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LAUNCH OPERATIONS CENTER

November 30, 1962

Preliminary Presentation Notes Lunar Trafficability Study

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LOC-FORM 168-1

ABSTRACT

The following presentation notes and enclosed illustrations summarize the findings of the Future Studies Branch, LOC, in the first phase of their study related to "Lunar Trafficability". The purpose of this initial phase was to evaluate "state of the art" mobility analysis techniques, propose a technique for vehicle locomotion analysis, and develop general criteria for a lunar roving vehicle. The figures shown are representative selections from those that will be included in a final report to be issued shortly. This report will include a complete set of procedures discussing the use of all working graphs for the evaluation of vehicle mobility capabilities.

The overall guidance and direction provided by Mr. G. Bucher and Mr. J. Downey of Research Projects Division during the course of this study and the assistance provided by Mr. J. Bensko in defining the lunar surface models is gratefully acknowledged.

Past Efforts by Future Studies Branch in Related Areas

1. "Lunar Soft Landing Study" - December 1959 - (Roving Vehicle) Report No. DLS-TN-36-30.

2. "Proposed Test Facility for Ground Test of Space Support Equipment" - March 1960 - (Lunar Roving Vehicle) Report No. DLS-TN-19-60.

3. "A Lunar Subsurface Sampling Device" - May 1960 - Report No. DLM-TN-36-60.

PRESENTATION NOTES

SLIDE #1 - Describes scope of work and general study outline

SLIDE #2 - Parameters to be Investigated

SLIDE #3 - These slides list the major parameters to be investigated as associated with soil, terrain, and vehicle.

SLIDE #4 - Profile Limitations - Basic Ground Rules

Describes the ground rule limitations established for slopes, crevices, and boulders.

SLIDE #5 - Lunar Soil Properties

Discusses lunar soil properties and the assumed ranges for n, k, and Ø. Although Ø was assumed to be constant @ 32^{o} for sample problem purposes, it too will be a variable in the parametric data to be presented in the report.

C, the component of lunar soil characteristics associated with cohesion, was assumed to be 0 for sample problems purposes. This concurs with the opinions expressed by the majority of known authorities on lunar soils. However, the probability of a cohesive component existing has been suggested by some. Since very little conclusive evidence is available regarding particle cohesion in a vacuum as a result of clean, filmless surfaces, and Van Der Waals forces of attraction, the assumption of C = 0 is justifiable and will result in conservative vehicle performance estimates. Of course, it must be noted that in the equation for maximum attainable thrust - $H_m = AC + W \tan Ø$, the cohesive component of thrust is not affected by gravity, and is strictly a function of surface contact area. If C is found to be of any significant value, then greater contact areas would appreciably improve vehicle performance. This would tend to lead more strongly to the consideration of tracked vehicles.

SLIDE #6 - Determination of C & Ø

To provide a better feeling for the physical significance of C and Ø, this slide outlines the test apparatus and procedures taken in establishing these characteristics for a given soil and derivation of the maximum thrust that may be attained by a vehicle when operating in these soils.

SLIDE #7 - Surface Models, Payload Limits, LRV Mission Requirements

This slide shows the four assumed lunar surface models, C-1B and C-5 soft-landed payload limits, and assumed lunar roving vehicle mission requirements. Model Number I is located in the maria, and presents the optimum area for navigation with the roving vehicle. It has gentle slopes over most of the area, and consists of dust, particles ranging in size from 2 mm. to 1 cm., isolated boulders and no crevices. Model Number II contains a profile of the maria near small craters, will exhibit crevices around the crater rim, and scattered particle sizes ranging from 2 mm. to 50 cm. Model Number III, the uplands and craters, is more rugged, and will contain isolated areas of high slopes and boulders which will generally be considered impenetrable to the roving vehicle. These areas will have to be bypassed. Obstacles ranging from particles of 2 mm. to boulders of 2-3 meters will exist. Boulders up to 1/2-meter minimum <u>must</u> be negotiated.

Model Number IV, the uplands and large craters, will contain large boulders up to 5-10 meters, and be impenetrable in many areas.

SLIDE #8 - Various Types of Locomotion Reviewed

This slide shows the type of locomotion mechanisms that were reviewed for possible lunar applications. This includes rigid, pneumatic and flexible wheels, tracked vehicles, and walking, jumping, crawling, and rocket-powered vehicles.

