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# STAGED CONVOY CONCEPTS IN LUNAR AND PLANETARY SURFACE EXPLORATION

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## SUMMARY

Staging concepts for surface explorations are described which utilize en route supply transfers between vehicles or travelers and the establishment of depots. Range increases of over 60 - 100% can be accomplished. An analysis of optimum stage distances and depot sizes and their spacings is given. A few examples of applications are provided.

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# STAGED CONVOY CONCEPTS IN LUNAR AND PLANETARY SURFACE EXPLORATION

## 1. Introduction

Exploration of unknown and barren territories, assaults on major mountain ranges, and logistic supply lines through hostile environments have for a long time used the advantages of staged convoys and of established depots to allow a few vehicles out of a large number to penetrate into otherwise inaccessible areas.

In spite of the fact that there are only simple mathematical relations involved, many have only a cursory, general, and often inaccurate idea about the exact logic of staging while exploring an area. Since the various methods of logistic staging could be of importance for lunar and planetary surface exploration activities, this paper tries to describe the various staging methods, their rationale, and practical application.

## 2. Approach and Discussion of Staged Convoy Concepts

The basic problem in logistics for surface explorations in a hostile environment is the fact that an explorer or vehicle can penetrate an unknown territory only as far as the supplies carried along will last. How would it be possible to form groups of explorers or vehicles and organize their operations in such a way that allows one of them to go farther out than it is possible by a single effort? A suitable procedure should be of great practical value for lunar and planetary surface exploration.

### Approach to the Problem

A fourfold approach to the problem is taken:

a. The en route supply transfer concept

b. The depot concept

c. One-way journey with no return

d. The round-trip journey

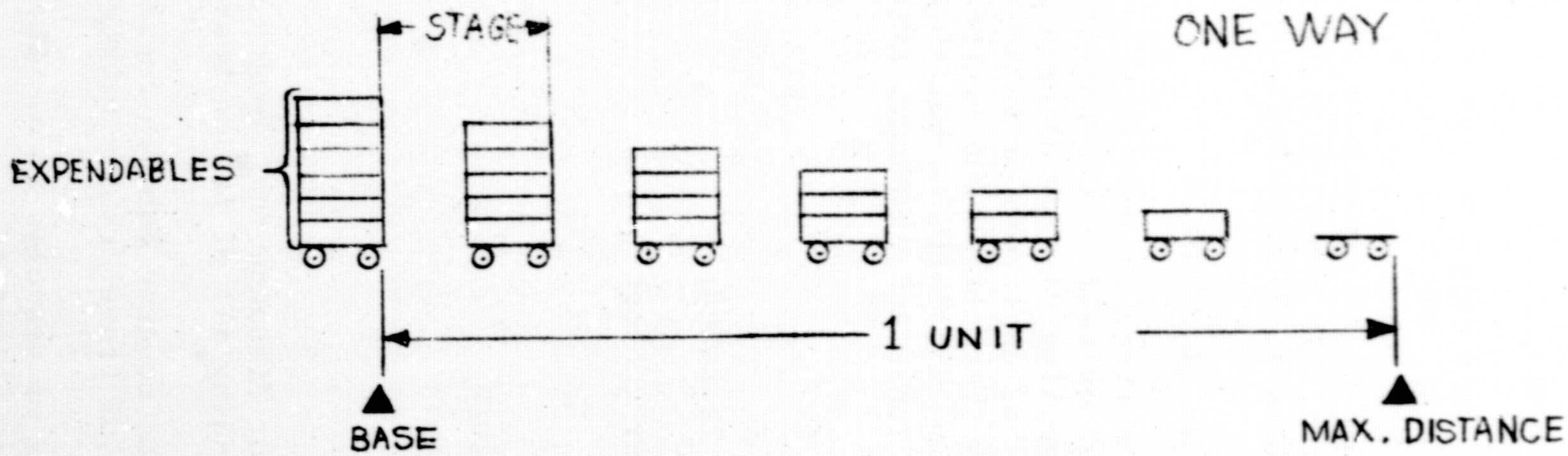
### 2.1 Definitions (Figure 1)

2.1.1 We select as the unit of distance that length which one explorer or vehicle can travel by expending all of its on-board supplies.

2.1.2 A stage is that distance covered between successive transfers of supplies between vehicles or travelers and between depots.

