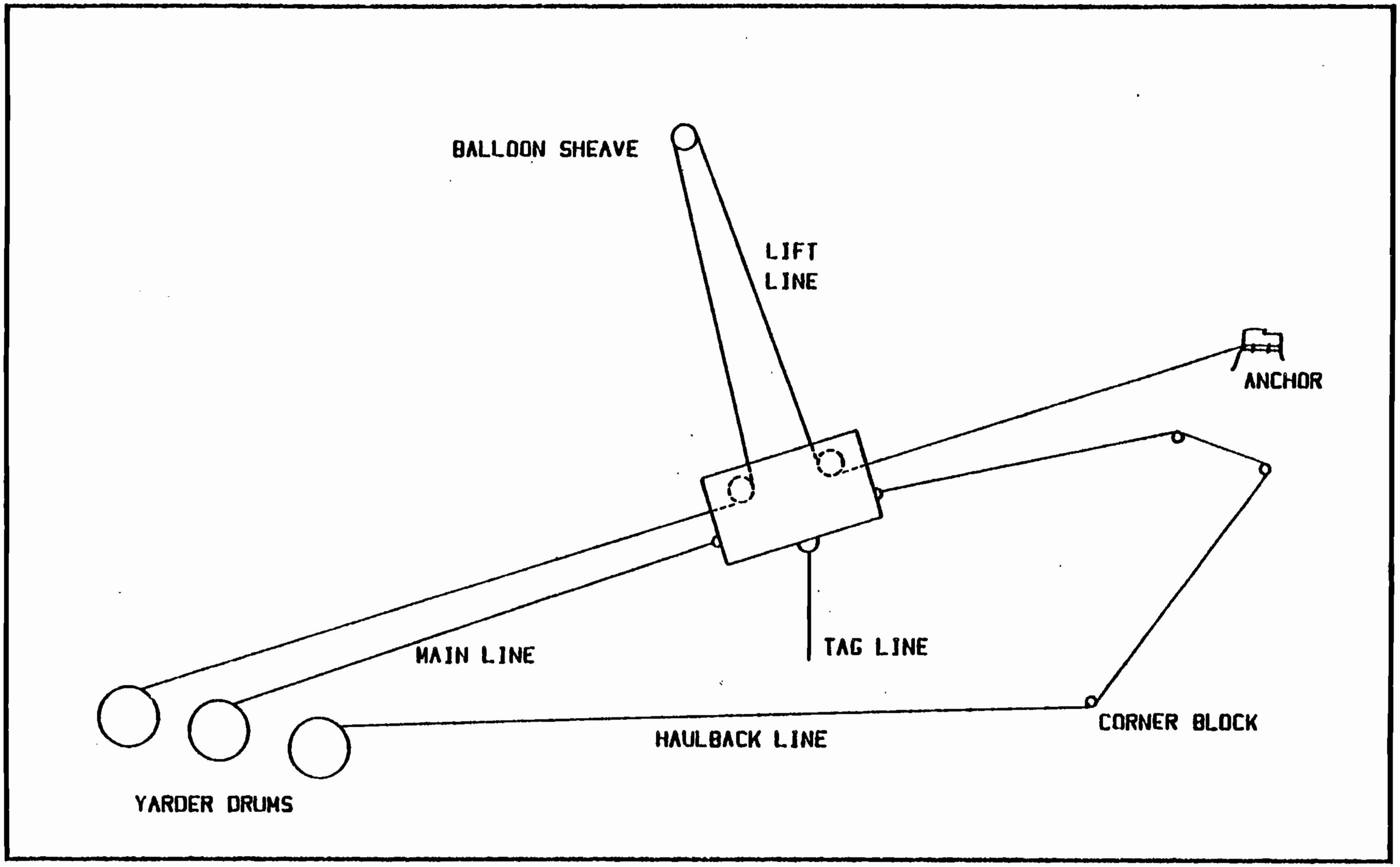


Figure 2
Inverted Tyler Rigging

line. Inhaul is accomplished by a combination of the pendulum swing and inhauling the mainline. Note that for downhill logging, the lifting line would have to be continuously let out to keep the log turn a constant height above the ground.

The Conventional Balloon System

A conventional balloon logging system is used as the basis for modeling and comparing the pendulum system. Figure 3 illustrates a conventional balloon logging operation rigged in the "Yo-Yo" configuration. Major components of the system are a 530,000 or 620,000 cubic foot natural shaped ballon and two large single drum yarders. The yarders pull the balloon to and from the landing in a yo-yo like fashion. The Yo-Yo system requires two yarder engineers. Communication between yarder engineers and with the woods crew is accomplished by two-way radio. A grapple skidder is required to swing logs from the landing to the processing area. See Appendix A for a complete list of equipment.

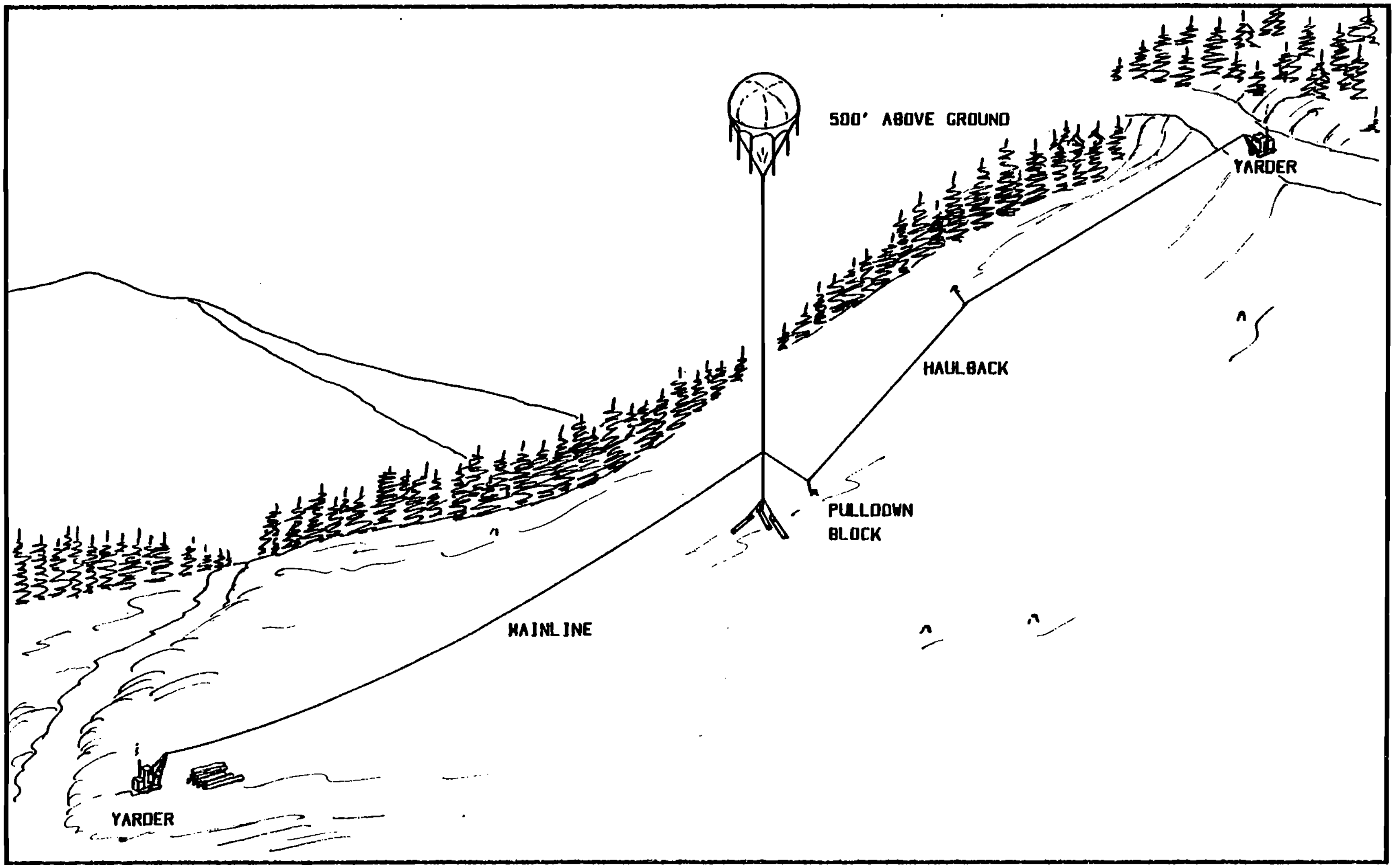


Figure 3
Yo Yo Balloon Logging System

THE STANDARD HARVEST UNIT

A simplified standard harvest unit is used for the pendulum swing analysis. A standard rigging configuration is also assumed. Figure 1 illustrates the general concept. The two front guylines are anchored 1000 feet apart. The back guyline is anchored 3000 feet upslope and is centered on the unit. The balloon is 1500 feet above the ground at a point 1200 feet from the landing.

This configuration has proved to be optimal in the production calculations for yarding distances of about 3000 feet. It is felt the pendulum system must be capable of external yarding distances of at least 2500 feet to be competitive.

TIME STUDY OF THE CONVENTIONAL SYSTEM

A detailed time study was done on a conventional balloon logging system in the Yo-Yo configuration. The yarding cycle was subdivided into elements. Time was recorded for each element using the snapback method of timekeeping. All data was collected by one recorder stationed at the landing.

Log volumes were estimated by measuring small end diameter and total log length. Log volumes were calculated using the Scribner log rule. The estimate was checked by comparing measured volume to the scaling tickets for the trucks loaded out during the study.

Data was collected on a Bureau of Land Management (BLM) timber sale on the Coos Bay district in southwestern Oregon. The logging contractor was Flying Scottsman of Eugene, Oregon. Data was collected on four yarding corridors which took nine days in June of 1983. Yarding was downhill and the average slope was about 50%.

The timber in the harvest area was primarily old growth Douglas-fir (*Pseudotsuga menziesii*) with small components of western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*) and red alder (*Alnus rubra*). The BLM timber cruise estimated the gross standing volume to be 74 Mbf/acre. The harvest prescription was clearcut.

Element Description

Two types of time are recognized in the time study, productive and nonproductive time. Productive time is further subdivided into elements.

Outhaul

The time required to return the rigging from the landing to the hook point. Outhaul begins when the mainline yarder begins unspooling the mainline and ends when the mainline yarder stops.

Position Rigging

The time required for the yarder engineers to lower the rigging to the hooktender after outhaul. This element begins at the end of outhaul and ends when the hooktender first touches the rigging.

Hook

The time required to attach the logs to the hook. Hook begins when the hooktender first touches the rigging and ends on the slack the haulback signal. Chokers were generally preset one turn ahead for this operation. The use of one time study recorder precluded segregating many of the delays which occurred in the hook element. Delays visible from the landing were recorded.

Slack the Haulback

The haulback line is slacked prior to inhaul so the balloon will lift and break the turn of logs out of its bed. This element begins on the "slack-the-haulback" signal and ends on the "ahead-on-the-mainline" signal.

Inhaul

The time required for the turn to travel to the landing. Inhaul starts on the "ahead-on-the-mainline" signal and ends when the mainline yarder stops reeling in line.

Load Positioning

The time required to position the incoming turn of logs so it sets down properly on the landing. This element does not occur on turns which can be inhauled onto the landing without any delay. Load positioning occurs when there are difficulties which are generally the result of an unusually heavy load or unfavorable wind conditions. Load positioning begins at the end of inhaul and ends when the turn is stationary on the landing.

Unhook

The time to unhook the logs from the rigging. Unhook begins when the turn is stationary on the landing and ends when outhaul begins.

Non Productive Time

Nonproductive time is that time which does not contribute directly to yarding production. Nonproductive time includes rigging time, mechanical downtime, and operational delays. Nonproductive time was recorded by cause of delay and time of delay.

Independent Variables

The independent variable measured to explain variation in turn time are summarized in Table 1.

The tagline consists of detachable 50 foot sections of wire rope which reach from the shackle where the mainline and haulback join to the rigging. Tagline length varied depending on the geometry of the particular setup.