SLIDE #9 - Comparison of Power Requirements, Man-made and Animal Locomotion

A comparison of power requirements for various man-made and animal locomotions indicates that such unorthodox mechanisms as crawling and jumping vehicles may be feasible for very special applications, but are extremely limited by excessive weight, excessive power requirements, and a high degree of mechanical complexity. Crawling mechanisms are inefficient and mechanically unreliable due to the complex mechanism required. Jumping machines take advantage of the low lunar gravity, but are mechanically unreliable, unstable during free flight, and subject payloads to undesirable shock loads. The rocket-powered vehicles are difficult to control when considering present state of the art systems, and may create significant hazards to personnel and equipment through the jet exhaust acceleration of lunar surface particles. In addition, both the jumping and rocket-powered vehicles must expend considerable energy in accelerating or lifting their own mass from one point to another even though no payload is present. Based on these considerations and on power requirements, only walking, wheeled, and tracked vehicles were given further review.

SLIDE #10 - Examples of Walking Mechanisms

Typical examples of proposed walking mechanisms are shown on this slide. Power requirements of many walking mechanisms may approach that as shown on the previous slide, which is comparable to wheels and tracks over certain terrain. Walking mechanisms are most advantageous for extremely rough terrain, short distances and light loads. The mechanism required for such a system is quite complex, and as such, prone to reliability problems. Packaging space is much larger than that required for a comparable wheel. Also, the contact area for a foot does not change with depth of sinkage; thus, with limited allowable sinkage, a wheel can carry a much greater load. Reduction of load/foot would result in an inefficient system. As in the case of the jumping and rocket-powered vehicles, the walking device must also lift its own weight with each step. The walking of a man may be likened to that of a rolling polygon, with radius equivalent to the man's leg length from hip to foot, and side equivalent to length of stride. It can be seen that as the length of the polygon's side and likewise the man's stride becomes shorter and shorter, the less energy is expended in raising the CG with each step. As the step becomes infinitely small, the following idealized walking mechanism results. (Ref. Slide #11)

SLIDE #11 - Idealized Walking Mechanism

As a result of the previous discussion, it was decided that detailed study effort should be devoted to wheels and tracks.

SLIDE #12 - Level Surface Locomotion

This slide presents the major equations defining the forces opposing vehicle motion on level surface. This force, commonly called rolling resistance, is broken into two major components: hard surface and soft surface. In hard surface analysis, the major rolling resistance is internal, with very little resistance attributable to external soil deformation. Rolling resistance of a rigid wheel is generally due to bearing and seal friction. A pneumatic tire develops rolling resistance flexure losses as a function of inflation pressure, carcass stiffness, and wheel diameter. Tracks exhibit losses through linkage friction, track tension, bearings, and seals.

In soft soils, the resistance to rolling due to soil deformation must be added to the internal resistance to obtain total rolling resistance. Equations are shown for the rolling resistance of a rigid wheel due to soil deformation and for pneumatic tires and tracks, whose soft surface resistance is a function of surface bearing pressure and associated sinkage. Here we introduce the equations for critical pressure to be used in inflatable tire analysis. There is a critical pressure above which the tire deflects in a given soil and acts as a flexible wheel. In analyzing pneumatic tires, curves defining the critical pressure must be consulted to establish whether a soft tire or rigid wheel analysis is required for a given set of conditions.

As discussed earlier, the maximum thrust a vehicle may attain is a function of the soil properties. The difference in this maximum attainable thrust and all rolling resistance (hard surface, soft surface, and slopes, which is merely W sin α) divided by the vehicle weight is commonly referred to as drawbar pull to weight ratio - $\frac{DP}{W}$. This is highly significant in judging vehicle performance, in that it indicates the net thrust remaining for acceleration, towing, and slope negotiation. The ratio of DP/W is an approximate indication of the maximum percent slope a vehicle may climb.

Actually, a flexible non-inflated wheel appears best suited from a dynamics, mobility, and lunar environment standpoint. Pneumatic tires are undesirable from a mobility gained and reliability standpoint. A sample problem will serve to illustrate this conclusion. Improved performance of a pneumatic tire over a rigid wheel is dependent upon tire deflection, subsequent increase in contact area, reduced ground pressures and reduced sinkage. On earth, with vehicles in the 1,000-5,000# class, weight results in significant tire deflection, increased contact area, and reduced sinkage as compared with a rigid wheel. However, in the environment of reduced lunar gravity, vehicle weights and ground pressures become relatively insignificant.