2.1.3 The number of explorers or vehicles is n. They have identical consumption rates for this investigation.

# SINGLE VEHICLE



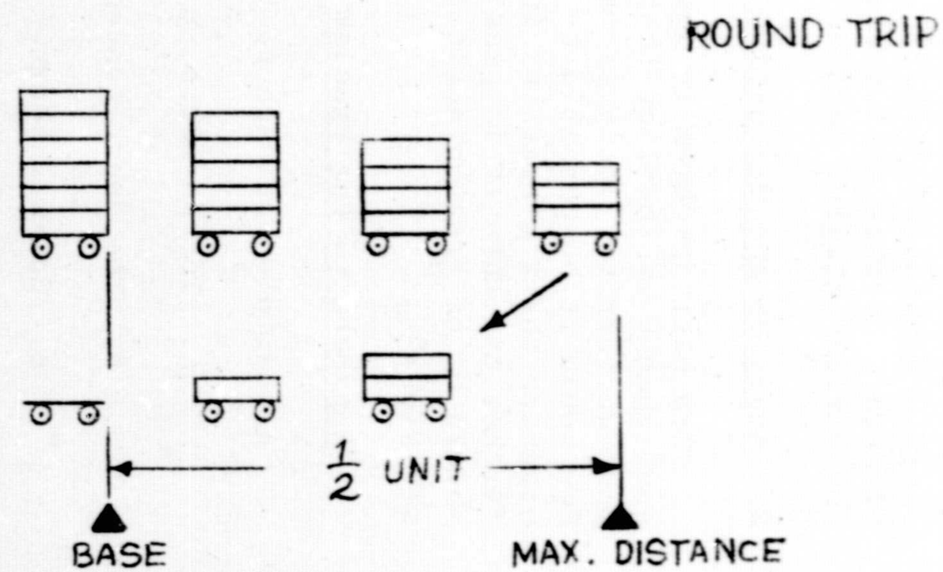




FIG 1

## 2.2 Analysis

### 2.2.1 The En Route Supply Transfer Concept (Figure 2)

Each vehicle or traveler divides his expendables into n + 1 parts. In the example shown, each of the five vehicles has its expendables divided into six parts. Each part then provides for a fixed stage length of $\frac{1}{n+1}$ units.

Vehicle number 1 expends its supplies for the first stage as follows:

$\frac{1}{n+1}$ used to move over one stage.

$\frac{n-1}{n+1}$ to be transferred to the other n - 1 vehicles.

$\frac{1}{n+1}$ used to return to the base.

TOTAL: 1

The following stages are handled in a similar way, for instance, vehicle number 3 expends:

$\frac{1}{n+1}$ used to move over the third stage.

$\frac{n-3}{n+1}$ to be transferred to the other n - 3 vehicles.

$\frac{3}{n+1}$ used to return to the base.

TOTAL: 1

In general, any returning vehicle must leave the others with complete supplies, enough to get back to the base. For each additional stage on the outward leg of the traverse, one more portion of the supplies is consumed, but at each subsequent stage there is one less vehicle to take care of. Of course, one more portion is also required for the return leg.

When the last vehicle has reached a distance of

$$D_1 = \frac{n}{n+1} \text{ units} \quad \text{------------------------(1)}$$

from the base, two possibilities exist. It can return to the base or continue on out on a one-way trip. In this case, a total distance of

$$D_2 = \frac{2n}{n+1} \text{ units} \quad \text{------------------------(2)}$$

from the base can be reached.

