OPTIMAL OPERATION OF HOISTS FOR DEEP MINES

A *Dissertation*
Submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Systems Engineering & Operations Research)

by

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ROORKEE (INDIA)
MAY 1976

ACKNOWLEDGEMENT

I am deeply indebted to Dr. L.M. Ray, Professor, Department of Electrical Engineering, University of Roorkee, for his able guidance, constructive criticism and continued encouragement throughout the course of investigations.

I express my sincere thanks to Dr. T.S.M. Rao, Professor and Head, Department of Electrical Engineering, University of Roorkee, for providing necessary facilities to carry out this work.

I also take this opportunity to thank Sri P.D. Gupta, Deputy General Manager, Bharat Gold Mines Limited, Kolar Gold Fields, and Sri M.S. Shankarnarayana, Chief Engineer, Champion Reef Mines, Kolar Gold Fields, Karnataka State, for their valuable help in providing the necessary data and other details for solving the present problem. I also thank Sri Jayant Pal, Lecturer, Department of Electrical Engineering, University of Roorkee, for his appreciable efforts taken to help me to complete this dissertation.

Lastly, I thank all those who have helped, directly or indirectly, at various stages during the progress of work, providing me necessary encouragement and guidance.

(RAKESH BABU)

Roorkee,
May 24, 1976

A B S T R A C T

This dissertation deals with the problem of optimisation of the operation of hoists used for deep mines (e.g. Gold Mines), from the point of view of overall economy. The hoisting system has been discussed in detail and a simplified equivalent system has been considered for analysis. A simple numerical method has been developed to determine the energy consumptions and ore outputs under conditions of varying operating parameters of the system, and the optimum operating point is determined by the comparison of these values of energy consumption and output. The approach discussed here can be used for the optimisation of the operation of other electrical/mechanical drives also.

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CHAPTER-1

INTRODUCTION

1.1 Introduction to Optimal Control

Recent trends in the development of modern civilization have been in the direction of optimal control. Increased competition plus man's desire to perform in an optimum fashion, combined with the fact that he faces an ever shrinking supply of natural resources, represent some of the reasons. And these reasons have forced all types of industry - chemical, steel, automobile, aircraft, textile, mining, defense production, etc. - to begin to seek greater and greater efficiency through optimal control of their systems.

A specific engineering problem does not have a unique solution; indeed, it has in most cases, an infinite number of possible solutions. As an example, a plant engineer may think the optimal control of the system to be that gives maximum production, whereas a system engineer will want the system to have maximum overall efficiency, a safety engineer will like the system to have minimum accidents, the owner will try to extract maximum profit out of the system, and so on. If we judge the various solutions on the basis of a specific pay-off or objective function (also termed as cost index, value function, index of performance , figure of merit , etc.), each possible solution is characterized, as a rule, by a different value of this function. The one solution associated with the optimum value is referred to as optimum solution. (It is appropriate to point out that the word 'optimum' may refer to either a minimum or maximum, depending upon the situation in hand.)

The most obvious method of optimization, or finding the optimal control, is an outright search process- all possible solutions in the total set of solution are compared and the best one is selected. Unless the search process is particularly attractive (as in the case of selecting Miss India out of 50 entries), this is not a recommended procedure, but it is one that nevertheless must be employed when no other road is open. Unfortunately, all other roads seem to be blocked in the case of the problem considered, and furthermore, it is easier to adopt this search process in the present problem, the problem has been satisfactorily solved by this search process and the optimum solution is determined

1.2 Introduction to the Problem

Much has been done , till now, in the field of theoretical development of optimal control and its application to some specific problems. But its importance will be increased manifolds if we apply this optimal control theory to some real life and industrial problems. Keeping this object in mind, the problem considered, quite simple, practical, and representative, has been taken from the mining industry.

Hoisting operation, to haul ore from great depths, is the most important part of mining, and hence optimum hoisting operation is very very important. Furthermore as Gold is one of the most precious metals, the extraction of its ore is very important for the economic stability of the country. Hence, the hoisting operation for a deep Gold mine has been considered in the present problem.

As the mining industry is quite developed in our country, and we are quite rich in our natural resources, there are a number of Gold mines. Every mine has a different hoisting equipment, hence it is not possible to consider the operation of hoists in general. With a view to be specific, and yet useful and important, the author has considered the operation of hoist used for Gifford's winder, Gifford's shaft. (Champion Reef Mines, Kolar Gold Fields, Mysore), the biggest winder in India and second biggest in the World. Practical data were obtained from the actual operation of the hoist in order to find its optimum control.

1.3 Criterion for Optimum Hoisting Operation

For optimal control of hoisting operation, we can optimize the system either with respect to time or with respect to energy consumption. For minimum-time hoisting, the hoisting motion should be started from rest with uniform (or variable) acceleration by applying maximum accelerating torque, and then switch over to retardation with uniform retardation by applying maximum retardation (or braking) torque, such as to reach the end of the motion just with zero velocity. Thus there is no period of constant speed motion. But we can not allow it to happen, in practice, because of the speed constraint involved, that is the speed of hoisting should not exceed the maximum safe permissible value. Also, when we want to optimize with respect to time, the energy consumption in hoisting will be maximum.

As for the optimisation of hoisting operation with respect to energy consumption, the minimum energy consumption will take place only when the hoisting time is infinite, which we can not allow to happen. Therefore, to optimize the hoisting operation, we have to make a compromise between the two optimization criteria-time-optimum and energy-optimum operations.

If the hoisting time is specified, we can find the minimum-energy control of the hoist to complete hoisting in that time, Or, otherwise, if the energy consumption is specified, we can determine the corresponding minimum-time control. But as there is no such specification made in the present problem, we shall have to consider all possible values of hoisting time and energy consumption for various values of system parameters and then select the optimum values associated with the optimum hoisting operation.

CHAPTER-2

GENERAL DESCRIPTION OF HOISTS AND HOISTING

2.1 Elements of Hoisting System

A mine hoist consists of the following elements:

a. The hoisting or Winding Machine- It is the most important element of the hoists. It may be driven either by steam or electricity, but modern practice is to use only electrically driven machines. The winding machine can be either an a.c. motor or a d.c. motor, but D.C. series motor is used most commonly because of better speed control under varying load conditions. The speed control of the winding machine is done by employing D.C. Ward-Leonard method.

b. The head frame- It consists of a pulley-system to guide the ropes properly into the mine-shaft.

c. The mine-shaft- To work deep inside the earth to dig ore, a deep pit or shaft is dug first. The depth of the shaft depends upon the availability of ore and working conditions. The shaft may be either vertical or inclined. The cages and skips are guided deep inside the mines through these shafts. Once we reach a certain level inside the mine, we can prepare a temporary platform there and dig side-ways also.

d. <u>The cages-</u> These are used for handling the material and transporting the men in and out of the shaft. There may be separate cages for men and material, or same cage with separate compartments for men and material, may be used. The cage is suspended in the shaft through wire ropes, carried over the head frame and connected to the winding drum.The cage runs on rails provided at the four corners of the mine-shaft.

e. <u>The Wire Rope-</u> It is used to hoist cages, cars, and skips in the mine-shaft. It has multistrand construction with Manila rope as its core. It has, normally, a factor of safety of 5 to 8 for carrying the load. Its normal life, as specified by Metalliferrous Mines Regulations is $3\frac{1}{2}$ years.

f. <u>The Safety Devices-</u> Various safety devices, e.g. end limit switch, emergency trip switch, safety dogs, Humble Hook and Catch plate, depth indicator with warning bell, automatic contrivances, etc. are provided with the hoists to check faulty operation and avoid damage to men and material.

2.2 Types of Hoists and Hoisting:

Gold mines, normally, are very deep, the depth ranging from 2000 metres to 3000 metres. Hoisting from such great depths may be done in one or more than one stages, usually not more than three, each stage comprising a separate and complete hoisting system. Unless restricted because of unfavourable working conditions, it is preferred to adopt single stage hoisting.

Usually the same hoist, with separate cages, or separate compartments in the same cage, is used for both men and material transportation, but some times separate hoists are provided for the two . (Men and material in the same cage, or same compartment, are not allowed by Mines Act). These hoists may operate in separate shafts, or in separate compartments of the same shaft.

Hoists are arranged to operate unbalanced, balanced, or counter-weighted. Unbalanced hoisting consists of a single drum winding machine which winds or unwinds one rope attached to the cage, operated in a single compartment or shaft. The winding machine provides the entire force necessary for hoisting. Balanced hoisting consists of either a single-drum winding machine which winds two ropes, or a double drum machine, each drum of which winds one rope. In either case, one rope is wind 'on' while the other rope winds 'off'. The ropes are attached to cages which operate in separate compartments of the shaft. Thus when one cage (loaded) goes up, the other cage (empty) comes down. The winding machine provides only the force necessary to nullify the difference in rope pulls between the ascending load and the descending load. Counter-weighted hoisting is similar to single-drum balanced hoisting, except that one of the ropes is attached to a counterweight, equal in weight to that of the empty cage plus one half of the weight of the material. The advantage of using the counterweight is that the net torque required for winding is reduced, hence the energy consumption is also less than the unbalanced hoisting.

2.3 <u>Ore Handling Capacity</u>

In general, hoists for shallow mines have larger load capacities with lower speeds, while those for deep mines have smaller load capacities with higher speeds. In hoists for deep mines, the weight of the wire rope is a large proportion of the lifted load, which consists of the cage together with its contents, plus the weight of the length of rope from which the cage is suspended. This total load is limited by the strength of the wire ropes available, which is the reason that hoists for shallow mines can carry greater loads than those for deep mines. To compensate for the reduced lifted load for deep mines, it is necessary to use higher rope speeds to obtain the desired output. The limitation on the rope speed is the horse power of the available hoisting motors. This limitation applies to hoists for deep and shallow mines both.

During any given period - a working day, for example- effective or handling capacity of the hoists depends upon the maximum load a hoist can carry on each trip, and the number of round trips it can make. Load per trip depends on the hoist size and its lifting power, and trips per day on its speed. Load per trip multiplied by the number of trips per day, multiplied again by the number of hoists in operation, roughly indicates the total handling capacity of the hoisting system. It should include ample margin for future expansion of the work(if expected), as providing extra capacity in the beginning is often less expensive than making alterations later on.

CHAPTER-3

DESCRIPTION OF THE HOISTING SYSTEM AND ITS OPERATION

3.1 Hoisting System

The hoisting system for Gifford's vertical shaft, Champion Reef Mines, Kolar Gold Fields, Mysore State, consists of double-drum Gifford's Winders (called North winder and South Winder), along with two D.C. series motors, geared to the drum-shafts. The two drums, having opposing winding motion, are connected through clutch plate, one drum being 'fixed' and other 'free'. The speed of the D.C. motors is controlled employing D.C. Ward Leonard method of speed control. The drums have V-grooves and the rope is carried in these grooves. One cage, having double-decks, is connected to each winding drum through wire rope, carried over the head-frame pulley. The two cages run in two separate compartments of the same shaft. The cages run over four rails, provided on the four corners of the shaft compartment. Safety devices, speed indicator, depth indicator , emergency trip switch, automatic contrivances etc., are provided near the operator's seat within his easy reach. The operator's seat is on a raised platform to avoid usual disturbances. Communication through telephones, and other signalling facilities are provided between the operator and main control room, and between the operator and persons working inside the mine.

3.2 Operational Data:

The operational data, regarding the hoisting equipment and its operation is noted below:

Maximum Depth of Wind	: 2000 metres
Length of Rope	: 2210 metres
Dia. of the Rope	: 0.0477 metres
Weight of Rope per metre	: 9.04 kg/m.
Number of Drums	: Two
Dia. of the Drum	: 6.0 metres
Rotational Moment of Inertia of the drum	: 80,000 kg.sec^2 (ap
Revolutions per minute of the drum	: 26.6
Revolutions per minute of the motor	: 250
Number of Motors	: Two
Rated voltage of motor	: 500 volts (D.C.)
Rated h.p. of each motor	: 1,250 h.p.
Maximum Peak h.p. of each motor	: 3,000 h.p.
Method of Speed Control	: D.C.Ward-Leonard
Weight of cage, attachments and trolleys	: 5055 kgs.
Maximum Ore carrying capacity	: 4535 kgs.