<u>Sample Problem</u>

Case (1) - Earth - K = 3 n = 1.25
Vehicle Wt. - 5,000#
Wheel dia. - 80" - inflation pressure 14 psi
Tread width - 4"

Analysis shows that for a rigid wheel, $\frac{DP}{W} = .435$

For the pneumatic tire (P_i = 14 psi) $\frac{DP}{W} = .555$

Thus, on earth, substantial performance is gained in this soil with a pneumatic tire.

Case (2) - <u>Moon</u>

Now take the same vehicle on the moon and assume similar soil conditions. A look at the critical pressure curves indicates that 14 psi has exceeded the critical pressure, and this tire will behave as a rigid wheel on the moon.

For a rigid wheel on the moon, $\frac{DP}{W} = .53$

Thus, the rigid wheel on the moon is nearly as good as the pneumatic tire on earth. Also, the rigid-wheeled vehicle performance on the moon has increased considerably over the same rigid wheeled vehicle on earth because the rolling resistance reduces at a much greater rate than the net available thrust under reduced gravity conditions.

For this particular vehicle, the tire pressures would have to be lowered below a critical pressure of 4 psi before tire deflection would occur. This would increase $\frac{DP}{W}$ to .58 which is an insignificant amount over that available with a rigid wheel.

The temperature extremes of the lunar environment and the hazards of puncture make the use of a pneumatic tire seem even more unfavorable.

A typical working graph for determining the rolling resistance of a rigid wheel on a soft surface is shown on slide #13.

SLIDE #13 - Rolling Resistance (R) of Hard Tires on a Soft Surface Working Graph

SLIDE #14 - Comparison of Tracks and Wheels

This slide shows the comparison between a track and an equivalent wheel diameter. It should be noted that although the performance of the tracked vehicle is superior to that of the wheel throughout the given range of soil consistencies, the difference in performance decreases fairly rapidly as the soil strength increases. Since the lunar surface is assumed to be of a fairly high strength (min. bearing pressure of 6 psi), the wheel is selected as the desired means of lunar locomotion because of its inherent simplicity, reliability, and lower weight requirements.

Of course, both systems have their merits. For extremely rugged terrain, large crevice negotiation, and locomotion in cohesive type soils, the merits of a tracked system are apparent.

SLIDE #15 - Two-Wheel and Four-Wheel Drive Analysis

Upon selection of the wheel as the desired means of locomotion, a detailed analysis of two- and four-wheel drive vehicles was performed. Some of the more important equations derived from this analysis are shown on slide #15. For the two-wheel drive vehicle, it can be shown that the rear wheel is generally the limiting case for the most probably encountered range of A/ℓ.

An A/ℓ value of approximately .5 is optimum, since at this point, the friction requirements for both front and back wheels are identical. For A/ℓ values greater than approximately .5, the rear wheels are capable of negotiating a larger crevice than the front wheels; conversely, for A/ℓ ratios less than .5, the front wheels will negotiate a larger crevice than the rear wheels for a given f value. The optimum occurs when these f curves for front and back cross, and this is approximately @ $A/\ell = .5$.

The friction and torque equations for a 4-wheel drive vehicle for complete front and back wheel negotiation of an obstacle are as shown. Again, the rear wheel is generally the limiting case.

A comparison of two and four-wheel drive systems is shown in slide #16.

SLIDE #16 - <u>Friction Requirements for Crevice and Step Negotiability</u>

This slide illustrates quite conclusively that for a given value of f, the 4-wheel drive vehicle will negotiate a much larger step or crevice than the 2-wheel. Thus, the 4-wheel drive system was selected for detailed analysis.

<u>SLIDE #17</u> - <u>Friction Requirements for Four-Wheel Drive Vehicle Negotiating a Crevice</u>

This shows a plot of the equations previously described for f (front and back wheels) for an r/ℓ ratio of 1/4. Similar curves are plotted for other values of r/ℓ. For a given f, A/ℓ, and r/ℓ, this graph will show the maximum crevice crossing capability of this vehicle and indicate whether the front or back wheel is the limiting case. A series of these graphs for various r/ℓ ratios also indicates that beyond ratios of 1/4, crevice crossing capability does not improve to any significant extent.