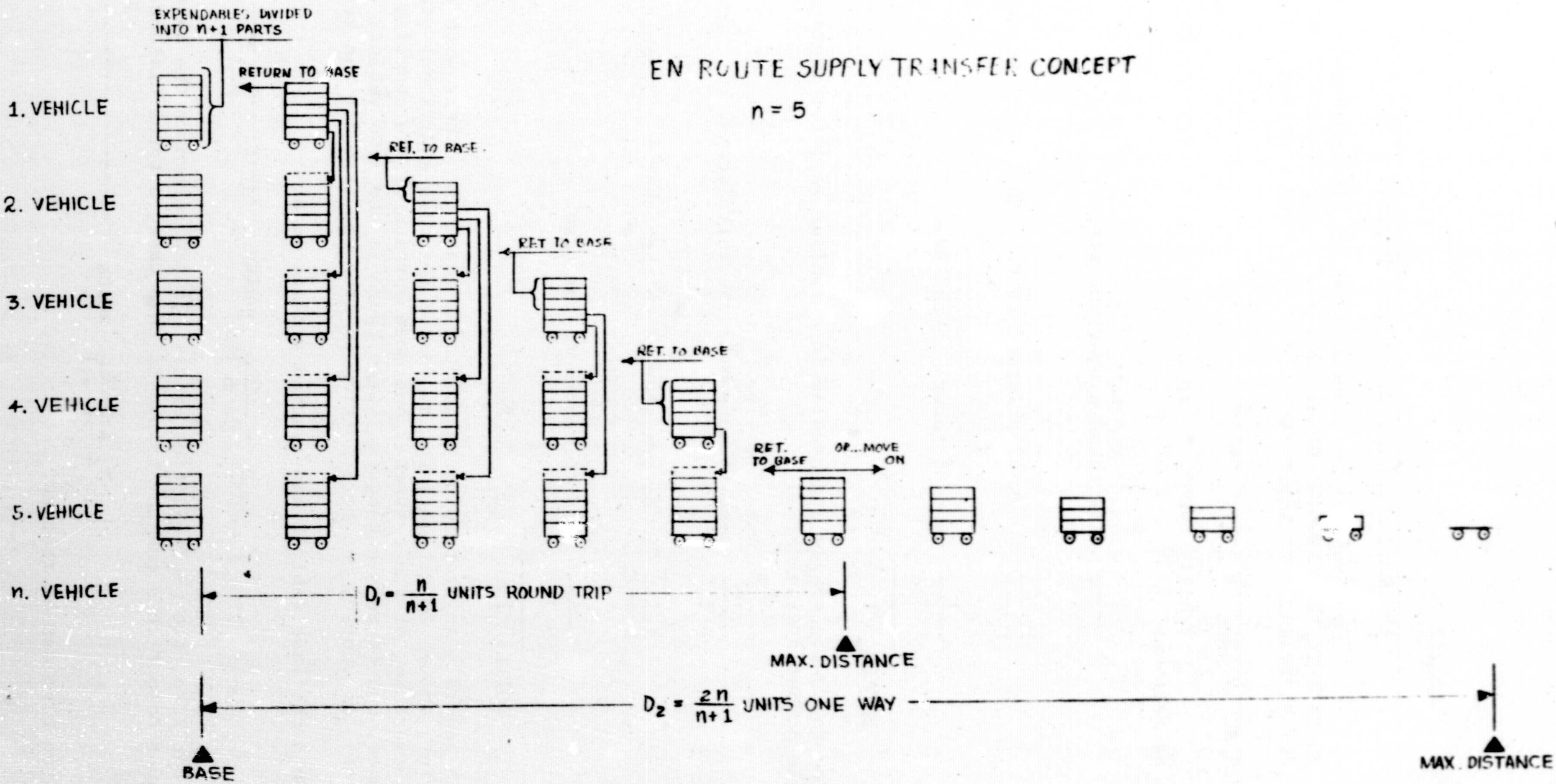

EN ROUTE SUPPLY TRANSFER CONCEPT
n = 5
EXPENDABLES DIVIDED INTO n+1 PARTS
RETURN TO BASE
RET. TO BASE
RET. TO BASE
RET. TO BASE
RET. TO BASE
OR... MOVE ON
1. VEHICLE
2. VEHICLE
3. VEHICLE
4. VEHICLE
5. VEHICLE
n. VEHICLE
$D_1 = \frac{n}{n+1}$ UNITS ROUND TRIP
MAX. DISTANCE
$D_2 = \frac{2n}{n+1}$ UNITS ONE WAY
BASE
MAX. DISTANCE

FIG. 2

The gain with five vehicles on a round trip over a single vehicle is thus $\frac{n}{n + 1}$ - 0.5 units which in this case is 0.333 unit or 67%. Figures 3 and 4 show by the lower curves that relationship between the numbers of vehicles in the convoy and the achievable range by using the supply transfer concept. It can be seen that, for instance, four vehicles on a round trip can increase the penetration depth of exploration from 0.5 unit of a single vehicle to 0.8 unit or by 60%. Three vehicles on a one-way trip can increase their range from 1.0 unit for a single vehicle to 1.5 units or by 50%.

### 2.2.2 The Depot Concept

The method described so far can be substantially improved by establishing depots for the returning vehicles or travelers. This means that each traveler will have to carry his own supplies for a round trip, the supplies for his companions to continue their trip outwards, and the depots for their return trips.

This is the most efficient method. Of course, the total distance traveled by all vehicles is a constant depending on the total quantity of supplies. However, the efficiency is a maximum if those few who travel farthest traverse over longer stages than the bulk of the travelers. The vehicle that goes farthest must be loaded to capacity beyond the last depot and not take any of the others farther along.

#### 2.2.2.1 Round Trip (Figure 5)

Again the example uses a convoy of five vehicles. At the base the $n^{th}$ vehicle's supplies provide for a round trip of n vehicles over a first stage of $\frac{1}{2n}$ units.