Maximum Wind Speed	:	15.25 m/sec.
Maximum Acceleration rate	:	2.5 m/sec^2
Maximum Retardation rate	:	3.0 m/sec^2
Average Number of Trips per day	:	120

3.3 Motor Operation Under Varying Torque Conditions:

When a d.c. (or a.c.) motor has to work under varying conditions as regards to load, direction of torque and/or motion, it is helpful in understanding the motor operation to plot the speed torque curves according to the plan shown in Fig.1. The two axes fix four quadrants in one or more of which the speed and torque of a motor can be represented under all operating conditions. Thus, when speed and torque are both positive, as, for example, in hoisting a load, the top right hand section of the diagram, known as quadrant 1, is used. In the top left hand section, Quadrant 2, speed is positive and torque, directed as shown is negative. This means that, under this operating condition, the machine torque opposes, and therefore brakes, the motion. In the bottom left hand section, Quadrant 3, torque and speed both are negative or, in the case of the motion being used as an illustration, the load is driven by the motor in the downward direction (lowering). Finally, in Quadrant 4, speed is negative and

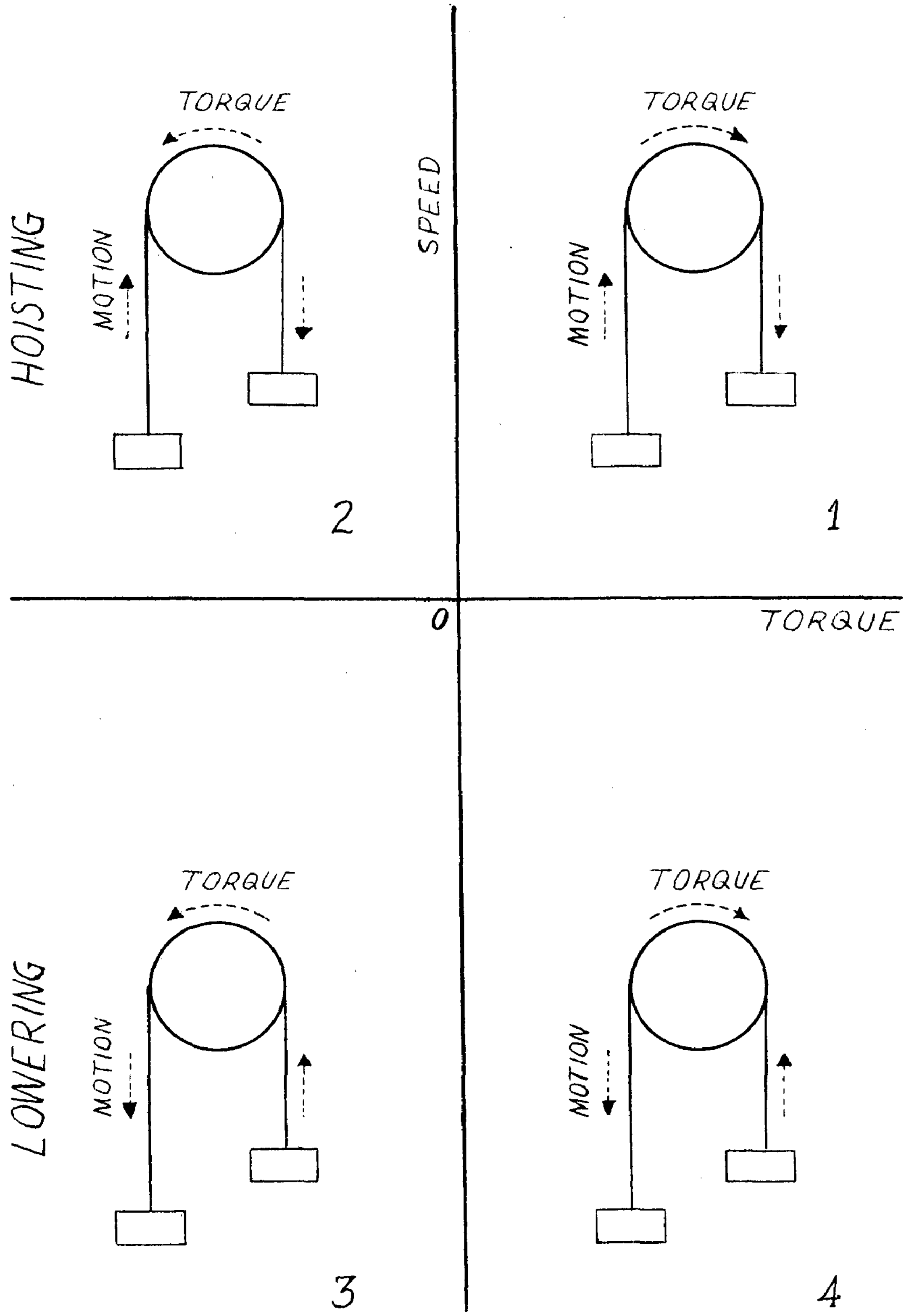

FIG. 1 - MOTOR OPERATION

torque is positive. Thus under this operating condition, the motion in the downward direction is resisted by the motor which acts as a brake. In other words, the overhauling load drives the machine as a dynamo, and the latter converts the energy of motion into electric energy.

3.4 HOISTING OPERATION

The schematic arrangement of the hoisting system considered is as shown in Fig.2. If we consider the ascending cage as loaded with ore, and the descending cage as empty, the hoisting operation can be explained as follows:

The ore is loaded in the empty cage at the bottom of the mine shaft, the loading time being proportional to the loaded ore. As the loaded cage is initially at rest, accelerating torque is applied to start the motion, till the cages attain the specified speed. Then the cages travel with this speed throughout a major part of their run.

As the loaded cage goes up, the empty cage, connected to the other drum, automatically comes down. With the uplift of ascending cage, the length of the rope suspension, and hence the weight of the corresponding length of the rope suspension, goes on decreasing on the ascending side, and the same is increased on the descending side. As the

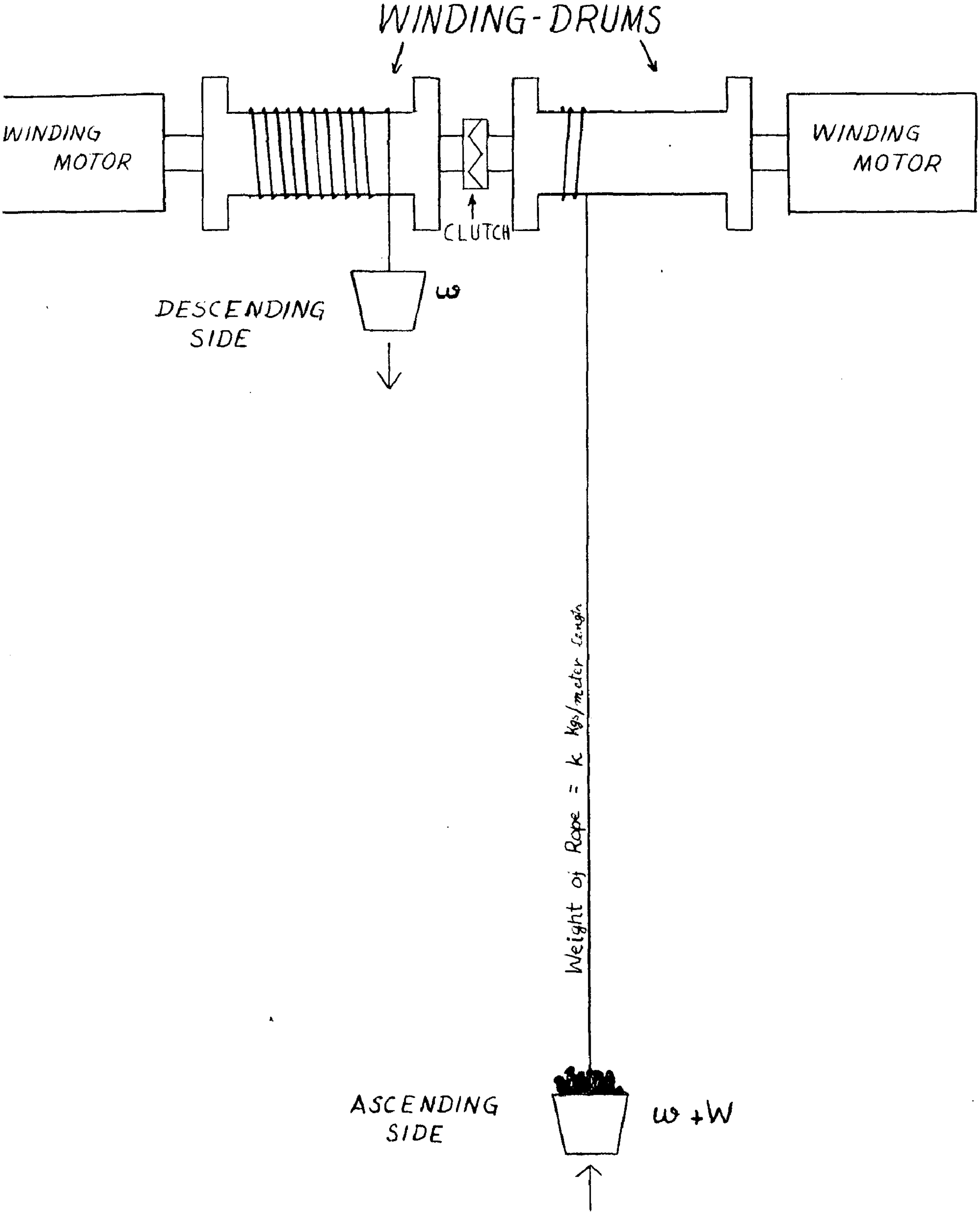

FIG. 2 - HOISTING SYSTEM

torque necessary to drive the winding drum depends on the difference of load on ascending side and descending side, it goes on decreasing with the travel of the cages because the difference of load on ascending side and descending side increases by the double weight of the length of rope increased or decreased on either side. After some time, when the weight of the empty cage plus the weight of the rope suspension becomes comparable with the weight of the loaded cages plus weight of rope suspension, the driving torque becomes negligibly small (only to compensate for frictional torque). With further travel of the cages, driving torque becomes negative, i.e. the winding machine works as a dynamo and some torque is developed which is effectively used for regenerative braking of the motor, to check against the overspeeding of the cages.

When the cages reach near the end of their travel, it is necessary that they are braked, so as to stop them just at the end points of their run. To achieve it, retarding torque that gives uniform retardation is applied to winding drum, and the cages are safely brought to rest. If, by chance, there is some mistake in operation, or proper retarding torque is not applied; the safety devices become operative and the cages are stopped at the end points, without causing any damage to men, material and equipment.

During the constant speed run of hoisting operation, when the driving torque becomes zero or negative, no energy is needed to be supplied to maintain the motion. Rather, the system develops some energy that may be used for regulating the speed of hoisting to keep it within the specified limits. Hence during this period of zero or negative driving torque, no energy consumption takes place.

During the retardation (braking) period, the negative torque developed is utilized for the regenerative braking of the hoist. As the energy required to provide the braking torque is generated by the system itself, no external energy is required to be supplied to the hoisting system for its braking. Therefore, during retardation also, there is no energy consumption.

Thus, it is clear from the above that during the hoisting operation, the energy is consumed only till the driving torque is positive (greater than zero). After the point of travel when the driving torque becomes zero, no energy is required to be supplied to the system for consumption.

CHAPTER -4

DERIVATION OF TORQUE EQUATIONS

4.1 Equivalent Hoisting System

As in Fig.(2), the actual hoisting system consists of two hoisting-drums, with their associated driving motors. The two drum shafts are engaged through a clutch assembly. The winding direction of the ropes on the two drums is opposite i.e. when the rope is wound on one drum, it is unwound onthe other drum and vice-versa. Thus, in fact, the two hoisting drums can be represented by a single equivalent hoisting drum, with the rope having a few turns (coils) on the drum, and carrying the cages on both of its ends. When the drum rotates, the rope is wound on the drum on one end, thus hoisting 'up' the cage on this end, and the rope, on the other end is unwound, thus hoisting 'down' the cage on this end. The length of the rope wound on the drum is equal to the length of the rope unwound from the drum. Thus at any time, and at all times, the number of turns of rope (coils) on the drum remains the same. The equivalent hoisting system is shown in Fig.3(a). Figure 3(b) shows the simplified schematic of the hoisting system, to be used to derive the various torque relationships.