<u>SLIDE #18</u> - <u>Maximum Axle Torque Requirements for Four-Wheel Drive Vehicle Negotiating a Crevice</u>

For given A/ℓ and r/ℓ ratios, the 4 torque equations previously discussed for complete obstacle negotiation were evaluated and the <u>maximum</u> value was plotted. These plots then indicate the maximum torque that two of the vehicle wheels must be capable of developing during the course of negotiating an obstacle rather than a specific wheel torque. This curve shows that A/ℓ ratios around .6 result in minimum torque requirements for a given crevice crossing. This may be more clearly seen in the next slide.

SLIDE #19 - Vehicle CG Location for Minimum Torque & Maximum Obstacle Negotiability

For a given r/ℓ , this slide clearly shows that ratios around .6 result in minimum torque requirements for crevice crossing. This is also the point for maximum crevice crossing capability, as shown on the previous slides - f vs. X/D.

SLIDE #20 - Crevice Width Converted to Obstacle Height of Equal Negotiability

Analysis has shown that a purely geometrical relationship exists between a vehicle's crevice crossing capability and its step negotiability. Design of a vehicle to negotiate a given crevice establishes directly its maximum step negotiability as shown by this graph.

SLIDE #21 - Power Systems - 1962 Areas of Optimum Applications

The power output of a number of powerplants, optimized with respect to weight, is shown on slide #21. More specifically, this figure shows the type of powerplant which would best be qualified to generate a given power level for a specified time duration.

From this figure, it appears that three (3) powerplants should be considered for use in the lunar roving vehicle; namely, nuclear, cryogenic or chemical dynamic and fuel cells. Since the areas defined by this figure overlap in the power level and duration considered for the LRV, a further look at the future appears in order.

SLIDE #22 - Power System Forecasts for 1966

This slide presents the same type of information as the preceding figure for the year 1966. From this figure, the use of fuel cells appears to hold the most promise.

SLIDE #23 - Power Systems Weight

This slide shows the power output of three (3) powerplant systems versus the systems weight for two different mission durations. Again, support appears for the selection of fuel cells.

Based on present knowledge and forecast predictions about the reliability and weights of the various systems considered, the use of fuel cells is recommended.

SLIDE #24 - Life Support Equipment Weight vs. Mission Duration

This graph presents an estimate of life support equipment weights to support from 1-4 men in a "shirt-sleeve" environment for missions ranging from 1 day to 18 days. The data as shown is based on the Apollo mission (3 men - 2 wks.) estimates, a 24-hr. mission estimate, and extrapolation between these end points. It should be noted that the weight requirements for missions ranging from 1-5 days do not vary appreciably, because there is an essential basic systems weight requirement regardless of mission duration. This lends support to recommendation of a 5 day's mission capability instead of the approximate 1-2 days needed for a 150-mile mission. Weight requirements for these two missions (2 men) are 875# vs. approximately 700#.

SLIDE #25 - Vehicle Dynamics

Due to the scope of this report and the limited amount of time available, vehicle dynamics has been touched only briefly.

The particular study of vehicle vibrations has reached such a point that a high-speed computer program is the only practical method of approach. The equations are of such complexity that a variation of the system parameters (spring constants, dampening constants, velocity of vehicle, wavelength of terrain, amplitude of terrain, pitch of vehicle, bounce of vehicle, etc.) without the support of a computer is impractical. The effect of the unsprung weights (wheels & axles) on the vehicle motion should also be considered in a computer program.

This slide also shows basic equations defining requirements for location of CG height and track width to prevent overturning or tipping in the cases of braking while going downhill or in negotiating a curve. The governing criteria in both cases is that for the maximum assumed values of lunar friction, the vehicle must always slide or "spin out" rather than overturn. On the graph shown, for a given lunar value of f, $\frac{D}{2H}$ and $\frac{B}{H}$ must exceed this value to insure that sliding will occur.

Other Criteria for Design

I. Dynamic Index $\cong$ 1 or $\frac{\bar{K}^2}{AB} = 1$

where; $\bar{K}^2$ = radius gyration about the CG; A&B - respective distances from the CG to the attached springs.