Table 1

Independent Variables

Variable (Abbreviation)	Mean Value	Minimum Value	Maximum Value
Yarding Distance in feet (YDIST)	824	450	1500
Number of Logs/Turn (NOLOGS)	2.9	0	9
Total Volume/Turn in bd. ft. (TOTVOL)	1160	0	2600
Tagline Length in Feet (TAG)	270	50	450

Yarding distance was estimated by comparing the pickup points to measured landmarks in the unit. Several variables are not used in the analysis. Chordslope is not used because of the direct correlation with yarding distance. Crew size is not included because the size of the rigging crew did not vary from four. There may have been instances when the hooktender was not actually helping with the hooking operation but this was not readily apparent to the recorder on the landing.

Data Analysis

Data analysis was done using the least square regression technique. The stepwise method was used and the F statstic to enter was 4. Results are summarized in Tables 2 and 3. Calculated times are in minutes.

Several general items should be noted about the Yo-Yo system. As stated earlier, it was often impossible to segregate the position rigging and hook elements. When it was possible, position rigging time made up approximately 30% of the total hook time. The rigging was observed to swing several hundred feet laterally when the tagline was long and the wind gusty.

Another important problem the Yo-Yo system can have is in yarding the last several hundred feet before the landing. As the turn approaches the landing, the balloon is almost directly over the mainline yarder. This means the mainline yarder is primarily pulling the turn down instead of in. This makes landing the turns difficult if there is a wind which blows the balloon off to the side. Long taglines and heavy turns often exaggerate this problem.

Lastly, unhook time for conventional balloon logging is increased because of the shifting of the balloon. The balloon shifting will often cause the turn to bounce after it is seemingly stationary on the landing. This causes the landing chasers to be more cautious than is necessary on a typical cable operation.

An attempt was made to verify the time study information with published research. The Pansy Basin Study (Dykstra, 1975 and 1976) reports detailed time study results on a balloon logging system. It proved impossible to make a meaningful comparison because Dykstra observed a balloon system which utilized different equipment and a different rigging configuration.

Table 2

Regression Results

Element	Coefficient (Variable)	F Statistic	Sample Size	R^2(%)
Outhaul	0.3013 +0.00081 (YDIST)	87.95 484.57	311	61
Position Rigging	0.5503 +0.0020 (TAG)	- 8.54	79	10
Hook*	1.992 +0.3392 (NOLOGS)	348.57 123.43	288	30
Slack the Haulback	0.4941 +0.0408 (NOLOGS)	81.34 7.02	296	2
Inhaul	0.5071 +0.00078 (YDIST) +0.00015 (TOTVOL)	42.93 142.37 17.58	306	33
Load Position	0.1176 +0.00032 (TAG) +0.00006 (TOTVOL)	7.38 8.47 18.84	318	8
Unhook	0.1229 +0.2070 (NOLOGS)	3.54 125.91	315	29
Total Turn Time	2.826 +0.00216 (YDIST) +0.5777 (NOLOGS) +0.00050 (TOTVOL)	51.21 31.58 91.21 6.91	268	47

*Hook time includes Position Rigging time. The time study recorder was unable to segregate the Position Rigging and Hook elements for most of the turns.

Table 3

Ninety-five Percent Confidence Intervals

Element	Mean Value (Minutes)	Confidence Interval*** (Minutes)
Outhaul	0.96	0.94 < x < 0.99
Position Rigging	1.01	0.90 < x < 1.12
Hook*	2.98	2.86 < x < 3.10
Slack the Haulback	0.61	0.55 < x < 0.68
Inhaul	1.33	1.29 < x < 1.37
Load Position**		
Unhook	0.72	0.65 < x < 0.80
Total Turn Time	6.86	6.67 < x < 7.05

* Hook time includes the Position Rigging element.

** The Load Positioning element occurred in 24% of the turns. The mean value for each occurence was 0.96 minutes.

*** The confidence interval given is calculated when the predictor variables are at their respective mean values.

Nonproductive Time

Delays excluding road changes are reported in Table 4. Nine road changes were observed and reported in Table 5.

Several types of road changes were observed. Changing yarding roads requires a new corner block. A sucker down block is added to a

Table 4

Delays Excluding Road Changes

Type of Delay	% of Turns Delay Occurred in	Average Time of Delay (Min)
Rigging - includes changing chokers, sending out blocks and straps	6.7	1.23
Equipment - includes moving saws and tools with yarder	10.2	1.67
Reset - Delay caused by the inability to break a turn out on the first try	7.0	4.11
Tag - Add or remove sections of tagline	5.4	2.34
Miscellaneous and Unknown Delays	6.0	2.12
Average*	35.0	2.48

*More than one delay can occur in a turn so figures may not sum.

Table 5

Roadchanges

Roadchange No.	Type of Roadchange	Total Time (Min)
1	Add sucker down block	17.00
2	Change sucker down block	22.45
3	Change corner and sucker down blocks	78.90
4	Change corner block	45.32
5	Change corner block	39.41
6	Change corner block	32.00
7	Change corner block	18.70
8	Add side block	12.94
9	Add sucker down block	16.72

corner block to facilitate logging a portion of a corridor. A side-block may also be added to a corner block to facilitate logging an unreachable corner.

Nonproductive time is used to prorate delay free time to calculate actual production per hour. Olsen (1984) used this data in the utilization calculations for the Yo-Yo system.

PENDULUM CYCLE TIME

The time study is the basis for estimating cycle times for the conventional balloon. Because the conventional system is the basis of comparison, the analysis for the pendulum system will be structured around that done for the Yo-Yo. Each element will be discussed individually. Elemental estimates can then be summed to predict delay free turn times.

Outhaul and Inhaul

Inhaul and outhaul times are a function of system geometry, payload, and yarder capability. Inhaul and outhaul can be thought of as a two-part process.

Acceleration and deceleration take the same amount of time regardless of the yarding distance. In a regression equation, the constant expresses this "fixed" time of the element. The assumption is that the Pendulum swing will use the same fixed time as the Yo-Yo system. For the outhaul element, the constant is 0.30 minutes. For the inhaul element, the constant is:

$$0.51 + 0.000154 \text{ (Mean Volume/Turn)} = 0.69 \text{ minutes}$$

The portion of the element when the turn is traveling in at full velocity is the variable time of the element. Yarding distance directly effects variable time. Potential velocity is a function of the mechanics of the yarder. A computer simulation model is used to predict linespeeds. The analysis procedure is flowcharted in

Figure 4. See Table 6 for the definitions of the variables used in Figure 4 and for the following analysis. The analysis procedure is almost identical for the inhaul and outhaul elements. The inhaul simulation is developed in this paper.

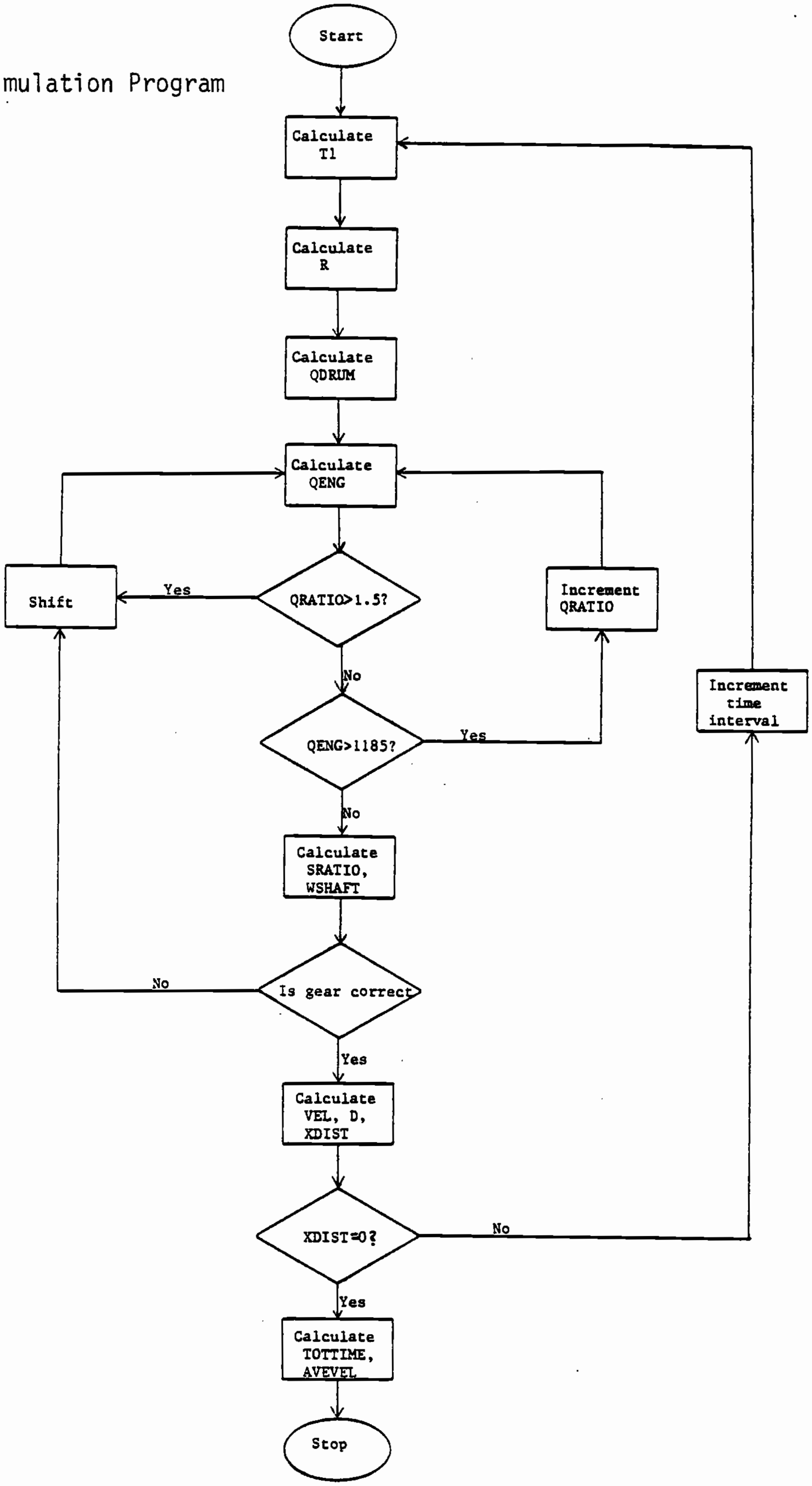
Table 6

Variables Used In Yarder Simulation

Variable	Definition	Units
Θ	Groundslope	Degrees
ϕ	Zenith angle made by a straight line from the carriage to the balloon	Degrees
Avevel	Average velocity for the carriage for in-haul	ft/min
D	Distance traveled by the carriage in a set time increment	ft.
EFF.	Drive train efficiency factor	-
GEAR	Gear reduction in transmission	-
GRD	Gear reduction at drum	-
GRDT	Gear reduction in drive train	-
N	Engine output shaft velocity	RPM
QDRUM	Torque required at drum	ft-lbs
QENG	Torque required of the engine	ft-lbs
QRATIO	Torque ratio in torque converter	-
R	Effective drum ratio of cable on the drum	ft.
SRATIO	Speed ratio in torque converter	-
T1	Tension in mainline	lbs.
T2	Tension in haulback line	lbs.
T3	Tension in lifting line	lbs.
TOTIME	Total time required to inhaul turn	min.
VEL	Average linespeed in set time increment	ft/min.
W(C)	Weight of carraige	lbs.
W(P)	Weight of payload	lbs.
WSHAFT	Velocity of output shaft of the transmission	RPM
XDIST	Distance from carriage to the yarder	ft.

Figure 4

Yarder Simulation Program



The linespeed the yarder can generate is a function of the line-pull required at a given instant. The simulation model is driven by the line tension generated by the carriage geometry. Line tensions are calculated using a static analysis. Figure 5 is a free body diagram of the carriage during inhaul. Refer to Figures 1 and 2 to compare the free body diagram to the system as a whole.