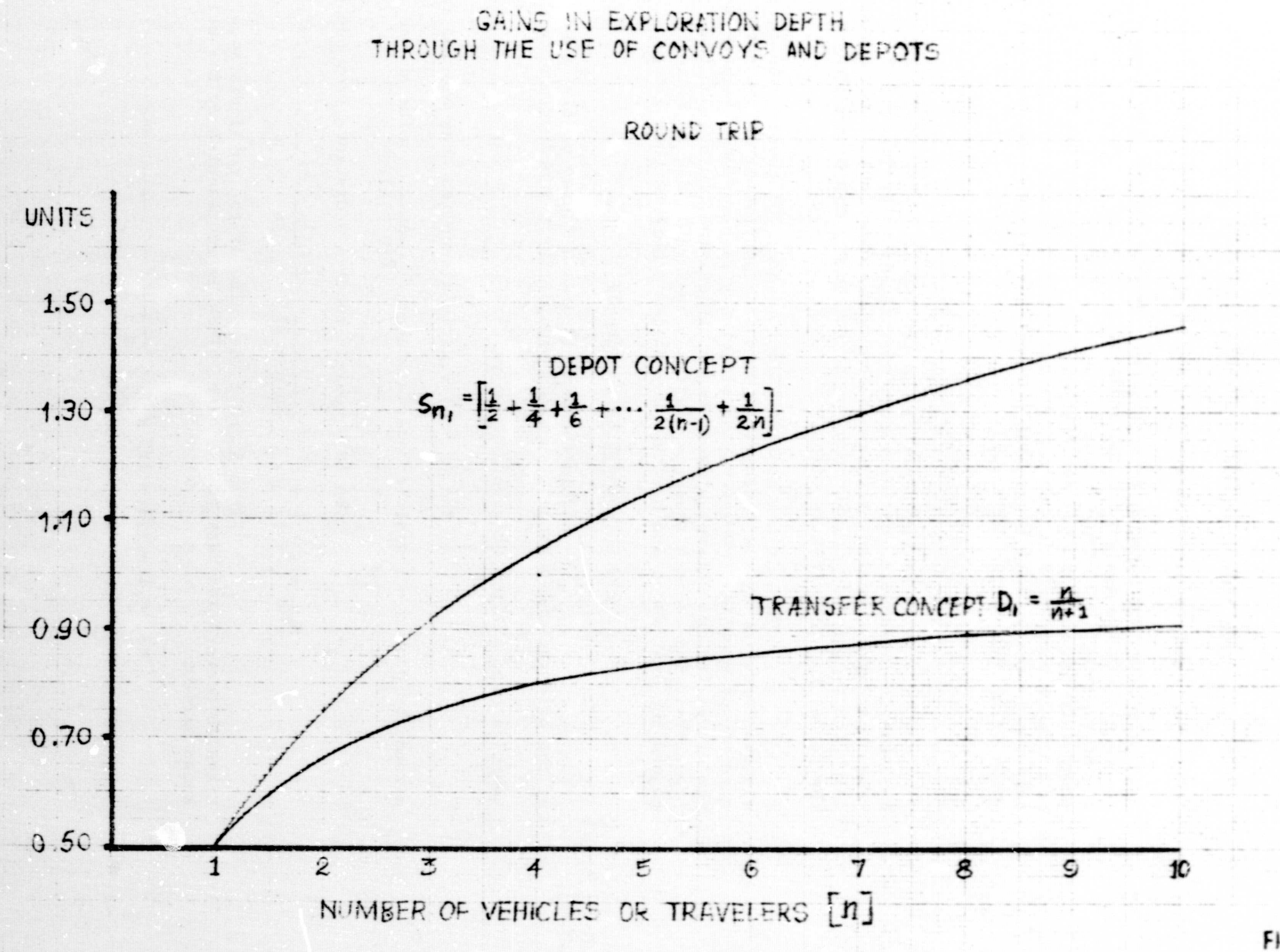
The (n - 1) vehicle's supplies then provide for a round trip of n - 1 vehicles over a stage of $\frac{1}{2(n - 1)}$ units and so on.