Physically speaking, when the dynamic index is equal to one, the centers of percussion of the vehicle are located at the front and rear axles. This means that theoretically there would be no reaction on either axle due to an action on the other axle. Possibly it is impractical to satisfy this condition, but the dynamic index should be approximately equal to one.

II. Static deflection of front suspension system should be 25-30% greater than the rear suspension. This can be seen if while passing over a disturbance the front will have a lower frequency and the rear will have a higher frequency. The slower motion is started first and the rear has a chance to catch up with it. This should put them close to being in phase and a minimum of pitch should result.

SLIDE #26 - Energy & Propellant Requirements for LRV Mobility Over Four Assumed Lunar Profiles

This slide indicates the energy and propellant needs of various weight lunar roving vehicles for locomotion over four lunar surface profiles.

Requirements for life support equipment, communications, etc., which may amount to an estimated steady drain of three KW have not been included. This data is based on a vehicle with a 72" wheel dia. (rigid) and a tread width of 6". H_2O_2 requirements are based on a fuel cell conversion efficiency of 75%. Efficiencies of 80% for electric drive motors and 90% gear box efficiency are assumed. Twenty (20) percent additional was added to account for the negotiation of obstacles of unpredictable occurrence. If a hard surface coefficient of friction of 0.8 is assumed to exist near a crevice or boulder this vehicle, with optimum location of CG (A/ℓ = .6) and r/ℓ = 1/4, can negotiate a crevice of 5.75 ft., and climb a step 2.18 ft. high.

It should be noted that all of the above information has been derived from data obtained from the previously discussed parametric study results. Any other vehicle could be analyzed in a similar fashion. The vehicle configuration selected was just an illustrative example to show how the parametric data derived may be utilized.

SLIDE #27 - Vehicle Power & Wheel Torque Requirements

For the assumed vehicle size, and five different earth weights, this slide indicates the maximum ~~horse~~power (KW) and torque requirements for negotiating the given surfaces and slopes at a speed of 5 miles per hour. The torque requirements for negotiation of a maximum size crevice of 5.75 feet are shown for comparison purposes. The variation in torque from straight level going to the maximum crevice to be negotiated will give an indication of the torque multiplication ratios required of the drive system. Horsepower requirements for crevice and step negotiations are not shown. Actually, the vehicle speed will be reduced to practically 0 for obstacle negotiation; thus, torque requirements will be high, but H.P. requirements, which are a function of vehicle velocity, will not be significant when compared with slope negotiation at 5 mph. It can be seen that a 2500# vehicle requires 3.49 KW (4.7 H.P.) to negotiate a 30° slope @ 5 mph in addition to the continuous requirements for life support, communications, etc.

SLIDE #28 - Lunar Slope Negotiability - 4-Wheel Drive Vehicle

This slide shows the slope climbing capability as a function of vehicle weight in three assumed lunar soils as compared with a theoretical hard surface maximum of approximately 46° (based on f - .8.) The data was obtained from DP/W curves and an assumed tan Ø = 32°. It clearly shows that in locomotion over deformable soils, lightweight vehicles are superior to heavier vehicles as far as mobility is concerned. This difference is quite significant in soft, fluffy soils (K = .5, n = .5) and not so significant for a K of 3 and n = 1.25 (hard-packed beach sand).

SLIDES #29 - #30

1. For first generation lunar roving vehicles, walking, jumping and crawling mechanisms are impractical from the standpoint of reliability, simplicity, and power requirements.

2. As a vehicle becomes lighter in weight and larger in physical dimensions, it becomes more mobile over rough terrain.

3. For obstacle negotiability and minimum rolling resistance, large diameter narrow tread wheels or long narrow tracks are most efficient.

4. When compared under an equivalent size or equal load basis, reasonable wheel diameters may be selected that will approach the performance of a track. The slight difference in performance is offset by the wheel's inherent simplicity, reliability, and lower weight requirements.

5. The performance gains exhibited by soft pneumatic tires on the lunar surface are not significant enough to warrant their use. Reliability is poor compared to non-inflated semi-rigid wheel.

6. A given vehicle on earth will exhibit a much greater DP/W ratio on the moon because the resistance to motion reduces at a much greater rate than the available soil thrust.

7. Vehicle dynamics considerations render a completely rigid wheel undesirable. A semi-rigid wheel capable of withstanding the extremes of lunar environment is desired.