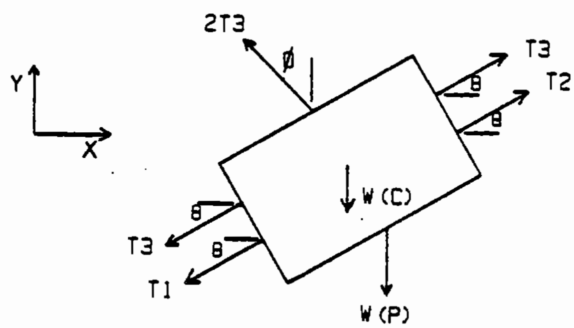


Figure 5. Free Body Diagram of the Carriage in Inhaul

Note that the lifting line actually has two segments that extend from the carriage to the balloon. The two segments are treated as a single force member for this analysis. The sheaves in the carriage are assumed to be frictionless. Additional assumptions are:

1. W(C) + W(P) = 20,000 lbs.
2. Θ = 30.96 (Ground angle for 60% slope)

Assumption 1 was checked against the payload analysis which is explained later in this paper. The maximum calculated theoretical payload (WC + WP) is 24,000 pounds. The increased payload increased the calculated inhaul time by about .3 minutes for a yarding distance of 1000 feet. This would increase the calculated cycle time by about 5% for a yarding distance of 1000 feet.

Summing the forces in the x and y directions results in equations 1 and 2. The angle ϕ is defined such that the sign of ϕ is positive when the lifting line is to the right of vertical. The sign of ϕ would be negative for the configuration shown in Figure 5.

$$T2\ (\cos\Theta) - T1\ (\cos\Theta) + 2T3\ (\sin\phi) = 0 \qquad (1)$$

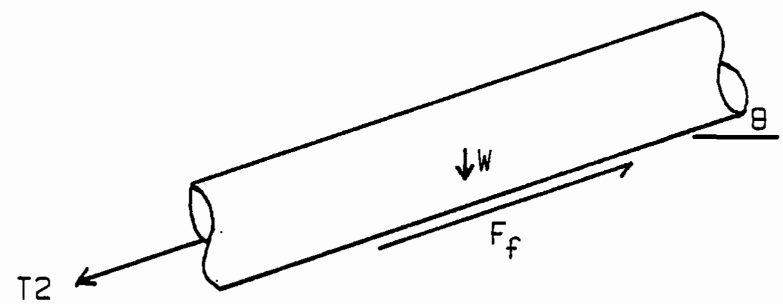
$$2T3\ (\cos\phi) + T2\ (\sin\Theta) - T1\ (\sin\Theta) - (W(C) + W(P)) = 0 \qquad (2)$$

Equation 3 is the result of combining equations 1 and 2.

$$T1 = \frac{T2\left(\frac{\cos\Theta}{\tan\phi}\right) - T2\sin\Theta + W(C) + W(P)}{\left(\frac{\cos\Theta}{\tan\Theta} - \sin\Theta\right)} \qquad (3)$$

The goal of the analysis is to solve equation 3 for T1. The variables T2 and ϕ are the unknowns in equation 3. The variable ϕ can be solved for by the known geometry of the setting. The haulback tension is calculated by the following analysis.

During inhaul, the haulback line is free spooling off the yarder. The force that is generated in the haulback which resists inhaul is a function of the length of line strung out on the setting. Figure 6 is an illustration of the forces involved. It is assumed the entire length of haulback line is dragging on the ground.



T2 - Haulback tension

F_f - Friction force

W - Weight/unit length of haulback

Θ - Angle made by ground

Figure 6. Free body diagram of unit length of haulback.

An expression for T2 can be written:

$$T2 = F_B + F_f + Fu$$

where F_B - Body force of haulback line

Fu - Force required to unspool line off yarder.

This equation can be rewritten to account for the length of line involved.

$$T2 = W \sin \Theta \, (HB_1 - HB_2) + uw \cos \Theta \, (HB_T) + 500$$

where: HB_T - Total length of haulback line strung out on the setting

HB_1 - Length of haulback between the tailblock and yarder.

HB_2 - Length of haulback between tailblock and carriage.

u - Coefficient of kinetic friction

500 - Assumed Fu

Iff (1977) measured a coefficient of kinetic friction of .43 for dragging wire rope on the ground. Different values were tried for HB_T, HB_1 and HB_2 which depended on carriage location in the corridor. It was found that 3500 pounds was the maximum value for T2 for 3/4 inch line and a yarding distance of 2500 feet.

Equation 3 can now be solved for mainline tension (T1). Note that there are two general cases in the solution for T1. When the carriage is in the back of the unit (ϕ is negative), there is a force imbalance in the negative X direction. This implies that the force required to achieve inhaul in the back of the unit is provided by the force imbalance. It is assumed the control of the carriage is provided by tensioning the haulback. The mainline tension required in this case is negligible. The second case of the analysis is when the carriage is in the front of the unit (ϕ is positive). In this instance, there is no force imbalance and equation 3 can be solved directly for T1.

Mainline tension at the yarder is needed to drive the yarder simulation model. If it is assumed that the mainline acts as a catenary:

$$T1_{(y)} = T_1 - (W*XDIST*\sin \Theta)$$

where: $T1_{(y)}$ = Mainline tension at the yarder

Torque required at the yarding drum can be calculated if the effective radius of the cable wrapping onto the mainline drum is known. It is a simple matter to estimate effective radius when the size of the drum, the size of the line, and the length of line on the drum is known. The expression for torque required at the drum (QDRUM) is:

$$QDRUM = T1_{(y)}*R$$

Equation 4 is the expression for torque required of the engine (QENG).

$$QENG = QDRUM*EFF/(GRD*GRDT*GEAR*TRATIO) \quad (4)$$

The simulation program iterates through the different transmission gear ratios and torque ratios until the torque required of the engine is within the performance limits of the engine. The iteration routine begins in the highest gear, tries all the torque ratios up to 1.5, and then shifts into the next highest gear. The process is continued until the gear and torque ratio is found which reduces the torque required of the engine to within the performance limits of the engine. The Thunderbird yarder modeled in the simulation uses a Detroit engine that can produce 1185 foot-lbs. of torque at full throttle and full load. A torque ratio limit of 1.5 is assumed because torque converter efficiency drops significantly beyond this point.

It is now possible to calculate the linespeed the yarder can generate. The engine RPM and the speed ratio of the torque converter must be known to calculate the velocity of the output shaft of the transmission. Data provided by the manufacturer suggests a strong relationship between torque ratio which is known and speed ratio. Figure 7 shows a linear fit that was done by the least squares regression method. The data points shown are from a pump absorbtion chart provided by the manufacturer. Equation 5 is the mathematical representation of the line illustrated in Figure 7.

$$SRATIO = 1.65143 - .77082\ (QRATIO) \tag{5}$$

It was also noted from the information provided by the manufacturer that there is a strong relationshp between SRATIO and the velocity of the engine output shaft in RPMs(N). Figure 8 is a plot of a least squares polynomial fit of the data. The equation of the line illustrated in Figure 8 is given in equation 6.

$$N = 2014.7-1879.1(SRATIO)+2136.1(SRATIO)^2 \tag{6}$$

The velocity of the output shaft of the transmission is given by equation 7.

$$WSHAFT = N*SRATIO/GEAR \tag{7}$$

The Allison transmission used in the Thunderbird yarder uses output shaft velocity to determine the shift points in the transmission. The gear ratio is now compared with the calculated WSHAFT. If the gear is not correct, the computer program iterates through the loop shown in Figure 4 until the correct gear is determined.

The linespeed generated by the yarder can now be calculated by equation 8.

$$Vel = WSHAFT*2*\ *R/(GRD*GRDT) \tag{8}$$

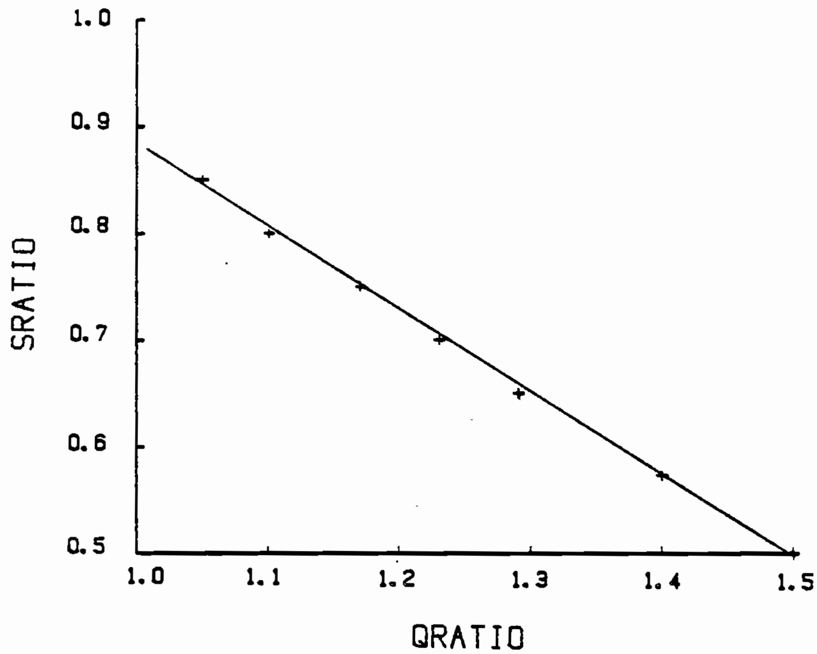


Figure 7. Torque Ratio vs. Speed Ratio

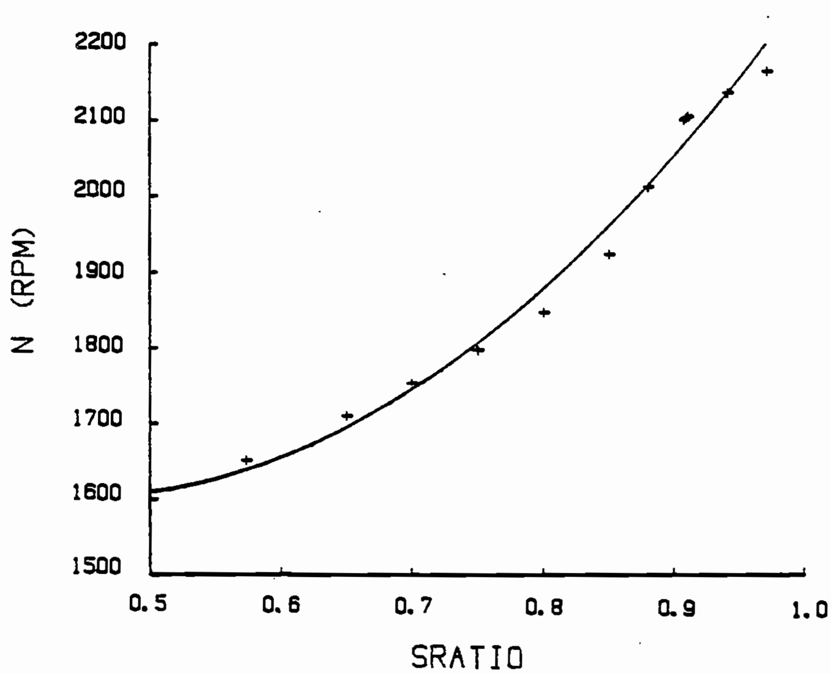


Figure 8. Speed Ratio vs. Engine RPM

The velocity calculated by equation 8 is for an instant when the carriage is at a particular location in the corridor. This velocity is multiplied by a very small time increment (.05 minute) to find the distance traveled during the time increment. The calculated distance is subtracted from the old carriage location to find the new carriage position. The analysis procedure is repeated for new carriage positions until the carriage travels the entire corridor. The time required to inhaul is the sum of the small time increments that linespeeds were calculated for.

Keep in mind that the time calculated by the simulation program does not include acceleration and deceleration time. Actual travel time is the sum of the travel time calculated by the simulation program and the fixed time given by the constants in the regression equations. Table 7 lists the calculated inhaul and outhaul times for the pendulum swing and Yo-Yo systems. The computer program is listed in Appendix B and a sample output from the program is in Appendix C.