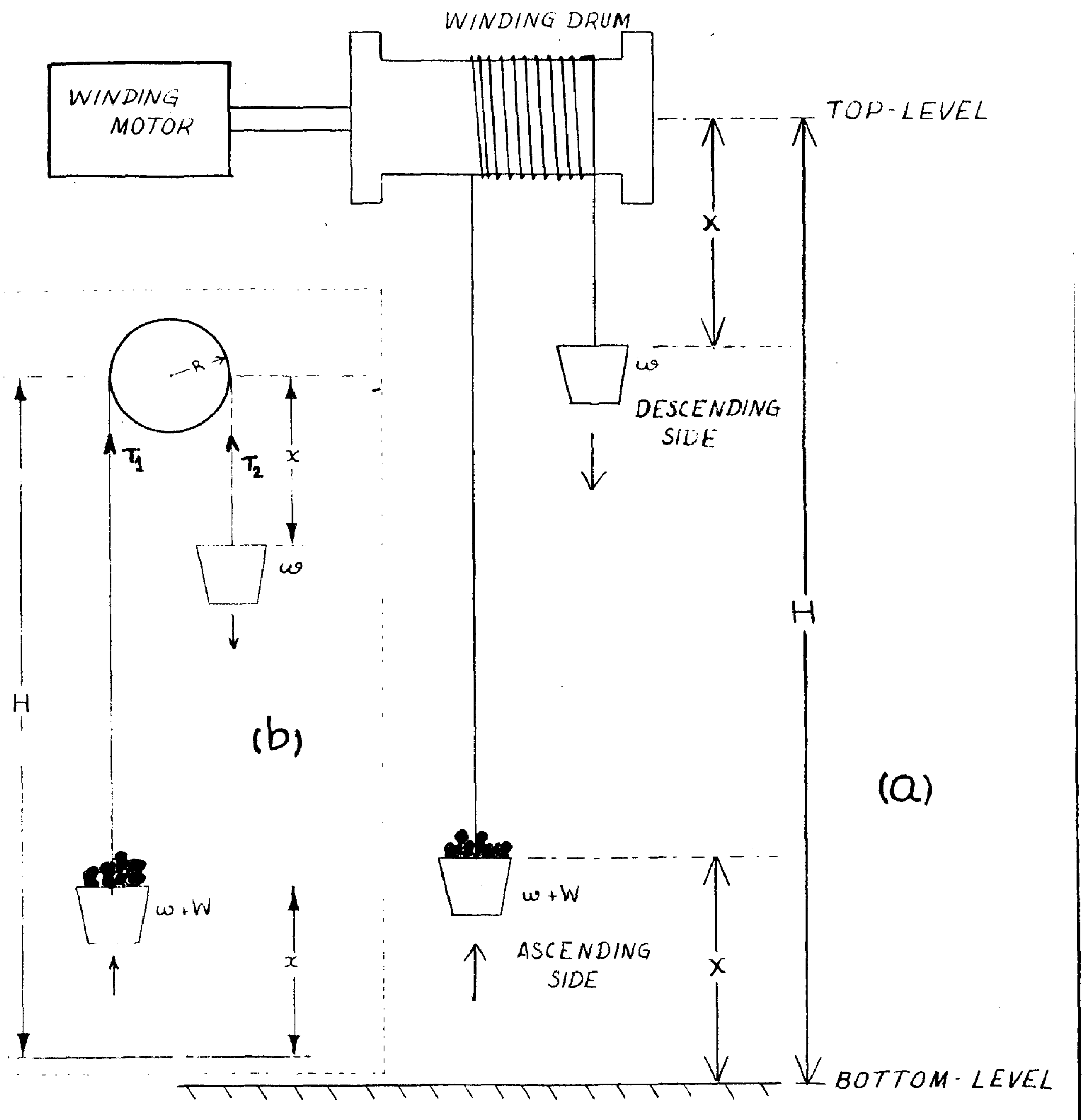

FIG. 3- EQVT. SINGLE DRUM SYSTM

4.2 Torque Equations Neglecting the Weight of the Rope.

The torque equations, for the equivalent hoisting system, neglecting the weight of the suspension rope can be determined inthe following way:

Let w = weight of the cage and its attachment,

W = weight of the ore loaded in the cage,

R = radius of the hoisting drum,

H = depth of mine,

α = linear acceleration rate (in m/sec^2)

β = linear retardation rate (in m/sec^2)

Let x be the displacement of the cages from the position of rest at any point of time t.

Let T_1 and T_2 be the tensions in the rope on the ascending side and descending sides respectively of the rope.

Then, during acceleration period,

force acting onthe ascending side $T_1-(W+w) = (W+w)\frac{\alpha}{g}$

force acting on the descending side $w - T_2 = w\frac{\alpha}{g}$

$$\therefore \quad T_1 = (W+w)\left(1+\frac{\alpha}{g}\right)$$

$$T_2 = w\left(1-\frac{\alpha}{g}\right)$$

$\therefore$ Effective force of tension on the drum

$$T_1-T_2 = (W+w)\left(1+\frac{\alpha}{g}\right)-w\left(1-\frac{\alpha}{g}\right)$$

$$\text{or} \quad T_1-T_2 = \left\{W + (W+2w)\frac{\alpha}{g}\right\}$$

$\therefore$ Effective torque on the drum, $= (T_1-T_2)\times R$

$$T_{accl} = \left\{ W + (W+2w)\, \frac{\beta}{G} \right\} R \qquad \ldots (4.1)$$

In this expression W is the difference between the loads on the two sides, namely $(w+W)-w$, and the masses undergoing acceleration are $\{(w+W)+w\}$ or $(W+2w)$, which is the sum of the loads on the two sides.

During retardation period,

force acting on the ascending side $T_1-(W+w) = -(W+w)\frac{\beta}{G}$

force acting on the descending side $w-T_2 = -w.\frac{\beta}{G}$

$$\therefore \; T_1 = (W+w)(1-\frac{\beta}{G}); \qquad T_2 = w(1+\frac{\beta}{G})$$

∴ Effective torque onthe drum

$$(T_1-T_2)R = (W+w)(1-\frac{\beta}{G})-w(1+\frac{\beta}{G}) \quad R$$

$$T_{retdn} = \left\{ W - (W+2w)\, \frac{\beta}{G} \right\} R \qquad \ldots (4.2)$$

(The numerical value of retardation rate (β) is taken as positive)

During constant speed run,

force on ascending side $T_1 - (W+w) = 0$

or $T_1 = (W+w)$

force on the descending side $w-T_2 = 0$

or $T_2 = w$

∴ Effective torque on the drum $(T_1-T_2)R = \{(W+w)-w\}R$

or $T_{const.speed} = W.R.$ ... (4.3)

4.3 Torque Equations Considering the Weight of Rope

The weight of the suspension rope (9.04 kg/metre) constitutes an appreciable, part of the total load hoisted up/down, hence it cannot be neglected for determining the torque equation. The weight of the rope on either sides will be proportional to the length of rope on that side.

At any time, when the cages have travelled a distance x from their rest position, the torque equations can be determined as follows:

During acceleration,

force acting on the ascending side

$$T_1 - \{(W+w)+(H-x)K\} = \{W+w+(H-x)K\}\frac{a}{g}$$

or

$$T_1 = \{W+w+(H-x)K\}\{1+\frac{a}{g}\}$$

on the descending side

$$(w+Kx) - T_2 = (w+Kx)\frac{a}{g}$$

or

$$T_2 = (w+Kx)(1-\frac{a}{g})$$

∴ Effective torque on the drum $= (T_1-T_2)R$

or

$$T_{accl} = \left[\{W+w+(H-x)K\}(1+\frac{a}{g}) - (w+Kx)(1-\frac{a}{g})\right]R$$

or

$$T_{accl} = R\left[\{W+(H-2x)K\} + \{W+2w+HK\}\frac{a}{g}\right] \quad \ldots (4.4)$$

Once again, the first term in this expression is the difference of the loads on the two sides, namely $W+w+(H-x)K - (w+Kx) = W+(H-2x)K$, and the second term represents the sum of the masses undergoing acceleration i.e. $W+w+(H-x)K \frac{a}{g} + (w+Kx)\frac{a}{g}$.

By analogy, the torque equation during retardation period, with retardation rate of β, is as given below:

$$T_{retdn} = R\left[\{W+(H-2x)K\} - \{W+2w+HK\}\frac{\beta}{g}\right] \quad \ldots (4.5)$$

During constant speed run, there is no acceleration or retardation, hence the torque equation is obtained by putting a or β as zero

$$T_{const.speed} = R\{W + (H-2x)K\} \quad \ldots (4.6)$$

In these equations, the torque due to frictional forces has been neglected. The effect of this frictional torque will be to increase the overall effective torque on the drum-shaft. This frictional torque may be taken as constant approximately. As the torques, and associated energy consumptions, are to be compared under varying operating parameters, it will not adversely affect the equations if this constant frictional torque is neglected. For this reason, and also for the sake of simplicity in the formulation, this frictional torque has been neglected.

4.4 Effect of Inertia of Winding Drum:

In the above mentioned torque equations, the effect of torque due to inertia of the hoisting drum has not been considered. In fact, this inertial torque plays an important role in the hoisting operation, hence it has to be incorporated in the torque-equations. During acceleration, the torque developed should not only be be able to accelerate the moving bodies (cages, load etc.) but also to accelerate the winding drum from its rest or inert stage. The torque, necessary to accelerate the drum, will be I.α, where I is the rotational moment of inertia of the drum, and it will be added to the torque necessary to accelerate the loads on both sides of the drum.

Thus nett torque during acceleration is given as

$$T_{accln} = \left\{W+(H-2x)K+(W+HK+2w)\frac{a}{g}\right\}R+I.\alpha$$

or

$$T_{accln} = \left\{W+(H-2x)K+(W+HK+2w+I.\tfrac{g}{R})\frac{a}{g}\right\}R \quad \ldots (4.7)$$

During the last stage of the run, i.e. before the cages are brought to rest by applying some retarding torque, the load on the descending side will be more than the load on the ascending side (because of the length of rope suspension). Hence loads will try to drive the drum in the opposite direction. This torque, trying to drive the hoisting drum in the opposite direct-ion, thus causing the driving motor to operate as a dynamo, will be opposed by the inertial torque of the winding drum. Hence the nett torque acting on the drum shaft during retardation period will be

$$T_{retdn} = \left\{W+(H-2x)K-(W+HK+2w)\frac{a}{g}\right\}R-I.\beta$$

or

$$T_{retdn} = R\left\{W+(H-2x)K-(W+HK+2w+I.\frac{g}{R})\frac{a}{g}\right\} \quad \ldots (4.8)$$

This torque is used for regenerative braking of the system, i.e. whatever energy is developed during this period, that is consumed for regenerative braking of the system or , in otherwords, the mechanical energy stored in the moving hoisting system and rotating hoisting drum is converted into electrical energy, and this electrical energy is used for regenerative breaking of the hoisting system. Thus net energy consumption during this period may be taken as zero , if the torque during retardation period is negative.

During constant speed run, the inertial torque will not effect the hoisting motion ($I.\alpha = 0$ as $\alpha = 0$). Therefore, the torque equation during constant speed run will remain unchanged.

$$\therefore T_{const.speed} = R\left[W+(H-2x)K\right] \quad \ldots (4.9)$$

CHAPTER 5

FORMULATION OF OPTIMAL OPERATION PROBLEM FOR THE ANALYSIS OF HOISTING SYSTEM

5.1 Parameters of the system

Before laying out the objectives of the system and proceeding for their detailed analysis, it becomes necessary to first enumerate the various parameters, fixed and/or variable, effecting the operation of the system. These parameters are listed below:

(A) Fixed Parameters- Depth of Mine; Weight of cage and its attachments; weight of rope per unit length; loading capacity of the cages.

(B) Variable parameters-

(i) independent- velocity of operation; rate of acceleration; rate of retardation, loading/unloading time.