8. Four-wheel drive vehicles are far superior to two-wheel in obstacle negotiability.

9. For four-wheel drive vehicles, a CG location slightly forward of the midway point (A/ℓ = .6) will provide minimum torque requirements and equal friction requirements for both front and back wheels.

10. Radius of wheel to wheelbase ratios (r/ℓ) beyond 1/4 do not provide any significant improvement in obstacle negotiability.

11. A 1500# vehicle appears marginal and limited in usefulness for manned lunar roving applications.

SLIDE #31 - The Ideal, Most Versatile Lunar Mobility Concept (Mountain Goat)

SLIDE #32 - Recommendations

1. Non-inflated flexible wheels are recommended for lunar application.

2. For the first lunar vehicle a four-wheel individually powered drive system is recommended.

3. In addition to the 150-mile roving capability, the initial lunar roving vehicle should include an environmentally controlled cabin with life support equipment capable of supporting two men for at least five days in the event of a vehicle malfunction at some distance away from the base shelter.

4. The currently proposed 1500# for vehicle weight is not sufficient to cover the requirements for powerplants and desired life support equipment and still provide a versatile and useful vehicle. It is recommended that future lunar roving vehicle studies be reoriented around a 2500# - 3000# vehicle.

5. The roving vehicle should be made as versatile as possible through the use of a modular design. A standard basic self-supporting locomotive carrier module should be designed, complete with running gear system, chassis system, powerplant system, and propellant tank system.

Add-on Modules could include the following:

A. Remote Control Module - Complete with communication, auxiliary power, and vehicle control systems.

B. Manned Control Module - Complete with life support, communications, auxiliary power, and vehicle control systems.

C. Various Mission Modules - For hoisting, grading, digging, drilling, etc.

6. All modules should be interchangeable on the same basic carrier.

7. All carriers should be capable of moving singularly or in a train.

SLIDE #33 - Follow-on Study Requirements

1. Perform detailed analysis of vehicle dynamics to establish relationships between lunar surface wave forms, vehicle suspension system characteristics (transmissivity, spring constants, damping), and vehicle critical velocities.

2. Thoroughly review and refine available data on powerplant and life support systems applicable to the lunar roving vehicle.

3. Provide detailed design criteria and preliminary design of a proposed lunar roving vehicle.

LUNAR TRAFFICABILITY STUDY

FIRST PHASE REPORT BY
FUTURE STUDIES BRANCH, LOC
TECHNICAL DIRECTION — RESEARCH PROJECTS DIV. MSFC
INITIATION OF STUDY - SEPT. 13, 1962
FIRST PHASE OF EFFORT - THRU NOV. 30, 1962
FOLLOW-ON STUDIES - DEC. 1, 1962 - MARCH 1963

A. SCOPE OF FIRST PHASE STUDY

1. EVALUATION OF "STATE OF THE ART" MOBILITY ANALYSIS TECHNIQUES
2. DEVELOPMENT OF VALID CRITERIA FOR A ROVING VEHICLE

B. STUDY OUTLINE

1. REVIEW OF PARAMETERS & QUANTITIES TO BE EVALUATED
2. BASIC ASSUMPTIONS & GROUND RULES
   a. LUNAR SURFACE MODELS
   b. LUNAR PAYLOAD LIMITS
   c. PAYLOAD MISSION REQUIREMENTS
3. REVIEW OF BASIC MECHANISMS & SELECTION OF PROMISING MECHANISMS
4. FUNDAMENTAL ANALYSIS OF LOCOMOTION ON HARD & SOFT SURFACES
   a. ROLLING RESISTANCE ENERGY REQUIREMENTS
   b. MAXIMUM VEHICLE THRUST & GRADABILITY
   c. NEGOTIABILITY OF SLOPES, CREVICES & STEPS
5. SELECTION & DETAILED ANALYSIS OF OPTIMUM LOCOMOTION SYSTEM
   a. TORQUE & ENERGY REQUIREMENTS
   b. DYNAMIC CONSIDERATIONS
   c. POWERPLANT REQUIREMENTS
   d. OVERALL PERFORMANCE
   e. DESIGN FLEXIBILITY
   f. WEIGHT
   g. STATE OF THE ART & DESIGN FLEXIBILITY
   h. RELIABILITY
6. CONCLUSIONS & RECOMMENDATIONS
7. DEFINITION OF FUTURE STUDY REQUIREMENTS