Table 7 illustrates two important differences between the logging systems. Calculated outhaul time is consistently less for the pendulum system. Outhaul for the Yo-Yo system is done under a full load because the yarders are working against the lift of the balloon. The excess lift of the balloon is taken up by the guylines in the outhaul element for the pendulum system. Consequently, the power demands on the yarder are less and higher linespeeds are achieved.

Calculated inhaul times are also less for the pendulum system. The time difference generally increases as the yarding distance

Table 7

Inhaul and Outhaul Times

Yarding Distance	Element Time in Minutes Pendulum Swing Inhaul	 Outhaul	Yo-Yo* Inhaul	 Outhaul
500	.84	.45	1.08	.71
750	.94	.58	1.28	.91
1000	1.04	.60	1.47	1.11
1250	1.19	.70	1.67	1.31
1500	1.34	.78	1.86	1.52
1750	1.49	.85	2.06	1.72
2000	1.64	1.00	2.25	1.92
2250	1.89	1.15	2.45	2.12
2500	2.14	1.40	2.64	2.33

*From regression equations

increases. This is expected because the increased linespeeds that the pendulum system can achieve makes a bigger difference in total inhaul time for the longer yarding distances. Note also the differences level out and then decrease as yarding distances approach 2500 feet. The pendulum configuration is such that the required linepull near the landing increases as the balloon is moved further away from the yarder. The increased linepull in turn slows the inhaul. The balloon postion for the pendulum system is assumed to be halfway between the landing and hooksite for each of the yarding distances shown in Table 7. Note also the regression equation for the Yo-Yo is extrapolated to a yarding distance of 2500 feet even though the data set stops at 1500 feet.

Hook

Hook time is a function of both the logging system and the harvest unit. The hooking operation for the pendulum system is much like the hooking operation for a typical highlead. Unlike the Yo-Yo, the pendulum system has no tag line to swing around in the breeze. Similarly, the balloon need not be physically pulled down to bring the rigging to the hooktender as with the Yo-Yo system.

It is assumed that the hook time equation for the Yo-Yo can be tailored to fit the pendulum system by subtracting the mean position rigging time from the constant in the Yo-Yo hook time regression equation. Equation 9 will be used to predict hook time for the pendulum system.

Yo-Yo hook time equation:	Hook = 1.999 + .3392 (NOLOGS)	
- Mean position rigging time:	- 1.014	
Pendulum hook time equation:	Hook = 0.985 + .3392(NOLOGS)	(9)

Dykstra (1975) found differences of 0.9 and 1.4 minutes in comparing average balloon hook time to the average hook times of two different highlead operations. Both Dykstra (1975) and Sherar (1978) report hook times varying from 2 to 3 minutes for the highlead systems they observed.

It is calculated from a later analysis that the average payload for the pendulum system averages 40% greater than was observed in the time study of the Yo-Yo system. If the mean number of logs reported in the Yo-Yo time study is increased by 40%, the mean hook time for the pendulum system as calculated by equation 9 is 2.36 minutes.

Slack the Haulback

The purpose of slacking the haulback for the Yo-Yo system is to break the log turn out of its bed. This is accomplished by the balloon rising when the haulback is slacked, which then provides lift to the turn through the tagline. It was observed that there was occasional difficulty in breaking the turn out because the balloon can only pull up.

The pendulum system will break out a turn by inhauling the lifting line. Both the mainline and haulback are directly attached to the carriage which could expedite breaking out the turn by providing pull in several directions.

Consequently there may be an opportunity to save some time in this element for the pendulum system. Because a difference would be difficult to quantify, the time required to break out the turn will be estimated by the mean "slack-the-haulback" time for the Yo-Yo system, .61 minutes.

Load Positioning

Load positioning occurs in the Yo-Yo system because a turn of logs can be very difficult to bring the last little bit into the landing. The pendulum system is rigged such that the mainline is pulling the load in as opposed to pulling the balloon down as is the case in the Yo-Yo system. Consequently, load positioning time will be eliminated for the pendulum swing system.

Unhook

The unhook element for the pendulum system should be much the same as unhook for the Yo-Yo system. The process of unhooking chokers from logs is mostly independent of the logging system. There was, however, some extra delay in the unhook element for the Yo-Yo system because the turn would often bounce on the landing because of the instability of the balloon. This undesirable effect can be eliminated in the pendulum configuration because once the logs are on the landing, the lifting line can be slacked and the lift of the balloon will be taken up by the guylines.

The time required to unhook logs for the Yo-Yo system was about 10% of the total turn time. Because any time savings in the unhook element will be small in comparison to the total turn time, the regression equation for unhook time for the Yo-Yo system will be used to predict unhook time for the pendulum system.

$$\text{UNHOOK} = .1229 + .2070\ (\text{NOLOGS}) \qquad (10)$$

It is calculated in a later analysis that the average payload for the pendulum system is 40% greater than for the Yo-Yo system. If the mean number of logs reported in the Yo-Yo time study is increased by 40%, the mean unhook time for the pendulum system as calculated by equation 10 is 0.96 minutes.

Total Turn Time

Total turn time for the pendulum system is the sum of the times required for each element. Table 8 is a summary of delay free turn times for the pendulum and Yo-Yo systems.

Table 8

Delay Free Turn Times

Yarding Distance	Turn Times (minutes) Yo-Yo*	Pendulum**
500	6.71	5.22
1000	7.78	5.62
1250	8.32	5.82
1500	8.86	6.05
1750	9.40	6.27
2000	9.94	6.57
2250	10.48	6.97
2500	11.02	7.47

*Calculated from total turn time regression equation assuming a 14,400 pound payload

**Assumes 16,000 pound payload, the balloon is positioned 1,200 feet from the landing and 1,500 feet above the ground.

PAYLOAD ANALYSIS

Payload must also be known to estimate production for the pendulum swing system. The Yo-Yo system will again be the basis for comparison. For comparison purposes, theoretical payload for both the Yo-Yo and pendulum systems will be computed.

The Yo-Yo System

Lift is generated by the balloon for the Yo-Yo system. Not all of the lift is available to lift the payload however. A static analysis will be used to determine the net balloon lift. Figure 9 is a free body diagram of the shackle which joins the operating lines during the inhaul element. Refer to Figure 3 to see how the free body diagram fits into the system as a whole.

The drag force (D) is shown as a dashed arrow because the force does not act directly on the shackle. Balloon drag is the force which is generated by the air resistance of the traveling balloon. Drag in pounds is given by the following equation (Goodyear, 1964):

$$D = C_D \, 1/2 \, pV^2 \, V^{2/3}$$

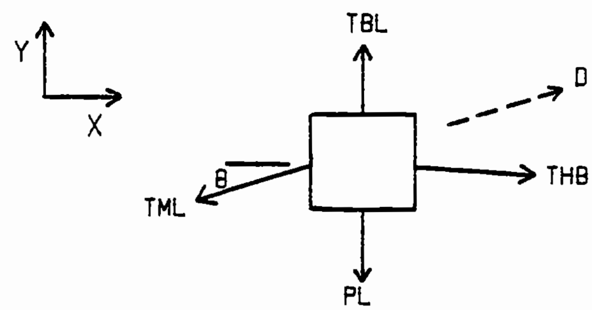
where: C_D - Drag coefficient (0.3 for natural shaped balloons)

P - Air density in slugs/ft^3 (0.002378 at sea level)

V - Wind speed in ft/sec.

V - balloon volume in ft^3

For this application, wind speed is assumed to be the inhaul velocity of the balloon. A velocity of 12 ft/sec. is assumed.



Θ - The angle the mainline makes from horizontal

PL - Payload

TML - Tension in mainline

THB - Tension in haulback

TBL - Tension in balloon line (static balloon lift)

D - Balloon drag

Figure 9. Free body diagram of shackle

Equations 11 and 12 are the result of summing the forces in the X and Y directions from the free body diagram illustrated in Figure 9.

$$- TML\ (\cos \Theta) + D\ (\cos \Theta) + THB_{(H)} = 0 \qquad (11)$$

$$TBL + D\ (\sin \Theta) - PL + THB_{(V)} - TML\ (\sin \Theta) = 0 \qquad (12)$$

where $THB_{(H)}$ - The horizontal component of the tension in the haulback

$THB_{(V)}$ - The vertical component of the tension in the haulback

The variables TBL and D are known for this formulation. If the mainline is assumed to act as a rigid link, the following relationship holds:

$$H = Vu - \frac{wl}{2} (d/h) \qquad (13)$$

where: The variables are defined in Figure 10.

The rigid link assumption treats a cable segment as a rigid member whose body weight acts at the center of the horizontal span of the segment. The rigid link assumption is appropriate for high tension cable segments.

By comparing Figures 9 and 10, it is apparent that V_u = TML (sin Θ) and H = TML (cos Θ). Equation 12 can be rearranged such that:

$$PL = TBL + D (\sin \Theta) - V_u + THB_{(V)} \qquad (14)$$

Equations 11, 13, and 14 can be solved by an iteration routine by first assuming a V_u in the mainline. If the geometry of the yarding configuration is known, equation 13 can be solved for H. The horizontal component of the tension in the haulback line (THB_H) can be found by solving equation 11. If $THB_{(H)}$ and the yarding geometry are known, the vertical component of the tension in the haulback (THB_V) can be calculated using the catenary equations. The catenary equation assumes the entire length of the cable is suspended and hanging in a catenary shape. Equation 14 can now be solved for payload.

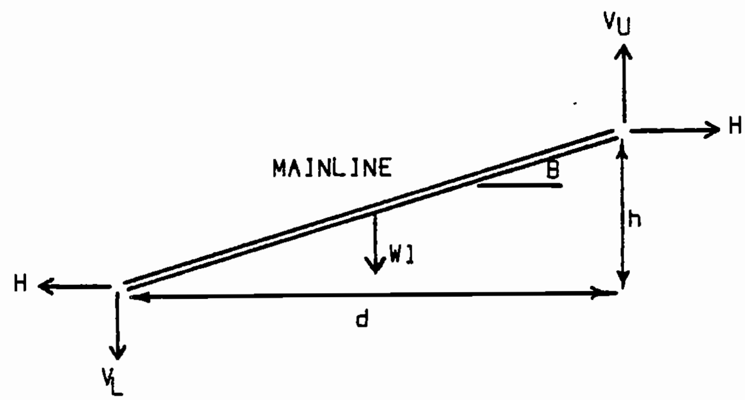


Figure 10. Rigid link representation of the mainline

H - Horizontal tension in cable segment
V_u - Vertical tension at upper end of cable segment
V_L - Vertical tension at lower end of cable segment
h - Vertical span of cable segment
d - Horizontal span of cable segment
w - weight/foot of line
l - straightline length of cable segment

This procedure is used to calculate a series of payloads for changing V_u's. Table 9 lists a series of solutions. The solutions are for a 530,000 cubic foot balloon with 17,142 lbs. of static lift. The turn is 100 feet from the landing so theta (Θ) is about 76 degrees.

Table 9

Solution for Net Payload for 530,000 Cubic Foot Balloon

V_u (lbs)	$THB_{(H)}$ (lbs)	$THB^{(V)}$ (lbs)*	PL (lbs)
2500	434	-6386	8,580
3000	553	-3637	10,829
3500	672	-2574	11,392
4000	790	-2043	11,422
4500	909	-1731	11,234
5000	1028	-1525	10,940

*The negative sign indicates the haulback is pulling down on the shackle.

Note that the optimal solution is about 11,400 lbs. This is the theoretical net payload of the Yo-Yo system when the turn is 100 feet from the landing.

There is also a strong relationship between calculated net balloon lift and distance from the landing.