(ii) dependent- times for acceleration and retardation, and also for constant velocity; no. of trips per day; distances travelled during acceleration retardation and constant velocity runs.

5.2 Objectives of Analysis

The broad objectives for the analysis of system can be laid down as:-

(1) To determine the optimum values of variable

system parameters (velocity, acceleration/retardation rates etc.), within the specified limits, to minimize the overall energy consumption during the hoisting operation.

(2) To determine the optimal economic operation of the system, keeping in view the energy consumption and the corresponding ore output.

(3) To determine the optimal number of trips per day, assuming the total time for the hoisting operation per day as specified.

To meet the first objective, it is required to determine the equations for the system operation, relating various fixed and variable parameters of the system. From these equations, the energy consumption for various values of variable parameters can be determined. The problem will then be to choose the values of these variable parameters, giving minimum energy consumption under specified conditions.

To meet the second objective, it is required to determine the energy consumption for different outputs. A number of sets of solutions will be obtained, giving energy consumption and associated ore output. A relationship between the two will have to be established, by comparison or plotting graphs etc. to determine the optimum operation of the system, from the point of view of economy.

To meet the third objective, it is necessary to see the effect of time of hoisting operation, time of loading/unloading the ore, on the energy consumption and ore output. Then the optimum time of operation per trip, ~~and the optimum time of operation per trip,~~ and the optimum number of trips per day as well, can be determined as the total time of operation per day is specified.

5.3 System Equations with Specified Constraints:

As has been seen in the previous chapter, the torque equation for the hoisting system is

$$T = R\left[W+(H-2x)K+(W+2w+HK+I.\frac{\Delta}{R})\frac{a}{g}\right]$$

or

$$\frac{T}{R} = W+HK-2Kx+(W+2w+HK+I.\frac{\Delta}{R})\frac{a}{g} \qquad \ldots (5.1)$$

or

$$a = \frac{2Kg}{(W+2w+HK+I.\frac{\Delta}{R})} \cdot x + \frac{T}{R} \cdot \frac{g}{R(W+2w+HK+\frac{I\Delta}{R})} - \frac{(W+HK)g}{(W+2w+HK+\frac{I\Delta}{R})} \qquad \ldots (5.2)$$

[Here $a>0$ for acceleration period, $a=0$ for constant speed run and $a<0$ for retardation period].

In the above expression, W, w, K, H, R, Δ, I are all system constants. Acceleration and retardation rates are also constant. Hence, this expression can be written in the following form also,

$$\alpha = K_1 x + K_2 \cdot \frac{T}{R} + K_3 \qquad \ldots (5.3)$$

where K_1, K_2, K_3 are constants.

In terms of displacement x, we can write

$$\alpha = \ddot{x} = K_1 x + K_2 \frac{T}{R} + K_3 \qquad \ldots (5.4)$$

If the normalised vectors are used , the above equation can be written in the following form also

$$\ddot{X} = X + u \qquad \ldots (5.5)$$

Now the motion of the hoisting system can be described approximately by the following state equations

$$\left.\begin{aligned} \dot{X}_1 &= X_2 \\ \dot{X}_2 &= X_1 + u \end{aligned}\right\} \qquad \ldots (5.6)$$

where X_1 denotes the normalised position of the cages, the origin of which is taken at the top and bottom ends of the mine, and the positive axis is taken in the direction of hoisting motion, and x_2 denotes normalised velocity of cages. u is the normalised control vector [$u = T/R$ in the present case] , where $u > 0$ means the exertion of hoisting force due to the action of prime mover (driving motor) and $u < 0$ means the application of braking force, and u is assumed to take the value in the range $-1 \leq u \leq u_H/u_B$, where u_H is the maximum value of hoisting force, and u_B is the maximum value of braking force.

The end point conditions are $X_1(o) = 0$, $X_1(t_f)=H$ and $X_2(o) = X_2(t_f) = 0$, where t_f is the final time at the end of the motion. It means that the initial and final positions of the cages are rest positions, and the cages travel a total distance H in time t_f. Since the energy consumption should be minimised, the performance criterion function must be

$$J = \int_o^{t_f} \frac{1}{2}(u+|u|)X_2 d\tau \qquad \ldots (5.7)$$

In the present case, the control vector is a direct function of displacement x_1, and not of velocity x_2, over the time t when this displacement takes place, hence the performance criterion index for energy consumption can be written as

$$J = \int_o^{x} \frac{1}{2}(u+|u|)t.dx \qquad \ldots (5.8)$$

This time t can be determined independent from the displacement x (t= velocity/acceleration), we can write

$$J = t\int_o^{x} \frac{1}{2}(u+|u|)dx \qquad \ldots (5.9)$$

Moreover the restrictions are $X_2 \leq V_m$, $|\dot{X}_2| \leq |a_m|$ where $|a_m|$ is the magnitude of maximum rates of acceleration/retardation. Besides these restrictions, the constraints $X_2 \geq 0$ and $0 \leq X_1 \leq H$ should be considered in order not to bring about such solutions that the hoist comes to stop or move backwards on its way to the other root position, but since these can be easily dealt with without resorting to any particular method of solving the bounded state variable problem, the substance which makes the problem interesting and complicated is the restrictions $X_2 \leq V_m$, $|\dot{X}_2| \leq |a_m|$

CHAPTER 6

SOLUTION OF THE OPTIMAL OPERATION PROBLEM

6.1 Analytical Approach for the Solution of the Problem

As has been seen in the previous chapter, the state equations defining the operation of the hoisting system are given in terms of normalised vectors, as

$$\dot{X}_1 = X_2$$

$$\dot{X}_2 = X_1 + u \quad , \qquad -1 \leq u \leq u_H/G_B$$

and the performance criterion index for minimum energy consumption as

$$J = \frac{1}{2}\int_0^{t_f} (u+|u|)X_2 d\tau$$

with associated constraints $0 \leq X_2 \leq V_m$, $X_1 \geq 0$ etc.

This problem, theoretically, is very much similar to the problem of minimisation of energy consumption for the operation of a train running between two fixed terminals, and can be solved as a bounded state variable problem by the method suggested by Kunihiko Ichikawa,[1] employing the Langrangian multipliers converting the problem into an unconstrained one, and Hamiltonian Jacobi equations. But here the problem is not concerned only with the minimisation of energy consumption, but also to maximise ore output so as to have overall economic operation. An analytical approach for the solution of the problem would have only complicated the issue. As the numerical values of various system parameters, constraints etc. are readily available from the actual data, it was decided to go for the numerical approach for the solution of the problem, giving a large number of sets of solutions for various values of system parameters. The optimum solution can then be determined by the comparison of these solutions, plotting graphs etc.

6.2 Numerical Approach for the Solution of the Problem

In the numerical approach for the solution of the problem, the value of energy consumption (from the performance criterion index) will be determined for different values of velocity, acceleration and retardation rates, loading etc. The total time of operation per hoisting trip and the total number of trips per day can also be determined, the total hoisting time per day being specified. The total energy consumption per day and associated ore outputs per day are also determined. These will be available for different values of velocity, acceleration, and retardation rates. By appropriately comparing these solutions, by plotting graphs etc. it will not be difficult to determine the optimum point giving the most economic operation under specified conditions. Thus the optimal hoisting time operation, giving minimum energy consumption related with maximum ore output, can be determined.

6.2. Numerical Approach for the Solution of the Problem

6.2.1 Evaluation of the Performance Criterion Index

As has been seen in the previous chapter, the performance criterion index for minimum energy control of hoisting operation is

$$J = \int_0^H \tfrac{1}{2}\tau(u+|u|)\, dX$$

Now, since the total hoisting operation consists of three periods -(a) acceleration period, with distance covered as X_1, (b) constant speed period, with associated distance covered as X_2, and (c) retardation period, with associated distance travelled X_3 (clearly, $X_1+X_2+X_3 = H$), the performance criterion index can be written as

$$J = t_1\int_0^{X_1} \tfrac{1}{2}(u+|u|)dx + t_2\int_{X_1}^{X_1+X_2} \cdot \tfrac{1}{2}(u+|u|)dX + t_3\int_{X_1+X_2}^{H = X_1+X_2+X_3} \tfrac{1}{2}(u+|u|)dX$$

or $\qquad J = J_1+J_2+J_3$

where $J_1 = \frac{t_1}{2}\int_0^{X_1}(u+|u|)dx$ for acceleration period

$J_2 = \frac{t_2}{2}\int_{X_1}^{X_1+X_2}(u+|u|)dx$ for constant speed period

$$J_3 = \frac{t_3}{T}\int_{X_1+X_2}^{H = X_1+X_2+X_3} (u+|u|)\,dx \quad \text{for retardation or braking period}$$

Here t_1, t_2 and t_3 are times for acceleration, constant speed and retardation periods respectively.

The values of J_1, J_2 and J_3 can now be determined separately also, but for the overall optimum operation, it is necessary to consider only J i.e. the sum of J_1, J_2 and J_3. The index J gives the energy consumption during the complete hoisting operation, whereas the indices J_1, J_2 and J_3 give the energy consumptions during acceleration period, constant speed period and retardation period respectively. The objective here is to minimize J with respect to the system parameters and are output.

It has also been seen in the previous chapter that the control 'u' is given by the force T/R. Hence,

$$u = T/R$$

Thus, during acceleration period,

$$u_1 = \frac{T_{accln}}{R} = \left[V+(H-2x)K+\left(V+HK+2v+\frac{I_a g}{R}\right)\frac{\alpha}{g}\right]$$

or

$$u_1 = (V+H.K)-(2K)x+\left\{\frac{1}{g}\left(V+H.K+2v+\frac{I_a g}{R}\right)\right\}\alpha \qquad (0 \le x \le X_1) \qquad \ldots (6.1)$$

Similarly, for constant speed period,

$$u = u_2 = \frac{T_{const.speed}}{R} = (V+H.K)-(2K)\,x \qquad (X_1 \le x \le X_1+X_2) \qquad \ldots (6.2)$$

and for retardation period

$$u = u_3 = \frac{T_{retdn}}{R} = (W+H.K)-(2K)x-\left\{\frac{1}{G}(W+HK+2w+\frac{IG}{R})\right\}\beta \quad \ldots (6.3)$$

$$(X_1+X_2 \leq x \leq X_1+X_2+X_3)$$

In these expressions, W, H, K, w, I, G, R etc. are all constants, hence the control equations can be written in the following form

$$u_1 = A + B\alpha - Cx \qquad (0 \leq x \leq X_1)$$

$$u_2 = A - C\,x \qquad (\alpha=0,\; X_1 \leq x \leq X_1+X_2)$$

$$u_3 = A - B.\beta - C\,x \qquad (X_1+X_2 \leq x \leq H)$$

where,

$$A = W + HK$$

$$B = \frac{1}{G}(W+H.K+2w+\frac{I.G}{R})$$

$$\text{or } B = \frac{1}{G}(A+2w+\frac{I.G}{R})$$

$$C = 2K$$

Thus, the performance criterion indices can be written as:-

$$J_1 = \frac{t_1}{2}\int_0^{X_1}(u_1+|u_1|)dx$$

$$J_2 = \frac{t_2}{2}\int_c^{X_2+X_1}(u_2+|u_2|)dx$$

$$J_3 = \frac{t_3}{2}\int_{X_1+X_2}^{H}(u_3+|u_3|)dx$$

6.2.2 <u>Evaluation of Energy Consumption</u>

Now, the type of performance criterion given above tells that energy consumption takes place only when control

is positive. If control (u) is zero or negative, the term within the bracket becomes zero as then [illegible],
$u = -|u|$, $u + |u| = 0$. It accounts for the regenerative braking of the system. It means that energy is consumed only when accelerating torque is applied to the system.