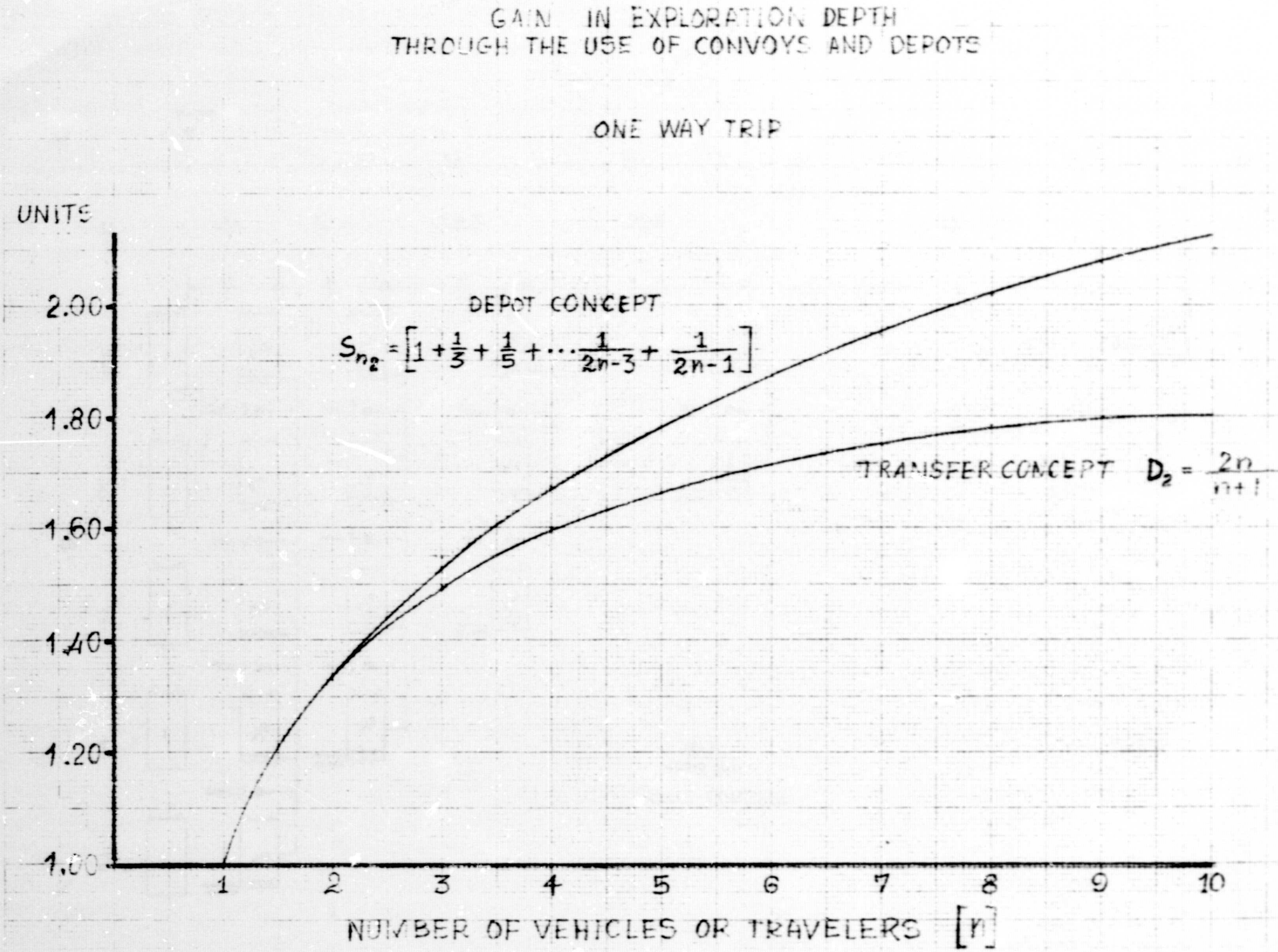
The last vehicle reaches a distance from the base

$$S_{n_1} = \tfrac{1}{2} + \tfrac{1}{4} + \cdot \cdot \cdot \frac{1}{2n(n - 1)} + \frac{1}{2n} \text{ ---------------(3)}$$

This is half the value of the total distance traveled outward and back to the base. This is represented by the well known series:

$$S_n = 1 + 1/2 + 1/3 + \cdot \cdot \cdot \frac{1}{n - 1} + \frac{1}{n} \text{ ---------------(4)}$$


GAINS IN EXPLORATION DEPTH
THROUGH THE USE OF CONVOYS AND DEPOTS
ROUND TRIP
UNITS
1.50
1.30
1.10
0.90
0.70
0.50
DEPOT CONCEPT
$S_{n_1} = \left[\frac{1}{2} + \frac{1}{4} + \frac{1}{6} + \cdots \frac{1}{2(n-1)} + \frac{1}{2n}\right]$
TRANSFER CONCEPT $D_1 = \frac{n}{n+1}$
1
2
3
4
5
6
7
8
9
10
NUMBER OF VEHICLES OR TRAVELERS [n]
FIG. 3