Yo-Yo System Payload (530,000 ft^3 balloon)

	$\theta(°)$	Calculated Net Balloon Lift (lbs)
At rest over the load	-	17,142*
700' from the landing	48	14,400
500' from the landing	53	14,100
300' from the landing	61	13,500
100' from the landing	76	11,400

*From Olsen (1984)

The loss of net lift as the turn approaches the landing is due to the increasing angle of the mainline (Θ). As Θ increases, the yarder exerts more downward force on the shackle which causes a loss of net lift. The limiting case is the net lift very close to the landing.

It is felt the 620,000 cubic foot balloon is the most productive balloon logging system currently available. Consequently, the larger balloon will be used as the basis of comparison. Using the analysis procedure previously discussed, the 620,000 cubic foot balloon has 14,600 pounds of net lift. It is assumed that the regression relationships developed for the small balloon are valid for the larger system.

The Pendulum System

Lift is generated for the pendulum system by the balloon and in some cases the haulback line. The goal of the analysis is to develop a procedure which is comparable to the payload analysis done for the Yo-Yo system.

Avery (1984) developed an iterative computer program which solves for available static balloon lift for any load point in a logging unit. Two important results are apparent from studying the output from the computer model. Available balloon lift is maximized directly under the balloon. Lift decreases much more rapidly at the back of a downhill yarding unit than it does towards the landing. The angle the lifting line makes with vertical (ϕ in Figure 11) increases more rapidly when the carriage moves uphill from the point beneath the balloon than when the carriage moves downhill from the same point. When ϕ is increased, there is a smaller proportion of lifting line tension available to provide lift.

The discussion up to this point has not included the effect of the operating lines on available lift. Figure 11 illustrates two possible carriage configurations in a downhill logging situation.

Figure 11a illustrates the carriage configuration as the turn approaches the landing. Figure 11b illustrates the configuration at the upper end of the unit. A brief examination of Figure 11b indicates there is an imbalance of horizontal force in the negative X direction if tensions T1 and T2 are equal. Consequently, the haulback must have considerably more tension than the mainline to resist the force imbalance. This being the case, the haulback will provide lift in the upper end of the unit as long as T2 has an upwards component to it.

A similar examination of Figure 11a indicates a force imbalance in the positive X direction. Consequently, the mainline requires a much higher tension than the haulback. This pulls the carriage down and causes a net loss of available lift as the turn approaches the landing.

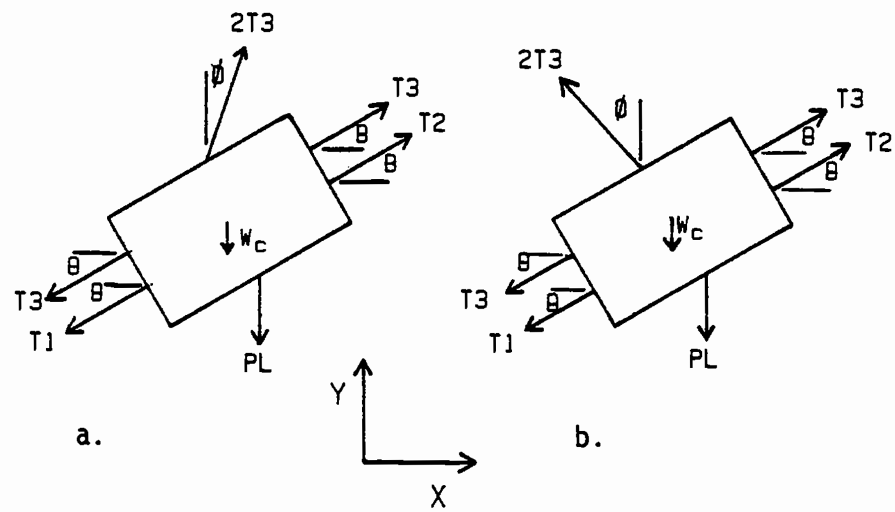


Figure 11. Free body diagram of two carriage configurations for the pendulum system.

T1 - Mainline Tension
T2 - Haulback Tension
T3 - Lifting line tension*
Θ - The angle the operating lines make with horizontal
ϕ - The angle the lifting line makes with vertical
W_c - Weight of the carriage
PL - Payload (weight)

*Note that there is actually two cable segments of the lifting line which reach from the carriage to the balloon. One force member is used to simplify the analysis.

The previous discussion is consistent with the assumptions made in the cycle time analysis. The assumptions are:

1. The mainline is under negligible tension when the carriage is uphill of the point directly under the balloon.
2. The haulback line has 3500 pounds of tension when the carriage is downhill of the point directly under the balloon.

The discussion also assumes that it is desirable that the yarder provide control of the inhaul. The alternative is to release tension in the mainline and haulback and allow the pendulum swing to provide the needed acceleration for inhaul. The former approach is chosen for safety reasons.

A static analysis is used to calculate total net available lift. Several assumptions are required.

1. The tension in the lifting line (T3) is given by Avery's model.
2. Sheaves are considered frictionless.
3. The angle Θ is assumed to be the angle of the ground.

Implicit in assumption 3 is that all of the lines act as weightless lines. The carriage configuration illustrated in Figure 11 is very complex. The weightless line approximation is the simplest approach to the problem. A more thorough analysis would model line tensions using the rigid link or catenary approximations. The more rigorous mathematical formulations is much more difficult and beyond what is required at this level of analysis.

The weightless line approximation assumes the force member which represents a cable acts in a straight line between the endpoints of the cable. Cable segments in high tension most closely approach acting in this manner. For the pendulum system, the lines which are in high tension are the lifting line, the mainline when the carriage approaches the landing and the haulback when the carriage is at the back of the unit. The weightless line model is least appropriate in low tension cable segments. Referring to Figure 11a, the haulback line (T2) is under low tension as the carriage approaches the landing. When this is the case, the haulback will hang in a catenary configuration and may well have a downward force component. For the pendulum system, the weightless line model assumes that T2 has an upwards component which exaggerates gross lift.

Given these assumptions, the payload is calculated by summing forces in the X, Y and Z directions. The Z axis is directed out of the paper in Figure 11. Forces are summed in three directions because it is possible for the haulback, mainline, and lifting line to act in different planes.

Figure 12 is the result of the analysis for numerous load points on the standard unit. Several observations are noted about Figure 12. The haulback is providing up to 30% of the lift near the back of the unit. Secondly, the largest gross payload which can be yarded to the landing for the situation illustrated in Figure 12 is 16,000 lbs. This is the gross lift at the landing.

Figure 13 illustrates the payload gain which occurs from repositioning the balloon in the corridor. The dark line indicates the actual gross payload when the balloon is positioned twice in the corridor. The 1300 feet of the corridor that is closest the landing is yarded with the balloon 800 feet from the landing. The limiting payload at this position is the gross lift at the landing which is 21,000 pounds. The balloon is repositioned at 1300 feet from the

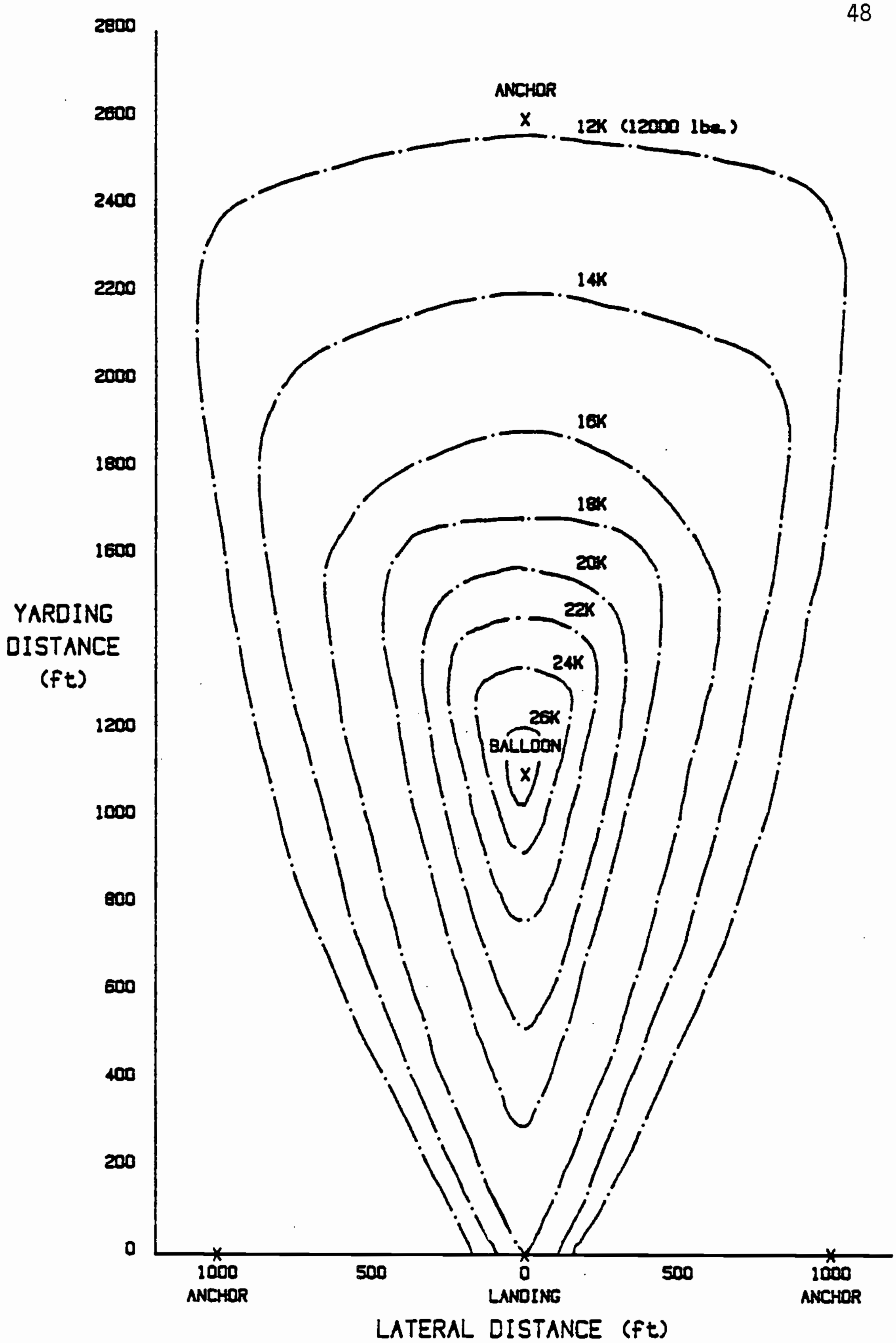


Figure 12
Lift Contours for Logging 60% Slope

landing to yard the remainder of the unit. The limiting gross payload for this balloon position is 16,000 pounds.