When no torque is applied (during coasting); or negative torque is applied, which is utilised for regenerative braking of the hoist, there is no energy consumption. In the present case, as the load is varying during constant speed period also, it is required to apply some positive torque to maintain the speed. Only during the retardation period, the torque may go negative. Hence the performance indices can be written as:

$$J_1 = t_1 \int_0^{X_1} u_1 . dX \qquad \ldots (6.4)$$

$$J_2 = t_2 \int_{X_1}^{X_1+X_2} u_2 dX \qquad \ldots (6.5)$$

$$J_3 = t_3 \int_{X_1+X_2}^{H} u_3 dX \quad \text{if} \quad u_3 \leq 0 \qquad \ldots (6.6)$$
$$= 0 \quad \text{if} \quad u_3 \leq 0$$

Substituting the values of u_1, u_2 and u_3,

$$J_1 = t_1 \int_0^{X_1} (A+B\ \alpha-Cx)dx \qquad \ldots (6.7)$$

$$J_2 = t_2 \int_{X_1}^{X_1+X_2} (A-Cx)dx \qquad \ldots (6.8)$$

$$J_3 = t_3 \int_{X_1+X_2}^{H} (A-B.\beta-Cx)dx \quad \text{or} \quad 0 \qquad \ldots (6.9)$$

Thus, during acceleration period,

$$J_1 = t_1 \left[AX + B.a.X - \frac{C}{2} X^2 \right]_0^{X_1}$$

or
$$J_1 = t_1.X_1 \left[A + B.a - \frac{C}{2} X_1 \right] \qquad \ldots (6.10)$$

During constant speed period

$$U_2 = A - C X$$

This control becomes zero when $X = A/C$ and negative when $X > A/C$. Hence

$$J_2 = t_{12} \int_{X_1}^{X=A/C} u_2.dX \qquad \text{for } X_1 < A/C$$

and
$$J_2 = 0 \qquad \text{for } A/C < X_1+X_2$$

(here t_{12} is the time taken to cover the distance for X_1 to $X=A/C$)

Let $X = A/C = X_{12}$

$$\therefore J_2 = t_{12} \int_{X_1}^{X_{12}} (A-CX)dX \qquad X_1 < X_{12}$$

or
$$J_2 = t_{12} \left[AX - \frac{C}{2} X^2 \right]_{X_1}^{X_{12}}$$

or
$$J_2 = t_{12}(X_{12}-X_1) \left[A - \frac{C}{2}(X_{12}+X_1) \right] \qquad \ldots (6.11)$$

For the distance from $X = X_{12}$ to $X = X_1+X_2$, the control is negative, making $u_2+|u_2| = 0$, hence no energy consumption will take place during this period. The hoisting motion will continue under the control of the loads themselves, as the load on the descending side becomes more than the load on ascending side because of the weight of suspension rope.

During retardation or braking period, control is

$$u_3 = A - B.\beta - CX \qquad X_1+X_2 \le x \le H$$

For $X = X_1+X_2$ or $H - X_3$,

$$u_3 = A - B\beta - C(H-X_3) \qquad = \text{a negative value}$$

For $X = H$, $u_3 = A - B\beta - CH$ = a negative value

Thus the control always remains negative during retardation period, making $u_3 + |u_3| = 0$,

and $$J_3 = 0 \,. \qquad \ldots (6.12)$$

The overall energy consumption is given by

$$J = J_1 + J_2 + J_3$$

or

$$J = t_1.X_1\left[A + B.a - \frac{C}{2}X_1\right] + t_{12}(X_{12}-X_1).\left[A - \frac{C}{2}(X_{12}+X_1)\right] \qquad \ldots (6.13)$$

It is now required to determine the values of variable system parameters (V, a, β) giving minimum value of energy consumption (J).

6.2.3 Evaluation of different distances covered and related times:-

During acceleration, the hoisting cages cover a distance X_1 in time t_1 with acceleration rate a to attain a velocity V from rest. Therefore,

$$X_1 = \frac{V^2}{2\alpha}, \quad t_1 = \frac{V}{\alpha}$$

or $$X_1 = \frac{1}{2}\alpha . t_1^2$$

During retardation, the cages come to rest from velocity V, with uniform retardation rate β, covering a distance X_3 in time t_3. Therefore,

$$t_3 = \frac{V}{\beta}, X_3 = \frac{V^2}{2\beta} = \frac{1}{2}\beta . t_3^2$$

During constant speed period, the remaining distance $X_2 = H - (X_1+X_3)$ is covered with velocity V in time t_2. Hence,

$$X_2 = H-(X_1+X_3), \quad t_2 = \frac{X_2}{V}$$

Furthermore, during constant speed period, the control ($u_2 = T/R$) becomes negative at a distance $X = X_{12} = A/C$ from rest. Then the time taken to cover the distance from X_1 to X_{12} is

$$t_{12} = (\frac{X_{12}-X_1}{V})$$

For t t_{12}, the control becomes negative, hence no energy consumption takes place.

6.2.4. Evaluation of No. of Trips, total energy Consumption and ore output per day.

It has been determined that the total hoisting time consists of time taken for acceleration, retardation and constant speed runs. Some time will be consumed in loading/unloading the hoist also. This time for loading/unloading will be approximately proportional to the load of ore in the cages. If this loading/unloading time is denoted by t_ℓ, then the total time of operation for a complete hoisting trip is given as

$$t_{trip} = t_1 + t_2 + t_3 + t_\ell$$

where t_1, t_2 and t_3 are the time for acceleration, constant speed and retardation runs respectively of the hoist.

The hoisting operation takes place only for a specified period in the day (normally 12 to 14 hours per day). Assuming that the hoist runs continuously during these hours of the day, the total number of trips per day is given as

$$N_{trip} = \frac{\text{total time of hoisting operation per day}}{\text{total time of operation per hoisting trip}}$$

Having determined the number of trips per day, the total energy consumption per day and total ore output per day can be determined simply by multiplying the energy consumption per trip and ore loading per trip by the number of trips per day.

CHAPTER -7

DISCUSSION OF THE RESULTS

A simple computer programme was developed to calculate the number of trips, energy consumption and ore output per day for different values of operating velocity, acceleration and retardation rates, and loading of the hoist. The results obtained are listed in the Appendix. Following observation can be obtained from these results.

1. As the velocity of operation is increased, the acceleration and retardation periods are increased, whereas the constant velocity running period is reduced. As the major part of energy consumption takes place during acceleration period only, the total energy consumption per trip is increased. At the same time, the time of operation per trip is reduced, making a larger number of trips per day possible. But this increase in number of trips is comparably less effected than the decrease in the energy consumption per trip, and hence the total energy consumption per day is also reduced.

2. For the same velocity of operation, as the rate of acceleration is increased, the time to reach that velocity is decreased, but the energy consumption is increased due to increased acceleration. At the same time, the time of

operation per trip is now reduced, thus making possible a larger number of trips and ore output per day.

3. For the same velocity of operation and acceleration/retardation rates, the ore output and energy consumption are effected by the loading of the hoist also. But the energy consumption is not effected as much as the ore output if the hoist is run under-loaded or overloaded. For example, for same velocity of operation and acceleration/retardation rates, if the hoist is operated 25% underloaded, the energy consumption is reduced by only 1.3% whereas the ore output is reduced by as much as 13.3% . Similarly for 25% overload, the energy consumption is increased by 2.4% whereas the ore output is increased by 10.1% . Hence the hoist should never be run under loaded.

4. For the same velocity of operation, and same loading, if the acceleration/retardation rate is increased, the rate of increase in energy consumption is more than the rate of change in ore output. For example, for velocity of operation at 15.25 m/sec. and full load, the increase in energy consumption, when the acceleration and retardation rates are increased from minimum to maximum, is 10.7% whereas the corresponding increase in ore output is only 1.6% .

Thus our observations can be summarised as below:

(1) The energy consumption decreases with an increase in the value of velocity of operation.

(2) For the same velocity of operation, the energy consumption increases with the increase in acceleration/retardation rates.

(3) Total number of trips per day is inversely proportional to the operating time per trip, and increases with an increase in velocity of operation, acceleration/retardation rates.

(4) Ore output is directly proportional to the number of trips per day, and hence inversely proportional to the time of operation per trip.

(5) For the same velocity of operation, acceleration and retardation rates, the energy consumption and ore output are increased/decreased with an associated increase/decrease in the loading of the hoist, but the ore output is more sharply affected, than the energy consumption, by these changes in the loading of the hoist.

(6) Minimum energy consumption takes place when the velocity of operation is maximum and the rates of acceleration/retardation are minimum.

(7) Maximum ore output is obtained with maximum velocity of operation, and maximum rates of acceleration and retardation, with maximum allowable loading.

CHAPTER -8

C O N C L U S I O N

From the results listed in the Appendix, their analysis and various graphs plotted, it is evident that the two objectives for the optimum economic operation of the hoist-minimisation of energy consumption and maximisation of ore output (which means minimisation of time of operation per trip so that a larger number of hoisting trips per day may be achieved)-are contradictory in nature. It is not possible to meet both the objectives simultaneously- only one objective can be achieved at the cost of the other, if nothing else has been specified. Two things are certain to meet either of the two objectives.

1. The system has to be operated at maximum permissible safe velocity, limited by safety considerations and mines regulations.
2. The system has to be operated at full load, or even somewhat overloaded, if permissible. It should never be operated under-loaded.

To decide the optimum point of operation, either the time limit for a hoisting trip, or the ore output desired per day, must be specified. Then the solutions having the time of operation equal to the specified time can be selected from the set of solutions listed, and the operating point giving the minimum energy consumption can be easily determined simply by observation. In the absence of any such specification, the only thing that can be said about the optimum operating point is that it can be obtained with maximum velocity of operation, maximum loading, minimum loading time and low values of acceleration/retardation rate. Thus , in the present case the optimum operating point has the operating parameters as-

Velocity (V) = 15.25 m/sec., loading = 100% of rated capacity, (if overloading not permitted), acceleration (α) = 1.0 m/sec.^{2} retardation (β) = 1.5 m/sec^2.