GAIN IN EXPLORATION DEPTH
THROUGH THE USE OF CONVOYS AND DEPOTS
ONE WAY TRIP
UNITS
2.00
1.80
1.60
1.40
1.20
1.00
DEPOT CONCEPT
$S_{n_2} = \left[1 + \frac{1}{3} + \frac{1}{5} + \cdots \frac{1}{2n-3} + \frac{1}{2n-1}\right]$
TRANSFER CONCEPT $D_2 = \frac{2n}{n+1}$
1 2 3 4 5 6 7 8 9 10
NUMBER OF VEHICLES OR TRAVELERS [n]
FIG. 4

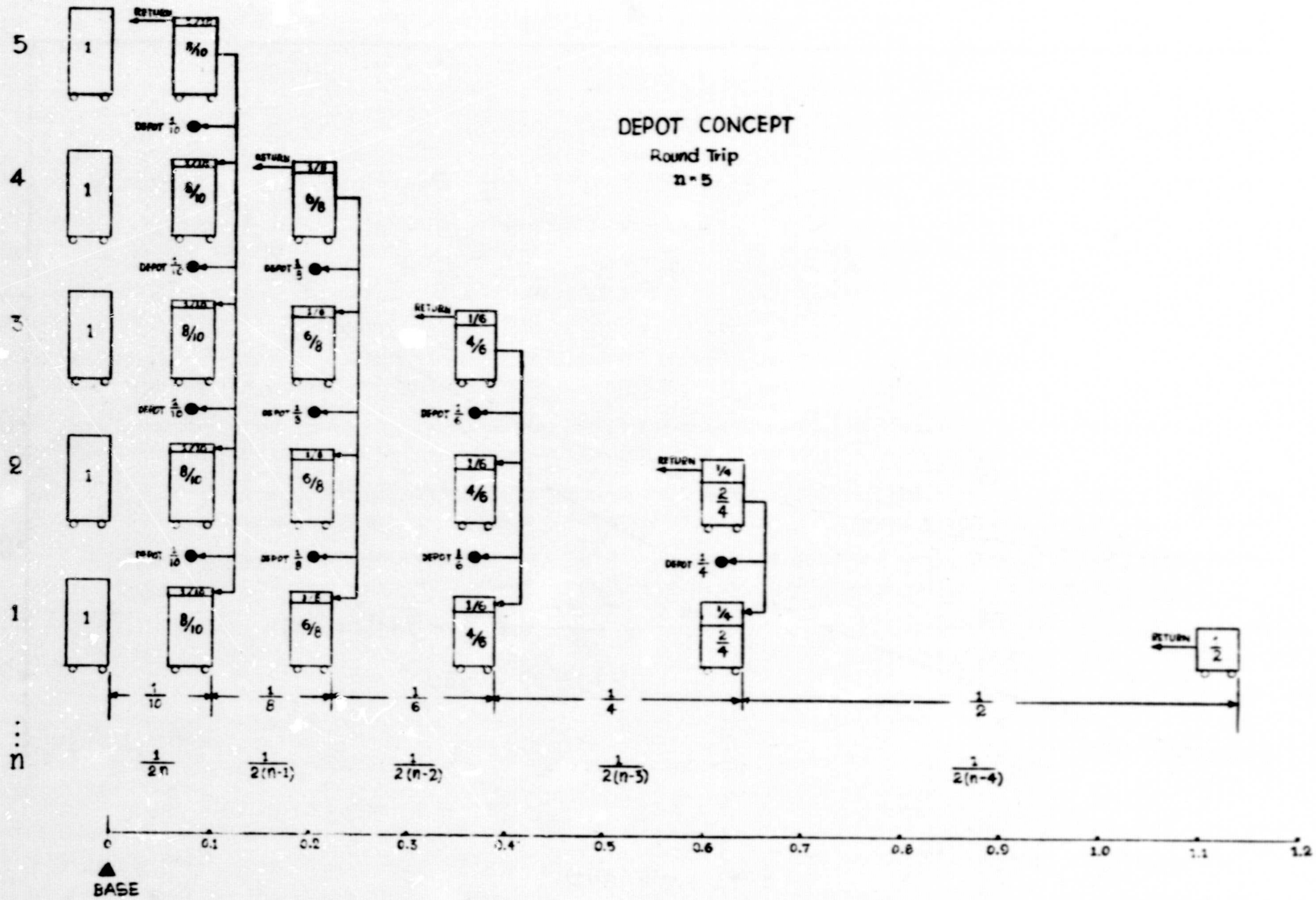



Fig. 5



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Good approximate totals can be obtained without having to add up all the fractions by using Euler's constant C = 0.577 215 665 as follows:

$$S_n \approx \ln n + C + \frac{1}{2n} \quad \text{-----------------------------(5)}$$