The carriage weight must be determined to calculate net payload. Carriage weight is calculated by studying the outhaul problem. The carriage must be heavy enough so that when the lifting line is slacked during outhaul, the carriage will lower. Referring to Figure 11, the forces are summed in the X and Y directions. Payload equals zero for the outhaul problem. Haulback tension (T2) is provided by the yarder to achieve outhaul. If it assumed the yarder provides no tension to the lifting line and mainline during outhaul, then T1 and T3 are a function of the length of line strung out between the carriage and the yarder. The limiting case is when the carriage is at the top of the corridor. The lifting line is a 3/4 inch line. Residual cable tension created by line weight and friction was calculated to be 3500 pounds for a 3/4 inch line by an earlier analysis. From a similar analysis, mainline tension is calculated to be 4400 pounds. The variables Θ and ϕ are estimated from the geometry of the system to be 30.96° and 40°, respectively. By summing the forces, it is calculated that the carriage must weigh approximately 8000 pounds to achieve an equilibrium condition. In studying the formulation, it was noted that the calculated carriage weight is very sensitive to lifting line tension. Reducing T3 to 2200 pounds reduces calculated carriage weight to 5600 pounds. Increasing T3 to 6000 pounds increases calculated carriage weight to 11,300 pounds. Changing the variables Θ, ϕ, and T1 had little effect on the calcu-

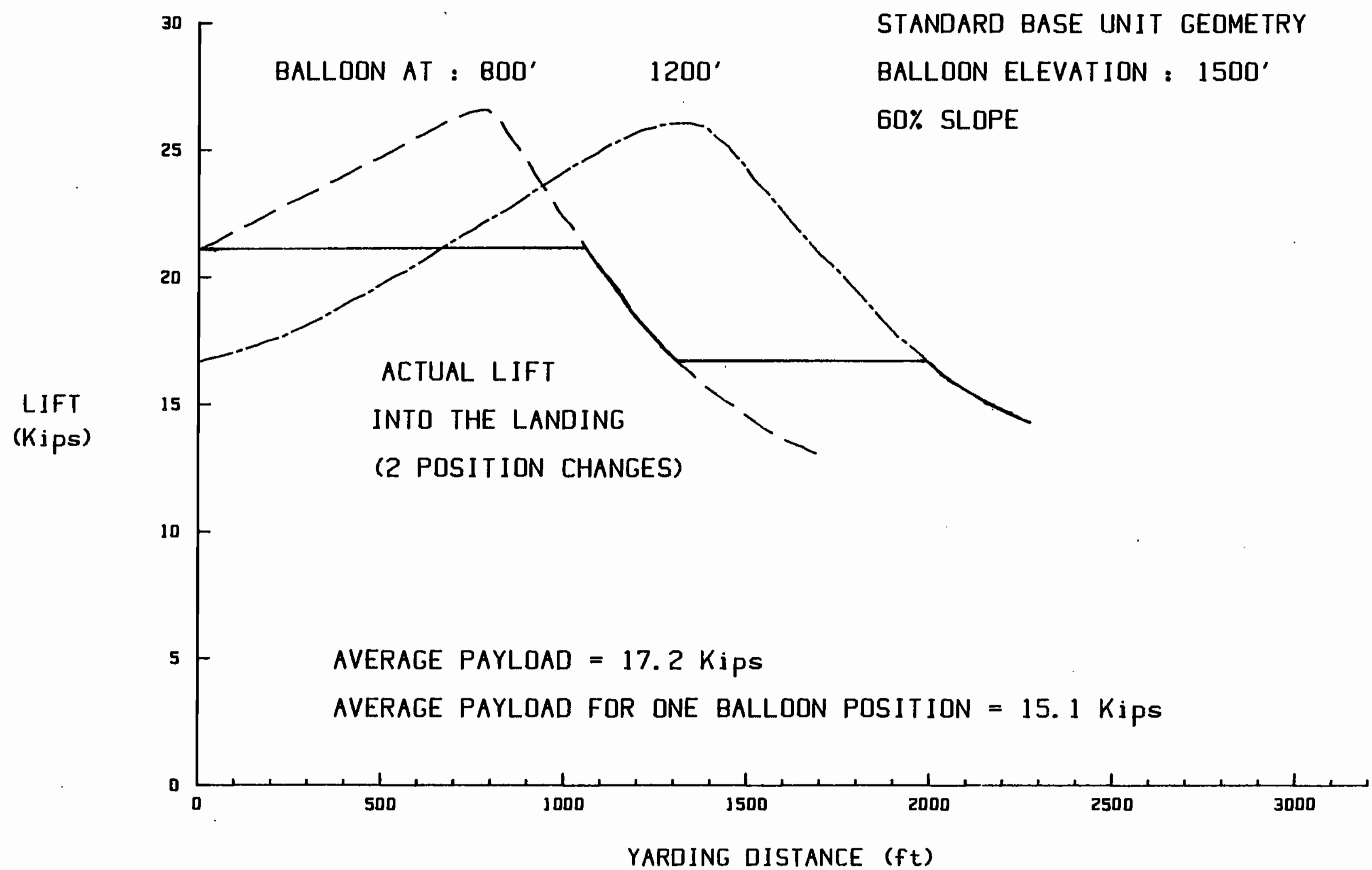


Figure 13. Gross Lift Gained by Repositioning the Balloon

lated carriage weight. A carriage weight of 8000 pounds is assumed for the payload analysis.

Average payload is determined by analyzing a single corridor which passes beneath the balloon. It is assumed the balloon will be repositioned up to 3 times within a corridor. Balloon positions of 300, 800, and 1400 feet from the landing are used in the analysis. It is further assumed the balloon will be moved to the side as needed so that the balloon is always over the corridor being yarded. Table 10 summarizes the payload determination.

Table 10

Pendulum Payload Summary

Yarding Distance (ft.)	Incremental Payload (lbs.)	Average Payload (lbs.)
0 - 500		16,400
501 - 1200	13,000	
0 - 1200		14,300
1201 - 1500	8,600	
0 - 1500		13,300
1501 - 1800	8,000	
0 - 1800		12,400
1801 - 2100	8,000	
0 - 2100		11,800
2101 - 2400	6,500	
0 - 2400		11,100
2401 - 2700	5,000	
0 - 2700		10,400

PRODUCTION SUMMARY

The production summary presented in Table 11 is for the standard unit geometry for the pendulum system. The total time regression equation is used to determine cycle time for the Yo-Yo system. Note that utilization ratios are used to calculate the turns per hour for each system. Utilization ratios are used to prorate expected delay time into a production analysis. Olsen (1984) reports utilization ratios for the pendulum and Yo-Yo systems as 73 and 78 percent, respectively. Both average and incremental production are reported. Incremental production refers to the production which can be achieved for the increment of yarding distances shown.

Figures 14 through 17 illustrate how the pendulum and Yo-Yo systems compare. Figures 14 and 15 show the advantage the pendulum system has in faster cycle times. Figure 16 illustrates the dramatic influence of yarding distance on payload for the pendulum system. Figure 17 is a graphical summary of the production analysis. For this analysis, a yarding distance of approximately 1100 feet is the breakeven point between the systems. The pendulum system is more productive for yarding distances less than 1100 feet. The Yo-Yo system is more efficient for the longer yarding distances.

Table 11

Production Summary

Yarding Distance (ft)	Incremental Production Turn Time (min)	Turns/ hr.	Production* (MBF/hr)	Average Production Turn Time (min)	Turns/ hr.	Production* (MBF/hr)
Pendulum System						
0 - 500				5.04	8.69	14.25
501 - 1200	4.97	8.81	11.45			
0 - 1200				5.00	8.76	12.61
1201 - 1500	4.88	8.97	7.71			
0 - 1500				4.97	8.80	11.63
1501 - 1800	5.06	8.66	6.92			
0 - 1800				4.98	8.77	10.84
1801 - 2100	5.39	8.12	6.50			
0 - 2100				5.04	8.68	10.22
2101 - 2400	5.65	7.75	5.03			
0 - 2400				5.11	8.56	9.57
2401 - 2700	6.04	7.25	3.62			
0 - 2700				5.21	8.42	8.91
Yo-Yo System						
0 - 500				6.43	7.28	10.48
501 - 1200	7.24	6.46	9.31			
0 - 1200				6.90	6.80	9.80
1201 - 1500	8.54	5.48	7.89			
0 - 1500				7.23	6.53	9.41
1501 - 1800	9.19	5.09	7.33			
0 - 1800				7.55	6.29	9.06
1801 - 2100	9.84	4.76	6.85			
0 - 2100				7.88	6.07	8.75
2101 - 2400	10.48	4.47	6.43			
0 - 2400				8.21	5.87	8.46
2401 - 2700	11.13	4.20	6.05			
0 - 2700				8.53	5.68	8.19