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A P P E N D I X --1

COMPUTER-PROGAM

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RAKESH BAI J  M.E.(S.E.O.R.)  OPTIMAL HOIST OPERATION
READ 1,WCAGE,WLOAD,WROPE,H,R,G,DINRT,TRUN
FORMAT(8F10.2)
FORMAT(F4.0,F7.2,2F5.1,F7.2,3F16.2)
WORE=1.25*WLOAD
TLOAD=360.0
A=WORE+H*WROPE
B=(A+2.0*WCAGE+DINRT*G/R)/G
DINRT IS THE INERT.A OF THE WINDING DRUM
C=2.0*WROPE
X12=A/C
SL=1.
V=11.25
ACCLN=1.0
RETDN=1.5
DO 20 I=1,200
T1=V/ACCLN
X1=0.5*ACCLN*T1*T1
T12=(X12-X1)/V
T3=V/RETDN
X3=0.5*RETDN*T3*T3
X2=H-X1-X3
T2=X2/V
TIMET=T1+T2+T3+TLOAD
TLOAD IS THE TOTAL TIME FOR LOADING/UNLOADING THE CAGES
TIMET IS THE TOTAL TIME PER HOISTING TRIP
E1=T1*X1*(A+B*ACCLN-0.5*C*X1)
E2=T12*(X12-X1)*(A-0.5*(X12+X1))
TRETD=A-B*RETDN-C*(H-X3)
IF(TRETD-0.0)16,16,18
E3=0.0
GOTO 19
E3=T3*X3*(A-B*RETDN-C*H+0.5*C*X3)
ETRIP=E1+E2+E3
ETRIP IS THE ENERGY CONSUMPTION PER TRIP
TRIPN=TRUN/TIMET
TRUN IS THE TOTAL OPERATING TIME PER DAY
TRIPN IS THE NUMBER OF HOISTING TRIPS PER DAY
EDAY=ETRIP*TRIPN/100.0
EDAY IS THE ENERGY CONSUMPTION PER DAY
WDAY=WORE*TRIPN
WDAY IS THE ORE OUTPUT PER DAY
PUNCH 2,SL,V,ACCLN,RETDN,TRIPN,ETRIP,EDAY,WDAY
SL=SL+1.
RETDN=RETDN+0.5
IF(RETDN-3.0)20,20,21
CONTINUE
ACCLN=ACCLN+0.5
IF(ACCLN-2.5)12,12,30
V=V+1.00
IF(V-15.25)11,11,40
STOP
END
1055.0    4535.0        9.04   2000.0        3.0        9.81  80000.0    43
```

A P P E N D I X --2
RESULTS

TLOAD=300.0
WORE=WLOAD

V	α	β	Trips	Energy/trip	Energy/day	Output/day
11.25	1.0	1.5	88.68	[illegible]	[illegible]	[illegible]
11.25	1.0	2.0	88.85	2789643400.00	2478585000.00	402932.6
11.25	1.0	2.5	88.95	2789643400.00	2481455800.00	403399.3
11.25	1.0	3.0	89.02	2789643400.00	2483379400.00	403711.0
11.25	1.5	1.5	89.02	2873889100.00	2558369900.00	403711.0
11.25	1.5	2.0	89.19	2873889100.00	2563321900.00	404492.4
11.25	1.5	2.5	89.30	2873889100.00	2566302400.00	404962.7
11.25	1.5	3.0	89.37	2873889100.00	2568293200.00	405276.9
11.25	2.0	1.5	89.19	2917967400.00	2602636900.00	404492.4
11.25	2.0	2.0	89.37	2917967400.00	2607684400.00	405276.9
11.25	2.0	2.5	89.47	2917967400.00	2610722300.00	405749.0
11.25	2.0	3.0	89.54	2917967400.00	2612751500.00	406064.4
11.25	2.5	1.5	89.30	2945047000.00	2629844400.00	404962.7
11.25	2.5	2.0	89.47	2945047000.00	2634950600.00	405749.0
11.25	2.5	2.5	89.57	2945047000.00	2638023900.00	406222.3
11.25	2.5	3.0	89.64	2945047000.00	2640076600.00	406538.4
12.25	1.0	1.5	91.24	2525190100.00	2303997600.00	413775.9
12.25	1.0	2.0	91.44	2525190100.00	2308975800.00	414669.9
12.25	1.0	2.5	91.56	2525190100.00	2311973100.00	415208.2
12.25	1.0	3.0	91.64	2525190100.00	2313975700.00	415567.9
12.25	1.5	1.5	91.64	2612877500.00	2394328600.00	415567.9
12.25	1.5	2.0	91.83	2612877500.00	2399524500.00	416469.7
12.25	1.5	2.5	91.95	2612877500.00	2402652900.00	417012.7
12.25	1.5	3.0	92.03	2612877500.00	2404743000.00	417375.4
12.25	2.0	1.5	91.83	2659227600.00	2442069900.00	416469.7
12.25	2.0	2.0	92.03	2659227600.00	2447401000.00	417375.4
12.25	2.0	2.5	92.15	2659227600.00	2450598800.00	417920.81
12.25	2.0	3.0	92.23	2659227600.00	2452735200.00	418285.1
12.25	2.5	1.5	91.95	2687850000.00	2471593400.00	417012.7
12.25	2.5	2.0	92.15	2687850000.00	2476975600.00	417920.81
12.25	2.5	2.5	92.28	2687850000.00	2480216200.00	418467.57
12.25	2.5	3.0	92.36	2687850000.00	2482381300.00	418832.88
13.25	1.0	1.5	93.51	2300694200.00	2151368000.00	424065.6
13.25	1.0	2.0	93.73	2300694200.00	2156522100.00	425081.61
13.25	1.0	2.5	93.87	2300694200.00	2159626500.00	425693.5
13.25	1.0	3.0	93.96	2300694200.00	2161701200.00	426102.47
13.25	1.5	1.5	93.96	2390816900.00	2246379200.00	426102.47
13.25	1.5	2.0	94.18	2390816900.00	2251786900.00	427128.2
13.25	1.5	2.5	94.32	2390816900.00	2255044100.00	427746.06
13.25	1.5	3.0	94.41	2390816900.00	2257220600.00	428158.94

13.25	2.0	1.5	94.18	2439025300.00	2297191900.00	427128.2
13.25	2.0	2.0	94.41	2439025300.00	2302735300.00	428150.9
13.25	2.0	2.5	94.55	2439025300.00	2306074200.00	428779.7
13.25	2.0	3.0	94.64	2439025300.00	2308305600.00	429194.6
13.25	2.5	1.5	94.32	2468972300.00	2328761100.00	427746.0
13.25	2.5	2.0	94.55	2468972300.00	2334388800.00	428779.7
13.25	2.5	2.5	94.69	2468972300.00	2337778500.00	429402.3
13.25	2.5	3.0	94.78	2468972300.00	2340043800.00	429810.4
14.25	1.0	1.5	95.53	2108392900.00	2014094600.00	433217.1
14.25	1.0	2.0	95.78	2108392900.00	2019397300.00	434357.7
14.25	1.0	2.5	95.93	2108392900.00	2022592400.00	435044.9
14.25	1.0	3.0	96.03	2108392900.00	2024728100.00	435504.3
14.25	1.5	1.5	96.03	2199873500.00	2112578600.00	435504.3
14.25	1.5	2.0	96.29	2199873500.00	2118170100.00	436656.9
14.25	1.5	2.5	96.44	2199873500.00	2121539200.00	437351.5
14.25	1.5	3.0	96.54	2199873500.00	2123791200.00	437815.7
14.25	2.0	1.5	96.29	2249495300.00	2165948900.00	436656.9
14.25	2.0	2.0	96.54	2249495300.00	2171696800.00	437815.7
14.25	2.0	2.5	96.70	2249495300.00	2175160300.00	438514.0
14.25	2.0	3.0	96.80	2249495300.00	2177475300.00	438980.7
14.25	2.5	1.5	96.44	2280532000.00	2199325600.00	437351.5
14.25	2.5	2.0	96.70	2280532000.00	2205171400.00	438514.0
14.25	2.5	2.5	96.85	2280532000.00	2208693800.00	439214.4
14.25	2.5	3.0	96.95	2280532000.00	2211048300.00	439682.6
15.25	1.0	1.5	97.33	1942599800.00	1890710800.00	441386.5
15.25	1.0	2.0	97.61	1942599800.00	1896139800.00	442653.9
15.25	1.0	2.5	97.76	1942599800.00	1899412100.00	443417.8