Error $< \frac{1}{12n^2}$

2.2.2.2 <u>One-Way Trip</u> (Figure 6)

If the final vehicle makes only a one-way trip, one less ration has to be provided on every stage. The first vehicle provides for a stage of $\frac{1}{2n - 1}$ units (once for the vehicle which will go one-way, and twice for itself and the others). The other vehicles have an identical problem with one vehicle less. The next stages are then $\frac{1}{2n - 3}$, $\frac{1}{2n - 5}$ units, etc., up to a last stage of 1/3 unit after which a single vehicle goes for 1 unit. The total distance thus is:

$$S_{n_2} = 1 + 1/3 + 1/5 + \cdots \frac{1}{2n - 3} + \frac{1}{2n - 1} \quad \text{--------(6)}$$

By the way $S_{n_2} = S_{2n} - 1/2\, S_n$ ! -------------------------------(7)

This harmonic series can likewise be approximately totalled as follows:

$$S_{n_2} \approx 1/2 \ln n + (1/2\, C + \ln 2) \quad \text{-----------------(8)}$$

The error is again $< \frac{1}{12n^2}$

With the staging concepts discussed here, exploratory traverses of theoretically any length can be provided for, however, a considerable decay in beneficial returns which occurs above a certain number of vehicles has to be watched. If the distance is given and the number of vehicles has to be determined then for one-way traverses this number is approximately

$$n = e^{2(S_{n_2} - 1)} + \frac{1}{27} e^{(S_{n_2} - 1)}$$

$$= 1.037\, e^{2(S_{n_2} - 1)} \quad \text{---------------------------(9)}$$

with an error of $< 1$.

The upper curves in Figures 3 and 4 show the relationship between the number of vehicles or travelers and number of units covered for both round trip and one-way trip with the depot concept.