*Includes Utilization ratios

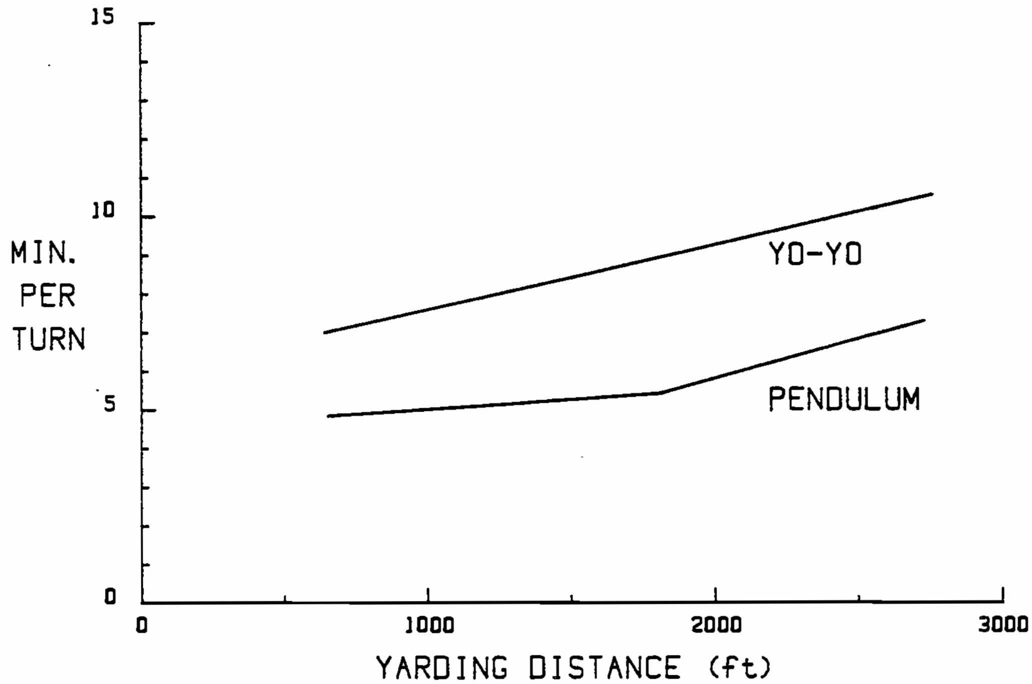


Figure 14. Comparison of Incremental Turn Time

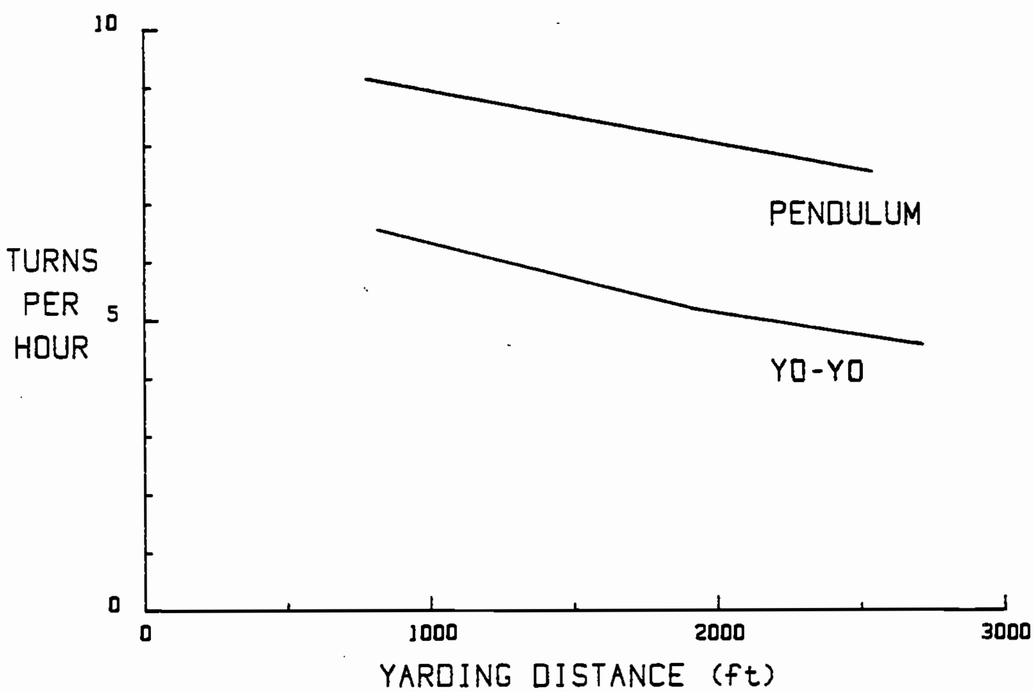


Figure 15. Comparison of Incremental Turns per Hour

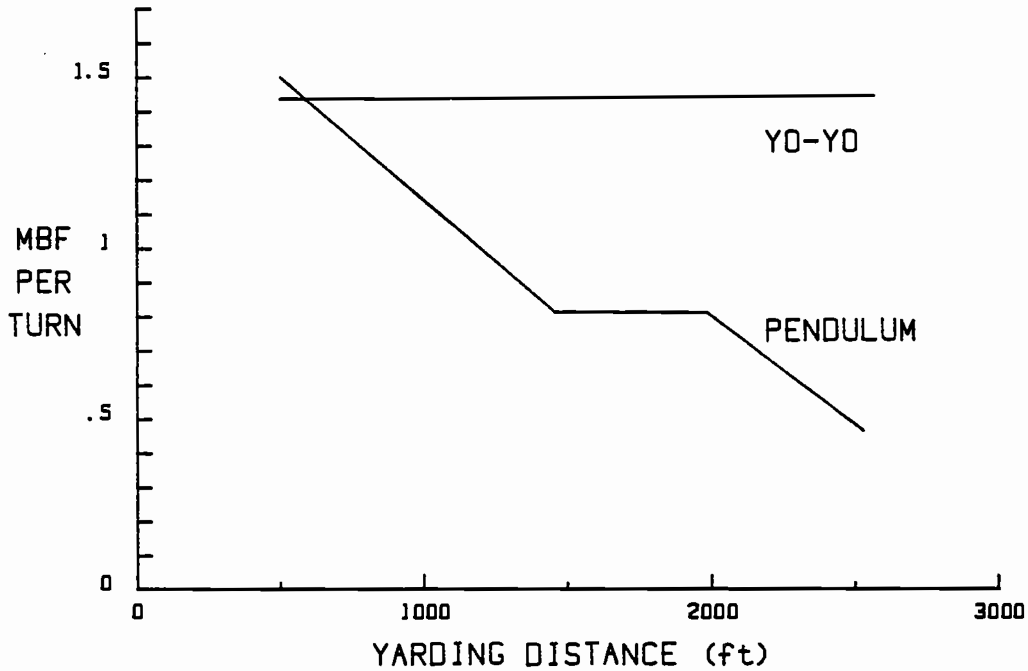


Figure 16. Comparison of Incremental MBF per Turn

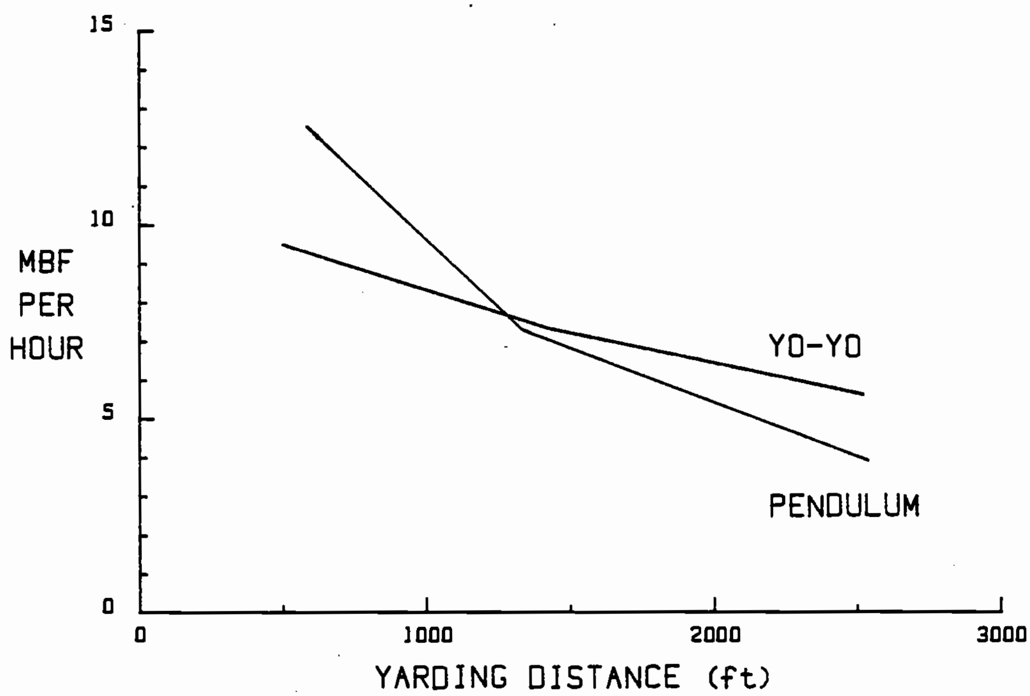


Figure 17. Comparison of Incremental MBF per Hour

Of interest also is how sensitive the calculated production results are to change or error in the estimated input variables. Sensitivity can be measured if one input variable is ranged while the remainder of the problem is left unchanged. Turn time and payload are ranged in the following table.

Sensitivity Analysis - Pendulum and Yo-Yo Systems

Percentage Change in Estimate	Percentage Change in Calculated Production (MBF/hour)
+25% Turn Time	-20%
-25% Turn Time	+33%
+25% Payload	+25%
-25% Payload	-25%

THE NO SLOPE CASE

Of interest is whether the pendulum swing is a workable concept when there is no slope. The Yo-Yo system has been tested as a ship to shore loading method. The pendulum system has potential for the same application. A brief discussion of how the pendulum system might behave when there is no slope will also illustrate the effect of the slope in the previous analysis.

Operationally, there should be little difference in controlling the carriage during inhaul and outhaul. The lifting line would need to be first shortened and then lengthened as the carriage traveled from behind the balloon position to in front of the balloon position. The lifting line would generally be continuosly lengthened for inhaul when downhill logging.

Calculated cycle times change very little from the downhill analysis. The geometry of the oprating lines change such that equivalent payloads generate slightly less mainline tension during inhaul. This in turn creates a 0.2 minute time saving in calculated inhaul time at 2500 feet yarding distance. Changing groundslope should make little difference in the remaining elements of the yarding cycle.

It would be expected that the calculated payload would change for the no slope case. Figure 18 illustrated how the calculated payloads compare for the 60% and no slope cases.

Note that the gross calculated payloads closely coincide. Two independent principles are the cause of this.

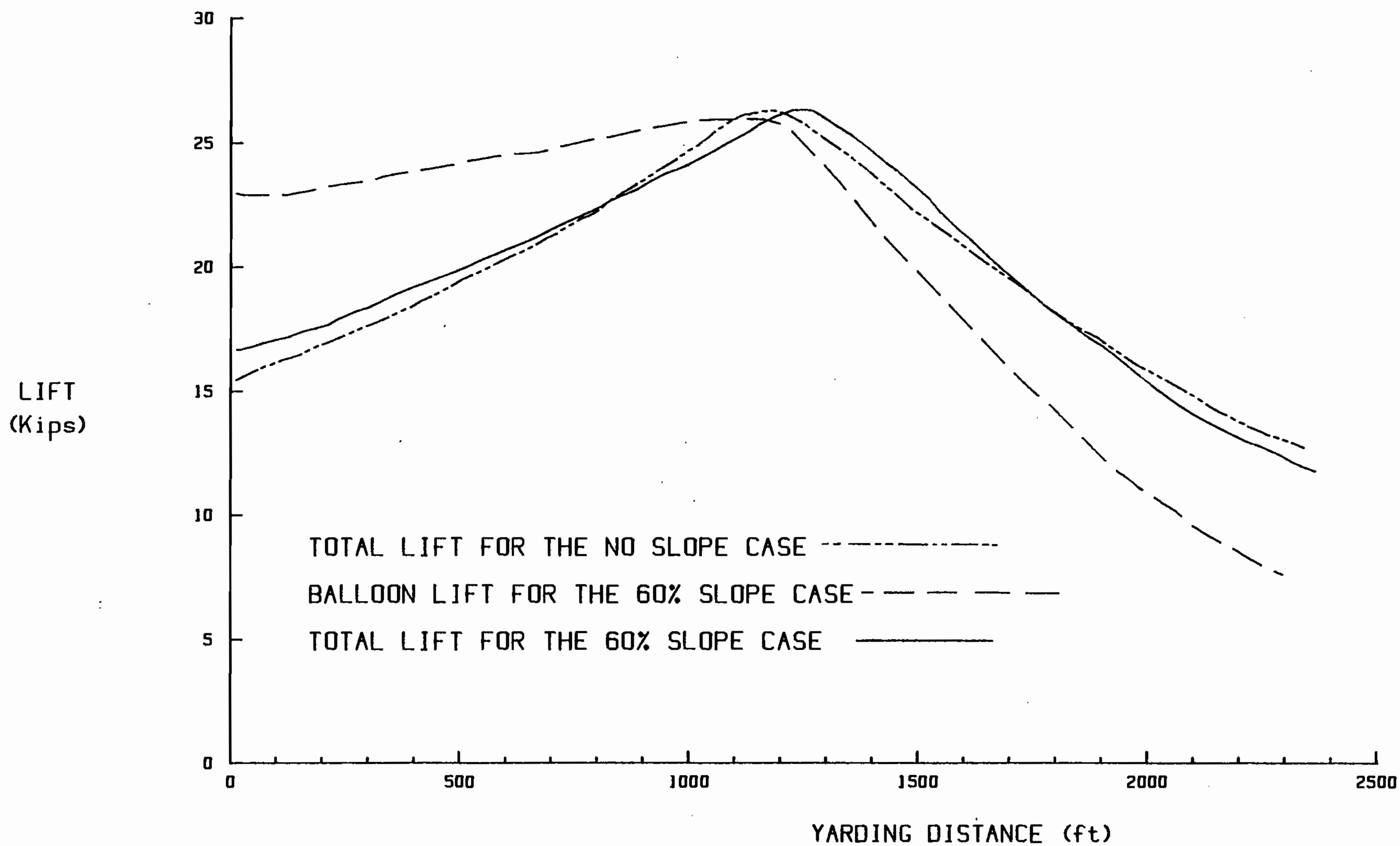


Figure 18
Comparison of Calculated Payload as a Function of Slope

The balloon generates more net lift at a given load point in the front of the harvest unit for the 60% case than for the no slope case. The reverse is true in the back of the unit. Note the angle ϕ in Figures 5 or 11. Phi (ϕ) increases more rapidly for a given slope distance for the no slope case when the carriage is in front of the point which is directly under the balloon. As phi increases, the lift of the lifting line decreases. The reverse is true behind the balloon position. Phi increases more rapidly for the 60% slope case. The result is decreased balloon lift for the 60% slope case as compared to the no slope case in the back of the unit.

The effect of the operating lines tend to counteract the relationship just described. When there is no slope, the mainline and haulback operate in an almost horizontal plane. Consequently, neither line has a significant vertical component which would increase or decrease total available lift. Contrast this to the 60% slope case. For an operating line which makes a 30 angle with the horizontal, the magnitude of the vertical force is approximately 1/2 of the line tension. This tends to decrease lift in the front of the harvest unit and increase lift in the back of the unit for the 60% slope case.

To summarize, the lift for the no slope case is nearly the same as the 60% slope case once the effect of the operating lines is included.

CONCLUSIONS

The following conclusions are drawn about the pendulum swing concept from the analysis.

1. The concept appears feasible from a production standpoint.
2. The system is best suited for downhill logging applications.
3. Optimal yarding production is achieved when external yarding distances are less than 1500 feet.
4. The external yarding distance is limited by the stationary balloon concept. Calculated lift drops to less than 8000 pounds at the back of the unit when the yarding distance exceeds 2100 feet.
5. The tethered balloon concept allows for the use of a very large balloon. The size of the balloon is limited for the Yo-Yo configuration by the size of the yarders. That is, a larger balloon translates directly into higher weight and horsepower requirements for the yarders in the Yo-Yo configuration. Yarder requirements are much less sensitive to balloon size in the pendulum system.
6. The pendulum swing feature appears to have the potential for decreasing cycle time compared to the conventional system.

7. Inhaul time is sensitive to balloon positioning. Balloon positioning near the landing minimizes inhaul time.
8. Effective application on the pendulum concept requires close coordination of the lifting line, the mainline, and the haulback line. This coordination may be difficult to achieve.