15.25	1.0	3.0	97.89	1942599800.00	1901600000.00	443928.6
15.25	1.5	1.5	97.89	2034292700.00	1991357700.00	443928.6
15.25	1.5	2.0	98.17	2034292700.00	1997108600.00	445210.6
15.25	1.5	2.5	98.34	2034292700.00	2000575300.00	445985.4
15.25	1.5	3.0	98.46	2034292700.00	2002893000.00	446500.1
15.25	2.0	1.5	98.17	2084852400.00	2046744200.00	445210.6
15.25	2.0	2.0	98.46	2084852400.00	2052672200.00	446500.1
15.25	2.0	2.5	98.63	2084852400.00	2056245600.00	447277.4
15.25	2.0	3.0	98.74	2084852400.00	2058634800.00	447797.1
15.25	2.5	1.5	98.34	2116727000.00	2081643300.00	445985.4
15.25	2.5	2.0	98.63	2116727000.00	2087682800.00	447277.4
15.25	2.5	2.5	98.80	2116727000.00	2091323500.00	448057.4
15.25	2.5	3.0	98.91	2116727000.00	2095757600.00	448576.9

WORE=0.75*WLOAD
TLOAD=240.0

11.25	1.0	1.5	101.13	2381748500.00	2408775800.00	343984.
11.25	1.0	2.0	101.36	2381748500.00	2414074000.00	344741.
11.25	1.0	2.5	101.49	2381748500.00	2417264400.00	345196.
11.25	1.0	3.0	101.58	2381748500.00	2419395800.00	345501.
11.25	1.5	1.5	101.56	2456474300.00	2495302800.00	345501.
11.25	1.5	2.0	101.81	2456474300.00	2500815600.00	346264.
11.25	1.5	2.5	101.94	2456474300.00	2504135300.00	346724.
11.25	1.5	3.0	102.03	2456474300.00	2506353000.00	347031.
11.25	2.0	1.5	101.81	2495691000.00	2540740200.00	346264.
11.25	2.0	2.0	102.03	2495691000.00	2546366000.00	347031.
11.25	2.0	2.5	102.17	2495691000.00	2549753400.00	347492.
11.25	2.0	3.0	102.26	2495691000.00	2552016700.00	347801.
11.25	2.5	1.5	101.94	2519820900.00	2568710900.00	346724.
11.25	2.5	2.0	102.17	2519820900.00	2574406000.00	347492.
11.25	2.5	2.5	102.30	2519820900.00	2577835400.00	347955.
11.25	2.5	3.0	102.39	2519820900.00	2580126500.00	348265.
12.25	1.0	1.5	104.48	2155337700.00	2251911000.00	355364.
12.25	1.0	2.0	104.74	2155337700.00	2257484500.00	356244.
12.25	1.0	2.5	104.90	2155337700.00	2260841900.00	356774.
12.25	1.0	3.0	105.00	2155337700.00	2263085800.00	357128.
12.25	1.5	1.5	105.00	2232801900.00	2344422500.00	357128.
12.25	1.5	2.0	105.26	2232801900.00	2350253900.00	358016.
12.25	1.5	2.5	105.42	2232801900.00	2353766600.00	358551.
12.25	1.5	3.0	105.52	2232801900.00	2356114400.00	358909.
12.25	2.0	1.5	105.26	2273909200.00	2393523600.00	358016.
12.25	2.0	2.0	105.52	2273909200.00	2399491900.00	358909.
12.25	2.0	2.5	105.68	2273909200.00	2403087200.00	359447.
12.25	2.0	3.0	105.79	2273909200.00	2405490000.00	359806.
12.25	2.5	1.5	105.42	2299343600.00	2423913200.00	358551.
12.25	2.5	2.0	105.68	2299343600.00	2429966500.00	359447.
12.25	2.5	2.5	105.84	2299343600.00	2433613000.00	359986.
12.25	2.5	3.0	105.95	2299343600.00	2436050100.00	360346.
13.25	1.0	1.5	107.47	1963429400.00	2110032300.00	365521.
13.25	1.0	2.0	107.76	1963429400.00	2115843900.00	366527.
13.25	1.0	2.5	107.94	1963429400.00	2119346500.00	367134.
13.25	1.0	3.0	108.06	1963429400.00	2121687800.00	367540.
13.25	1.5	1.5	108.06	2042662100.00	2207306900.00	367540.
13.25	1.5	2.0	108.36	2042662100.00	2213420400.00	368558.
13.25	1.5	2.5	108.54	2042662100.00	2217104800.00	369171.
13.25	1.5	3.0	108.66	2042662100.00	2219567800.00	369581.

13.25	2.0	1.5	108.36	2085259000.00	2259578300.00	368558.08
13.25	2.0	2.0	108.66	2085259000.00	2265853600.00	369581.66
13.25	2.0	2.5	108.84	2085259000.00	2269635900.00	370198.58
13.25	2.0	3.0	108.96	2085259000.00	2272164300.00	370610.98
13.25	2.5	1.5	108.54	2111786000.00	2292131800.00	369171.57
13.25	2.5	2.0	108.84	2111786000.00	2298508400.00	370198.58
13.25	2.5	2.5	109.02	2111786000.00	2302351400.00	370817.53
13.25	2.5	3.0	109.15	2111786000.00	2304920400.00	371231.30
14.25	1.0	1.5	110.14	1799389000.00	1981858000.00	374615.74
14.25	1.0	2.0	110.48	1799389000.00	1987876400.00	375753.36
14.25	1.0	2.5	110.68	1799389000.00	1991505200.00	376439.29
14.25	1.0	3.0	110.81	1799389000.00	1993931700.00	376897.95
14.25	1.5	1.5	110.81	1879352000.00	2082540000.00	376897.95
14.25	1.5	2.0	111.15	1879352000.00	2088902900.00	378049.51
14.25	1.5	2.5	111.35	1879352000.00	2092739200.00	378743.81
14.25	1.5	3.0	111.49	1879352000.00	2095304700.00	379208.11
14.25	2.0	1.5	111.15	1923008000.00	2137426600.00	378049.51
14.25	2.0	2.0	111.49	1923008000.00	2143977100.00	379208.11
14.25	2.0	2.5	111.70	1923008000.00	2147926800.00	379906.70
14.25	2.0	3.0	111.83	1923008000.00	2150567900.00	380373.82
14.25	2.5	1.5	111.35	1950399000.00	2171853100.00	378743.81
14.25	2.5	2.0	111.70	1950399000.00	2178521500.00	379906.70
14.25	2.5	2.5	111.90	1950399000.00	2182542300.00	380607.86
14.25	2.5	3.0	112.04	1950399000.00	2185230900.00	381076.73
15.25	1.0	1.5	112.54	1658361600.00	1866357200.00	382784.29
15.25	1.0	2.0	112.92	1658361600.00	1872556700.00	384055.78
15.25	1.0	2.5	113.14	1658361600.00	1876296100.00	384822.73
15.25	1.0	3.0	113.29	1658361600.00	1878797400.00	385335.74
15.25	1.5	1.5	113.29	1737951800.00	1968967300.00	385335.77
15.25	1.5	2.0	113.67	1737951800.00	1975551100.00	386624.27
15.25	1.5	2.5	113.90	1737951800.00	1979522900.00	387401.55
15.25	1.5	3.0	114.05	1737951800.00	1982179500.00	387921.47
15.25	2.0	1.5	113.67	1782206500.00	2025856000.00	386624.27
15.25	2.0	2.0	114.05	1782206500.00	2032653000.00	387921.43
15.25	2.0	2.5	114.28	1782206500.00	2036753100.00	388703.93
15.25	2.0	3.0	114.44	1782206500.00	2039495900.00	389227.38
15.25	2.5	1.5	113.90	1810216900.00	2061832700.00	387401.55
15.25	2.5	2.0	114.28	1810216900.00	2068764200.00	388703.93