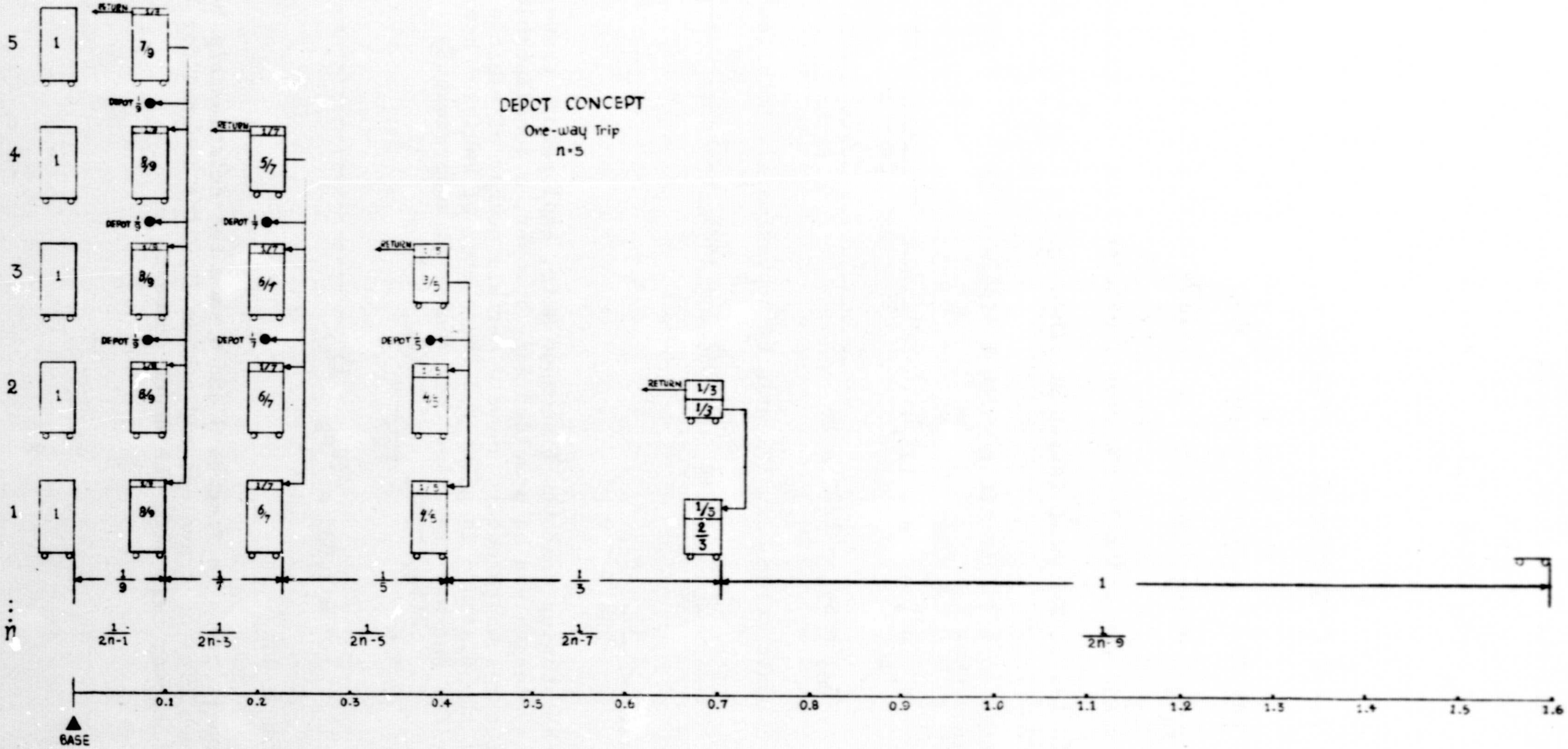


Fig. 6

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## 3. Applications

As to the practical application of the depot concept each vehicle or traveler can move quite independently within the limits of the available depots; and it is clear that it makes no difference when the depots are established as long as this occurs before they are to be used.

Each vehicle or traveler could go and return on his own within their proper order. Instead of n parallel operations, one single traveler can perform n excursions in series. Time is the only factor to be considered here.

3.1 Example I: There are three identical lunar surface vehicles at a lunar base. Fully supplied, each one has a capability of moving out for 100 miles and return, thereby expending all its supplies. How far can one of the vehicles go using all three vehicles as a convoy on a round trip by using (a) the transfer concept, and (b) the depot concept?

Single vehicle round trip = 1/2 unit = 100 miles

a. Transfer: 3 vehicles: $\frac{n}{n+1}$ = 3/4 unit = 150 miles

b. Depots: 3 vehicles: 1/2 + 1/4 + 1/6 = 0.92 unit = 184 miles

3.2 Example II: A lunar logistics supply vehicle landed 210 miles away from a lunar base. An expedition is to reach the stranded vehicle on a one-way trip. How many individual excursions have to be made from the base? How many and what size depots have to be erected at what separation distances? One-way action radius of base transportation systems is 100 miles (= 1 unit).

a. $n \approx 1.037 \quad e^{2\left(\frac{210}{100} - 1\right)} \approx 9.4$

This is rounded off to 10 excursions from the base.

b. With ten vehicles the first stage length is $\frac{1}{2n - 1}$ = 1/19 unit.

Therefore, the following distances and depot positions are required.

| STAGE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| I. | | | | | | | | | | | |
| INCREMENT: UNITS | 1/19 | 1/17 | 1/15 | 1/13 | 1/11 | 1/9 | 1/7 | 1/5 | 1/3 | 1 | 2.13 |
| INCREMENT: MILES | 5.26 | 5.88 | 6.67 | 7.7 | 9.1 | 11.1 | 14.3 | 20 | 33.3 | 100 | 213 |
| II. | | | | | | | | | | | |
| DEPOT SIZE | 9/19 | 8/17 | 7/15 | 6/13 | 5/11 | 4/9 | 3/7 | 2/5 | 1/3 | 0 | 3.935 |
| III. | | | | | | | | | | | |
| CONSUMED GOING OUT | 10/19 | 9/17 | 8/15 | 7/13 | 6/11 | 5/9 | 4/7 | 3/5 | 2/3 | 1 | 6.065 |

The table shows that, of course, the total of deposited supplies plus the supplies consumed on the outgoing leg is equal to unity which is equal to the total cargo capacity of each vehicle or traveler.

The total of all increments adds up to 2.13 units which gives a total distance capability of 213 miles.

## 4. Conclusions and Recommendations

It has been shown that surface exploration with a number of standardized identical vehicles can be greatly enhances and expanded by the staging and depot concept. The steps to larger vehicles with wider ranges as explorative depths increases can be spaced much farther apart by using the concepts discussed here than without. It is more economical to build several vehicles of the same model and employ them in stages than to have to develop vehicles of various larger sizes for wider ranges.

It is recommended that lunar and planetary surface exploration planning efforts consider the application of the staged convoy concepts, presented here, to enhance and economize the missions implementations.

It also seems quite possible that earth bound surface missions, like exploration of the Himalayas, deserts, and in Antarctica, can benefit by applying the more exact staging approach in their efforts.

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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