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APPENDIX A

EQUIPMENT REQUIREMENTS

Yo-Yo	Pendulum
2 Berger balloon yarders	Yarder similar to Thunderbird TMY-70
No tower	70' tower and 4 guylines
No carriage	Modified carriage similar to Danebo G-1 or Skookum Gd-1bW. Large sheave under balloon also.
Transfer vehicles used modified D8 (70500#) with winch & spooler	Transfer vehicles used Modified D9H (94300#)
Not applicable	Line horse for live guyline. 100 H.P. winch with torque converter transmission. To be mounted on above transfer.
Large self propelled swing-boom loader	Same
Large skidder, rubber tired	Not needed
620,000 ft^3 balloon fully equipped	1,100,000 ft^3 balloon fully equipped
Rigging	About twice the number of blocks, straps, etc.

EQUIPMENT LIST NOTES

Line Horse (Pendulum)

Line horse and transfer vehicle. Used crawler undercarriage with single drum capable of spooling 4,000 feet of 1-5/8" synthetic rope.

Pendulum System Guylines

Total of 10,000 feet of 1-5/8" Kevlar Phyllystrand synthetic rope.

Rigging

Includes rope blocks, lead blocks, lead straps, shackles, extensions, deadman straps, buff rigging, corner blocks, back blocks, sucker down blocks, stump chokers, choker tags, toggles, swivels, rigging tools, saws, balloon repair kit and Motorola FM radio system. The pendulum system includes a modified Skookum carriage and a 24" sheave to work with the inverted Tyler system. Tension measurement equipment is on both units.

Other Equipment

Used compressed gas trailer with 25,000 ft^3 of helium. Used landing crawler tractor and spool truck. Used fire trucker (tanker), crew bus, and pickup truck. Mobile home for weekend guard housing. Fueling equipment. Container for transporting deflated balloon.

Thunderbird TMY-70

Side mounted yarder/tower
Self propelled rubber mount
Slackline
4 @ 200' 1-1/8" guylines
70' Tower
Water cooled band brakes, 2 band on skyline. No interlock
57'3" (31'5" w/o tower) length
14'6" Overall (11'0" outside tire) width
120,000# New (5 drums machine w/lines & fuel weight)
DET8V92T Engine 430 H.P.
Drive Train
1. Haulback Ratio 74/27T
2. Main Ratio 86/27T
3. Skyline (lifting line) Ratio 98/27T

Drum Specifications

	Mainline	Haulback
Barrel dia.	14"	14"
Barrel length	34"	34"
Flange dia.	36"	39"

Detroit Allison 6061 (TC 680) transmission

Berger Balloon Yarder

Engine	Cummins V-12
Rated Engine Power	635 HP
Transmission	Twin Disc Omega Torque Convertor
Undercarriage	TD-24 Modified
Weight	120,000 lbs

Balloon Characteristics

	Yo-Yo System Model 620K	Proposed Pendulum System Model
Volume	620,000 ft^3	1,100,000 ft^3
Diameter	104 ft	134 ft
Height	125 ft	143 ft
Approximate Weight	7,600 lbs	10,560 lbs

Operating Lines

Yo-Yo system:	1" dia. line for both yarders
Pendulum system:	Mainline - 7/8" dia. Haulback - 3/4" dia. Lifting line - 5/8" or 3/4" dia.

Line sizes for the pendulum system have adequate safe working load to handle the line tensions calculated in the analysis.

HP-86 COMPUTER SIMULATION MODEL

```
10 PRINT "********************"
20 PRINT "   INHAUL PROGRAM"
30 PRINT "********************"
40 PRINT
50 ! THIS PROGRAM CALCULATES INHAUL TIME FOR THE PENDULUM SYSTEM
60 OPTION BASE 1
70 DIM GEAR(6,1)
80 DEG
90 GEAR(1,1)=4
100 GEAR(2,1)=2.68
110 GEAR(3,1)=2.01
120 GEAR(4,1)=1.35
130 GEAR(5,1)=1
140 GEAR(6,1)=.67
150 ! INITIALIZE INPUT VARIABLES
160 BALPOS=1292
170 VELSUM=0
180 TOTTIME=.05 ! MINUTES
190 GRD=86/27 ! GEAR REDUCTION AT MAINLINE DRUM
200 GRDT=40/20 ! GEAR REDUCTION IN DRIVE TRAIN
210 EFF=.95 ! ASSUMED EFFECIENCY FACTOR
220 WSHAFT1=5000
230 Z=6
240 W=16000 ! WEIGHT OF PAYLOAD AND CARRIAGE FOR AVERAGE TURN
250 T2=3500 ! ASSUMED TENSION IN HAULBACK
260 LINE=1.04 ! LINEWEIGHT IN LBS/FT
270 THETA=30.96 ! GROUNDSLOPE ANGLE AT 60% SLOPE
280 DISP "INPUT YARDING DISTANCE"
290 INPUT XDIST
300 PRINT USING 320 ; "YARDING DISTANCE=";XDIST
310 PRINT USING 320 ; "BALLOON POSITION (SLOPE DISTANCE)=";BALPOS
320 IMAGE K,4D
330 PRINT
340 PRINT "Z   WSHAFT      T1      VEL    YDIST   SRATIO   TRATIO"
350 PRINT "-   ------      ----    ----   -----   ------   ------"
360 ! CALCULATE REQUIRED PULL
370     PHI=ATN ((BALPOS-XDIST)*COS (THETA)/(1500+(BALPOS-XDIST)*SIN (THETA)))
380     DEN=COS (THETA)/TAN (PHI)-SIN (THETA)
390     T1=(T2*(COS (THETA)/TAN (PHI)-SIN (THETA))+W)/DEN
```

```
400      T1=T1-LINE*XDIST*SIN (THETA)
410      IF T1<0 THEN T1=0
420 ! ASSIGN EFFECTIVE DRUM RADIUS
430      CABLE=4400-XDIST ! AMOUNT OF MAINLINE CABLE OUT
440      IF CABLE<4184 THEN 460
450      R=16.9375 @ GOTO 750
460      IF CABLE<3799 THEN 480
470      R=16.3 @ GOTO 750
480      IF CABLE<3431 THEN 500
490      R=15.66 @ GOTO 750
500      IF CABLE<3077 THEN 520
510      R=15.02 @ GOTO 750
520      IF CABLE<2738 THEN 540
530      R=14.3875 @ GOTO 750
540      IF CABLE<2413 THEN 560
550      R=13.75 @ GOTO 750
560      IF CABLE<2105 THEN 580
570      R=13.11 @ GOTO 750
580      IF CABLE<1810 THEN 600
590      R=12.475 @ GOTO 750
600      IF CABLE<1532 THEN 620
610      R=11.8375 @ GOTO 750
620      IF CABLE<1268 THEN 640
630      R=11.2 @ GOTO 750
640      IF CABLE<1019 THEN 660
650      R=10.5625 @ GOTO 750
660      IF CABLE<785 THEN 680
670      R=9.925 @ GOTO 750
680      IF CABLE<566 THEN 700
690      R=9.2875 @ GOTO 750
700      IF CABLE<362 THEN 720
710      R=8.65 @ GOTO 750
720      IF CABLE<174 THEN 740
730      R=8.0125 @ GOTO 750
740      R=7.375
750 QDRUM=T1*R/12 ! REQUIRED TORQUE AT DRUM
760 GEAR=GEAR(Z,1)
770 QRATIO=1 ! TORQUE RATIO IN TORQUE CONVERTER
780 QENG=QDRUM/(EFF*GEAR*GRDT*GRD*QRATIO) ! TORQUE NEEDED AT ENGINE
790 IF QRATIO>1.6 THEN 820
800 IF QENG<1186 THEN 830 ! MAX TORQUE ENGINE CAN DEVELOP
810 QRATIO=QRATIO+.01 @ GOTO 780
820 Z=Z-1 @ GOTO 760
```

```
830 SRATIO=1.65143-.77082*QRATIO ! CALCULATE SPEED RATIO IN TORQUE CONVERTER
840 IF QRATIO<= 1 THEN SRATIO=.97
850 N=2014.7-1879.1*SRATIO+2136.1*SRATIO^2 ! ENGINE RPM,ABSORBTION CHART
860 IF SRATIO>= .94 THEN N=2100
870 WSHAFT=N*SRATIO/GEAR ! RPM AT OUTPUT SHAFT
880 IF Z=5 THEN WSHAFT1=1940
890 IF Z=4 THEN WSHAFT1=1440
900 IF Z=3 THEN WSHAFT1=960
910 IF Z=2 THEN WSHAFT1=720
920 IF Z=1 THEN WSHAFT1=480
930 Z1=6
940 IF WSHAFT<1950 THEN Z1=5
950 IF WSHAFT<1445 THEN Z1=4
960 IF WSHAFT<965 THEN Z1=3
970 IF WSHAFT<728 THEN Z1=2
980 IF WSHAFT<490 THEN Z1=1
990 IF Z1<Z THEN Z=Z-1 @ GOTO 760
1000 IF WSHAFT>WSHAFT1 THEN WSHAFT=WSHAFT1
1010 WOUT=WSHAFT/(GRD*GRDT) ! RPM AT DRUM
1020 VEL=WOUT*2*PI *R/12 ! LINESPEED IN FEET PER MINUTE
1030 VELSUM=VELSUM+VEL
1040 D=VEL*.05
1050 PRINT USING 1060 ; Z,WSHAFT,T1,VEL,XDIST,SRATIO,QRATIO
1060 IMAGE D,4X,4D,4X,6D,4X,4D,4X,4D,4X,.4D,4X,2D.2D
1070 XDIST=XDIST-D
1080 IF XDIST<= 0 THEN GOTO 1110
1090 TOTTIME=TOTTIME+.05
1100 GOTO 370
1110 PRINT
1120 AVEVEL=VELSUM/(TOTTIME*20)
1130 PRINT USING 1140 ; "AVERAGE VELOCITY=",AVEVEL
1140 IMAGE K,4D.2D
1150 PRINT USING 1140 ; "TOTAL TIME=",TOTTIME
1160 PRINT
1170 PRINT
1180 PRINT
1190 GOTO 150
1200 END
```

APPENDIX C

The following is the output for the HP-86 computer program which simulated the inhaul cycle for the pendulum system. All the variables are defined in Table 6 except Z which is transmission gear.

Each line of data indicates the calculated values for the selected variable at a specific instant. The decreasing YDIST indicates the carriage is traveling towards the yarder. The analysis ends when YDIST is less than or equal to zero (the carriage is at the yarder). Total time in the calculated inhaul time not accounting for any acceleration deceleration time.

****
INHAUL PROGRAM
****

YARDING DISTANCE=1500
BALLOON POSITION (SLOPE DISTANCE)=1292

Z	WSHAFT	T1	VEL	YDIST	SRATIO	TRATIO
6	3040	479	3595	1500	.9700	1.00
6	3040	2492	3753	1320	.9700	1.00
5	1940	4595	2395	1133	.9700	1.00
5	1666	5936	2057	1013	.8498	1.04
4	1440	7088	1853	910	.9700	1.00
4	1121	8126	1443	817	.8035	1.10
3	960	8934	1236	745	.9700	1.00
3	960	9627	1236	683	.9700	1.00
3	960	10319	1236	622	.9700	1.00
3	829	11011	1110	560	.8498	1.04
3	753	11633	1009	504	.8035	1.10
2	720	12198	965	454	.9700	1.00
2	720	12738	965	406	.9700	1.00
2	720	13278	965	357	.9700	1.00
2	720	13819	965	309	.9700	1.00
2	642	14359	860	261	.8652	1.02
2	612	14840	820	218	.8421	1.05
2	538	15299	750	177	.7804	1.13
2	513	15719	715	139	.7573	1.16
1	480	16120	668	104	.9700	1.00
1	480	16494	668	70	.9700	1.00
1	480	16868	668	37	.9700	1.00
1	480	17242	668	3	.9700	1.00

AVERAGE VELOCITY=1330.37
TOTAL TIME=   1.15