15.25	2.5	2.5	114.51	1810216900.00	2072945600.00	389489.58
15.25	2.5	3.0	114.67	1810216900.00	2075742700.00	390015.14

TLOAD=300.0
WORE=1.25*WLOAD

11.25	1.0	1.5	79.95	3242076900.00	2559755200.00	447571.5
11.25	1.0	2.0	79.09	3242076900.00	2564148700.00	448339.7
11.25	1.0	2.5	79.17	3242076900.00	2566792000.00	448801.8
11.25	1.0	3.0	79.23	3242076900.00	2568557200.00	449110.5
11.25	1.5	1.5	79.23	3336368400.00	2643260400.00	449110.5
11.25	1.5	2.0	79.36	3336368400.00	2647812700.00	449884.0
11.25	1.5	2.5	79.44	3336368400.00	2650551700.00	450349.4
11.25	1.5	3.0	79.50	3336368400.00	2652380800.00	450660.1
11.25	2.0	1.5	79.36	3385571500.00	2686861300.00	449884.0
11.25	2.0	2.0	79.50	3385571500.00	2691496800.00	450660.1
11.25	2.0	2.5	79.58	3385571500.00	2694285800.00	451127.1
11.25	2.0	3.0	79.64	3385571500.00	2696148300.00	451439.0
11.25	2.5	1.5	79.44	3415758200.00	2713622300.00	450349.4
11.25	2.5	2.0	79.58	3415758200.00	2718308800.00	451127.1
11.25	2.5	2.5	79.66	3415758200.00	2721128500.00	451595.1
11.25	2.5	3.0	79.72	3415758200.00	2723011500.00	451907.6
12.25	1.0	1.5	80.98	2935676200.00	2377272300.00	459047.9
12.25	1.0	2.0	81.13	2935676200.00	2381830000.00	459928.0
12.25	1.0	2.5	81.23	2935676200.00	2384573100.00	460457.7
12.25	1.0	3.0	81.29	2935676200.00	2386405300.00	460811.5
12.25	1.5	1.5	81.29	3034159100.00	2466461900.00	460811.5
12.25	1.5	2.0	81.45	3034159100.00	2471208900.00	461698.4
12.25	1.5	2.5	81.54	3034159100.00	2474065800.00	462232.2
12.25	1.5	3.0	81.60	3034159100.00	2475974100.00	462588.7
12.25	2.0	1.5	81.45	3086039000.00	2513463100.00	461698.4
12.25	2.0	2.0	81.60	3086039000.00	2518309800.00	462588.7
12.25	2.0	2.5	81.70	3086039000.00	2521226900.00	463124.5
12.25	2.0	3.0	81.76	3086039000.00	2523175300.00	463482.4
12.25	2.5	1.5	81.54	3118021100.00	2542447300.00	462232.2
12.25	2.5	2.0	81.70	3118021100.00	2547355600.00	463124.5
12.25	2.5	2.5	81.79	3118021100.00	2550309700.00	463661.6
12.25	2.5	3.0	81.86	3118021100.00	2552282900.00	464020.3
13.25	1.0	1.5	82.76	2675256500.00	2214068700.00	469151.2
13.25	1.0	2.0	82.94	2675256500.00	2218762100.00	470145.8
13.25	1.0	2.5	83.04	2675256500.00	2221567700.00	470744.5
13.25	1.0	3.0	83.11	2675256500.00	2223475500.00	471144.6
13.25	1.5	1.5	83.11	2776888500.00	2307944500.00	471144.6
13.25	1.5	2.0	83.29	2776888500.00	2312857700.00	472147.5
13.25	1.5	2.5	83.40	2776888500.00	2315815600.00	472751.4
13.25	1.5	3.0	83.47	2776888500.00	2317791900.00	473154.6

.25	2.5	1.5	85.05	2646271200.00	2253571700.00	482113.55
.25	2.5	2.0	85.25	2646271200.00	2255969500.00	483243.29
.25	2.5	2.5	85.37	2646271200.00	2259041600.00	483923.67
.25	2.5	3.0	85.45	2646271200.00	2261164000.00	484378.32
.25	1.0	1.5	85.74	2258719800.00	1936590300.00	486031.84
.25	1.0	2.0	85.96	2258719800.00	1941496200.00	487260.81
.25	1.0	2.5	86.09	2258719800.00	1944446200.00	488001.79
.25	1.0	3.0	86.17	2258719800.00	1946417900.00	488496.03
.25	1.5	1.5	86.17	2363128200.00	2036476500.00	488496.04
.25	1.5	2.0	86.39	2363128200.00	2041653000.00	489737.51
.25	1.5	2.5	86.52	2363128200.00	2044770100.00	490485.45
.25	1.5	3.0	86.61	2363128200.00	2046854000.00	490985.33
.25	2.0	1.5	86.39	2420449400.00	2091086800.00	489737.51
.25	2.0	2.0	86.61	2420449400.00	2096414800.00	490985.32
.25	2.0	2.5	86.75	2420449400.00	2099624600.00	491737.07
.25	2.0	3.0	86.83	2420449400.00	2101769900.00	492239.52
.25	2.5	1.5	86.52	2456401800.00	2125383000.00	490485.45
.25	2.5	2.0	86.75	2456401800.00	2130811600.00	491737.07
.25	2.5	2.5	86.88	2456401800.00	2134073000.00	492491.11
.25	2.5	3.0	86.97	2456401800.00	2136263000.00	492995.31
	23746.75			30118.12	18.08	

OP END AT S. 0040 + 01 L. 7

.25	2.0	1.5	83.29	2831017900.00	2357941800.00	472147.59
.25	2.0	2.0	83.47	2831017900.00	2362972100.00	473154.84
.25	2.0	2.5	83.57	2831017900.00	2366000700.00	473761.28
.25	2.0	3.0	83.65	2831017900.00	2368024100.00	474166.43
.25	2.5	1.5	83.46	2864570900.00	2388939300.00	472751.43
.25	2.5	2.0	83.57	2864570900.00	2394042400.00	473761.28
.25	2.5	2.5	83.66	2864570900.00	2397114600.00	474369.26
.25	2.5	3.0	83.75	2864570900.00	2399167300.00	474775.45
.25	1.0	1.5	84.34	2451806100.00	2067799100.00	478099.[illegible]
.25	1.0	2.0	84.53	2451806100.00	2072604000.00	479200.79
.25	1.0	2.5	84.65	2451806100.00	2075497700.00	479860.84
.25	1.0	3.0	84.73	2451806100.00	2077431300.00	480316.[illegible]
.25	1.5	1.5	84.73	2555470400.00	2167236800.00	480316.91
.25	1.5	2.0	84.93	2555470400.00	2170321800.00	481438.24
.25	1.5	2.5	85.05	2555470400.00	2173366100.00	482113.55
.25	1.5	3.0	85.13	2555470400.00	2177400300.00	482564.80
.25	2.0	1.5	84.93	2611390900.00	2217814200.00	481438.24
.25	2.0	2.0	85.13	2611390900.00	2223003900.00	482564.80
.25	2.0	2.5	85.25	2611390900.00	2226129400.00	483243.29
.25	2.0	3.0	85.33	2611390900.00	2228217900.00	483696.66

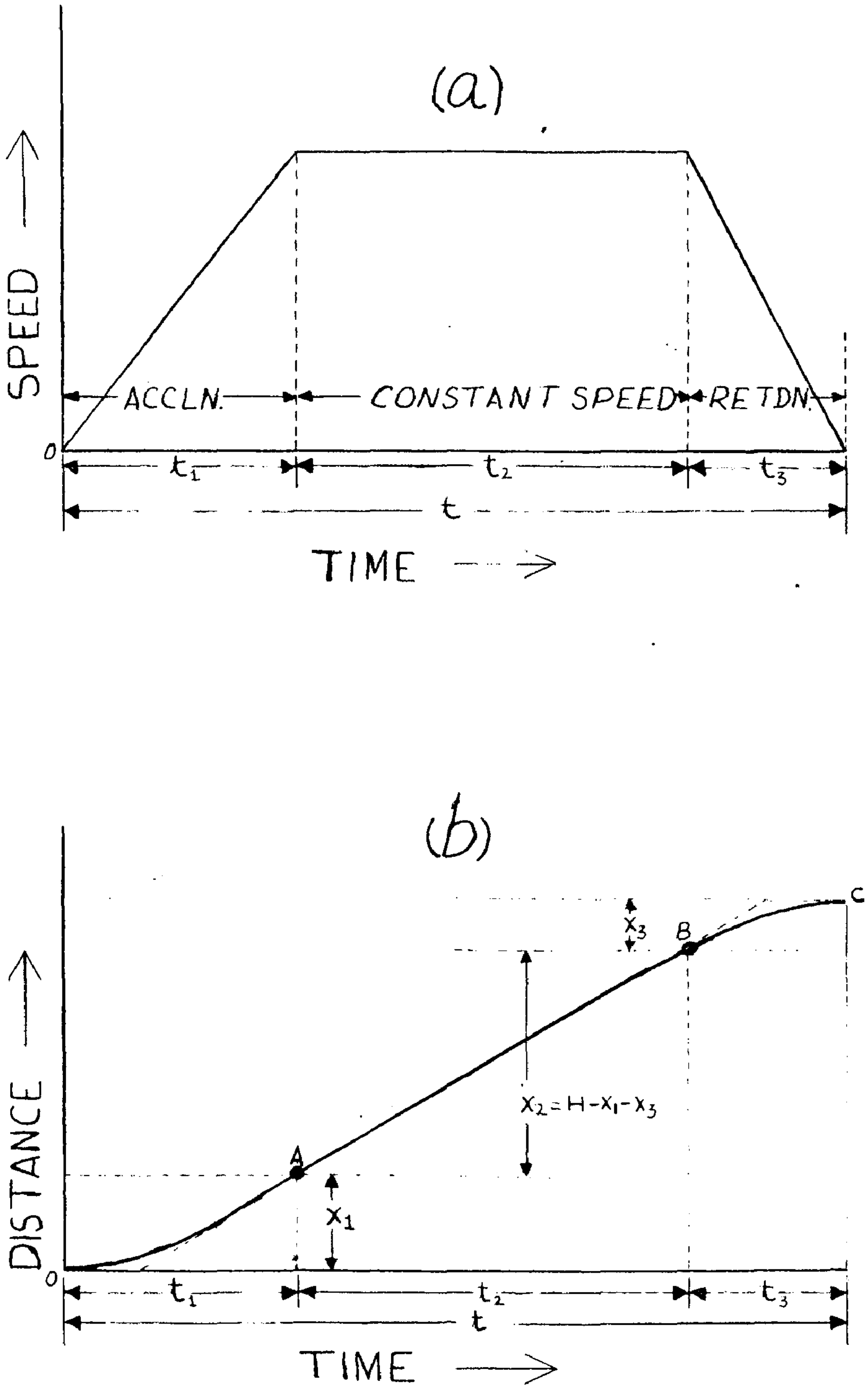

FIG.4 SPEED/DISTANCE VS. TIME CURVES

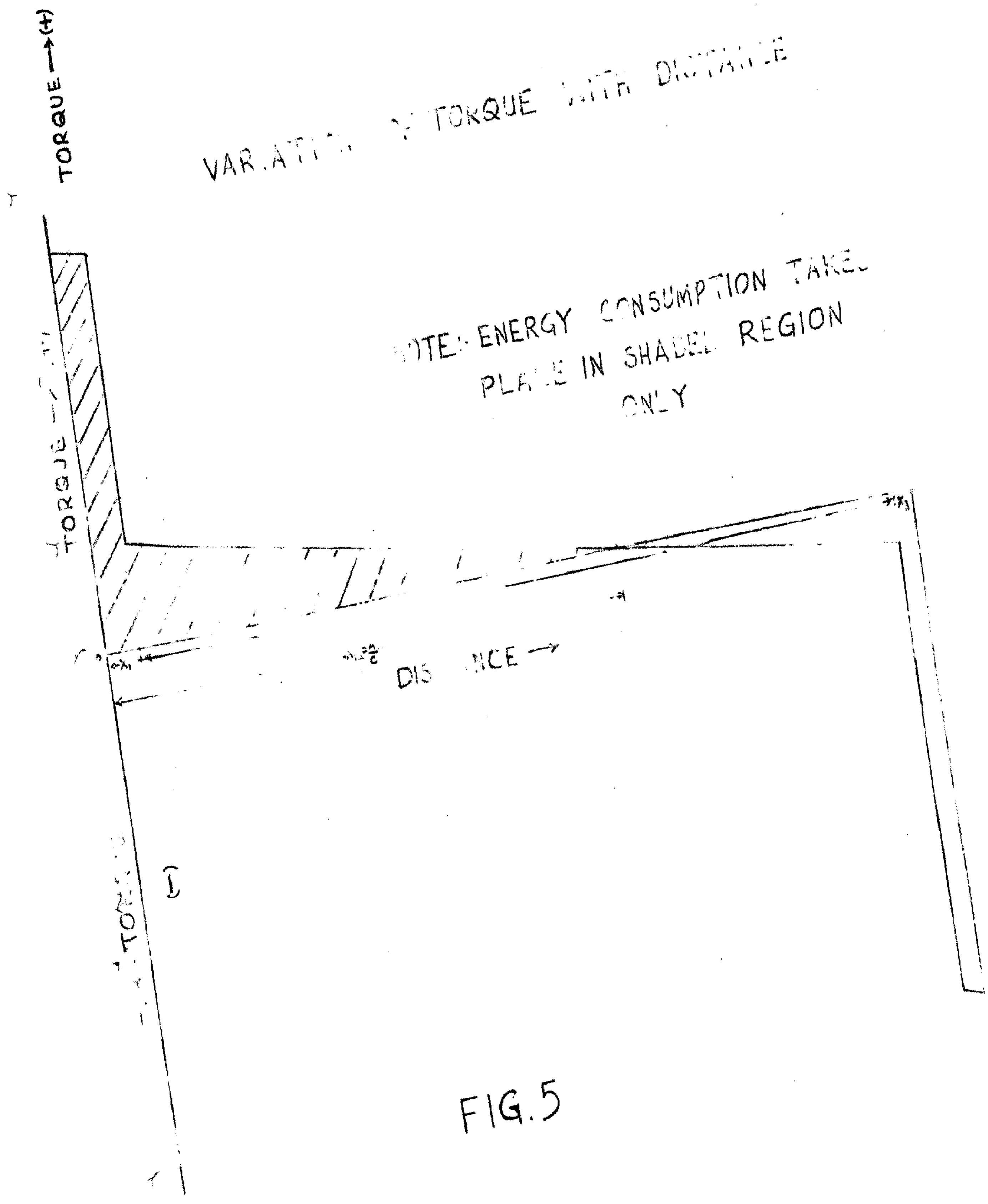
TORQUE ⟶ (+)
VAR.ATI TORQUE WITH
ENERGY CONSUMPTION
PLA IN SHADE REGION
ONLY
DIS NCE ⟶

FIG.5

VARIATION OF ORE OUTPUT/ENERGY CONSUMPTION WITH VELOCITY

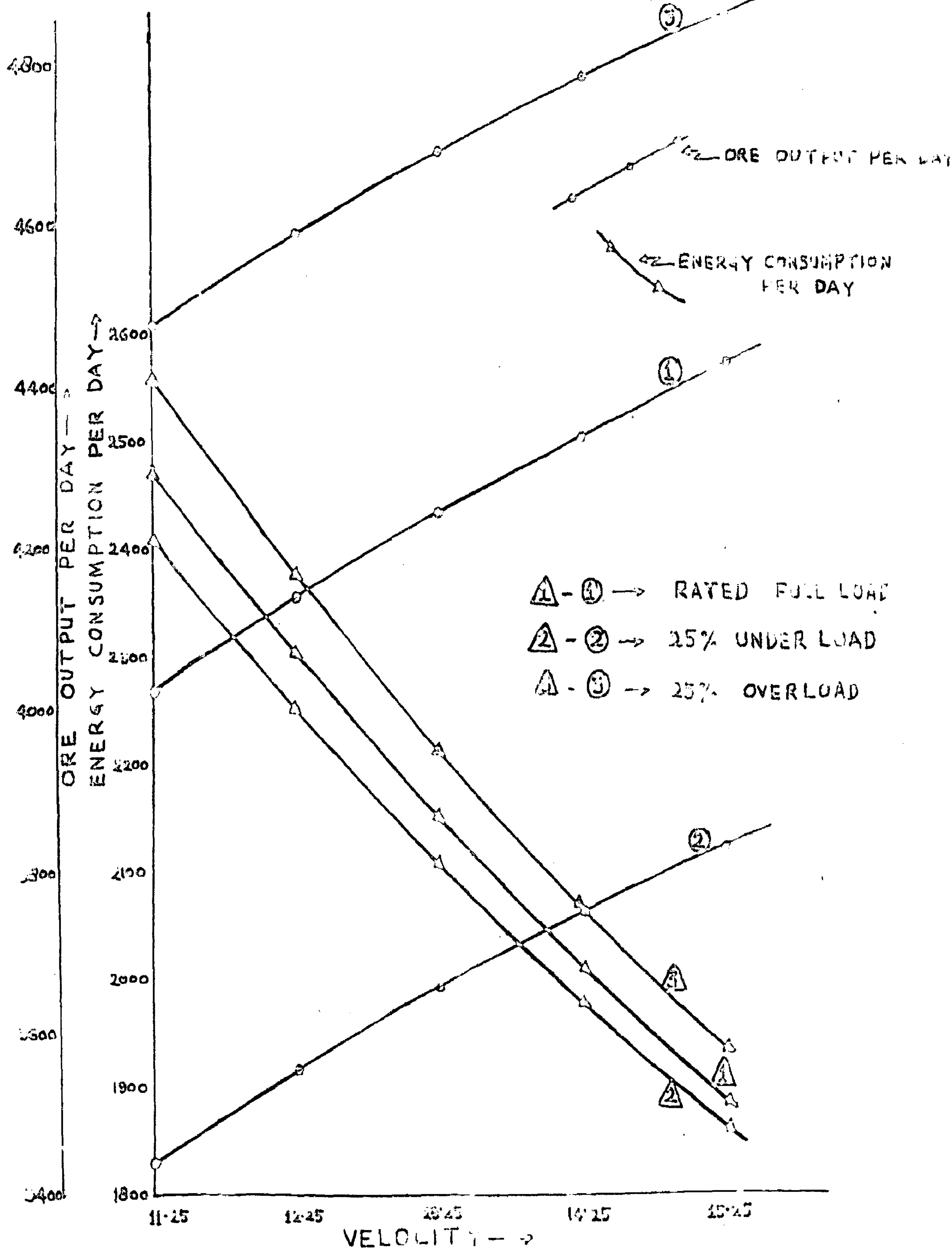

FIG. 6

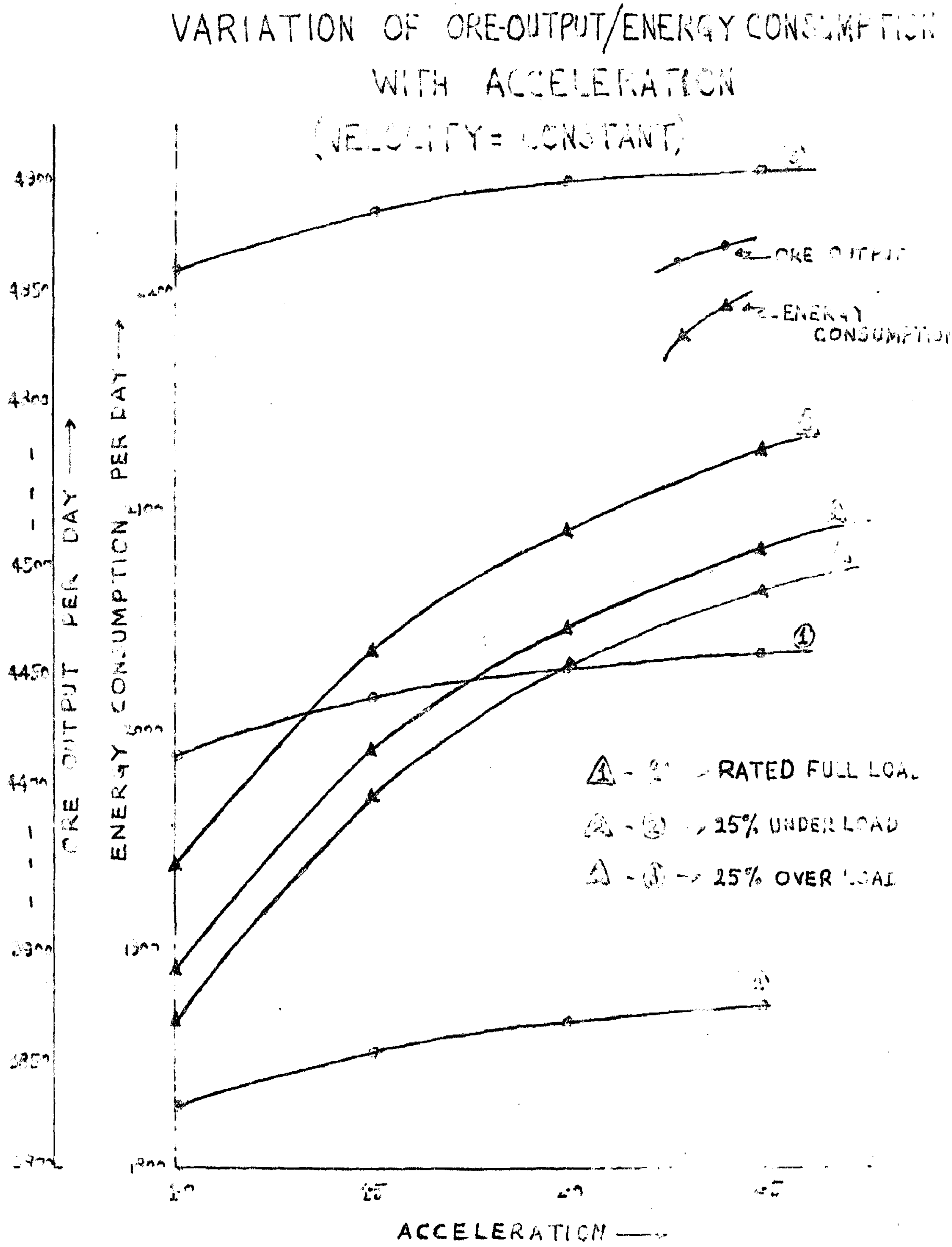
VARIATION OF ORE-OUTPUT/ENERGY CONSUMPTION
WITH ACCELERATION
(VELOCITY = CONSTANT)
ORE OUTPUT
ENERGY CONSUMPTION
ORE OUTPUT PER DAY
ENERGY CONSUMPTION PER DAY
RATED FULL LOAD
25% UNDER LOAD
25% OVER LOAD
ACCELERATION

FIG. 7