PARAMETERS & QUANTITIES TO BE EVALUATED

I. SOIL PROPERTIES

ϕ · ANGLE OF FRICTION (BETWEEN SOIL GRAINS) DEGREES

C · COEFFICIENT OF SOIL COHESION PSI

K_c · MODULUS OF SOIL DEFORMATION DUE TO COHESIVE INGREDIENTS OF TERRAIN $\frac{\#}{in.^{n+1}}$

K_ϕ · MODULUS OF SOIL DEFORMATION DUE TO FRICTIONAL INGREDIENTS OF TERRAIN $\frac{\#}{in.^{n+2}}$

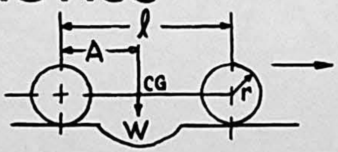
$K = \frac{K_c}{b} + K_\phi$ COMPOSITE MODULUS OF SOIL DEFORMATION $\frac{\#}{in.^{n+2}}$

n · EMPIRICAL EXPONENT OF SOIL STRESS-STRAIN RELATIONSHIP DIMENSIONLESS

N_c, N_γ } PURE NUMBERS DEPEND ON FRICTION ANGLE ϕ

f ~~μ~~ · COEFFICIENT OF FRICTION

II. VEHICLE CHARACTERISTICS



A · LOCATION OF CG WITH RESPECT TO REAR AXLE INCHES

ℓ · WHEEL BASE LENGTH OR TRACK LENGTH IN CONTACT WITH GROUND

b · TRACK OR TREAD WIDTH INCHES

$W_{E\,OR\,M}$ EARTH OR MOON WT. (LBS.) USED TO EXPRESS TOTAL VEHICLE WT. OR WT. PER WHEEL OR TRACK

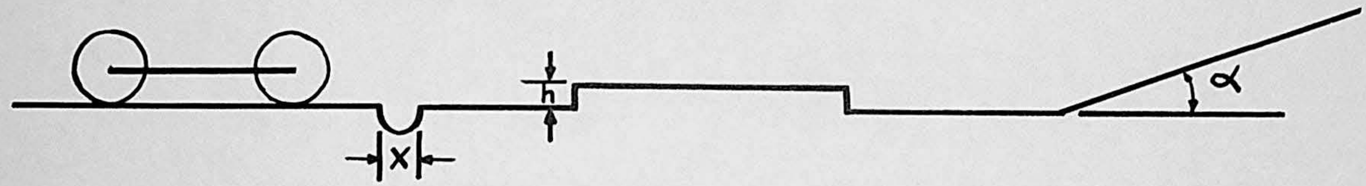
r · WHEEL RADIUS INCHES

D · WHEEL DIA.

SLIDE 2

PARAMETERS (CONT.)

III OBSTACLE CHARACTERISTICS



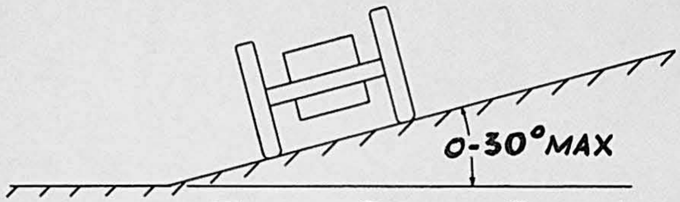
IV VARIABLES TO BE EVALUATED

$(P_i)_c$ CRITICAL TIRE INFLATION PRESSURE PSI
P_c CARCASS STIFFNESS PRESSURE PSI
F_{RW} COEFFICIENT OF HARD SURFACE ROLLING RESISTANCE FOR RIGID WHEELS
F_{FW} COEFFICIENT OF HARD SURFACE ROLLING RESISTANCE FOR FLEXIBLE WHEELS
F_T COEFFICIENT OF HARD SURFACE ROLLING RESISTANCE FOR TRACKS
a GROUND CONTACT AREA – $in.^2$
$\left.\begin{matrix}\mu \\ e\end{matrix}\right\}$ EMPIRICAL COEFFICIENTS DEPENDING ON TIRE STIFFNESS
R_{HS} HARD SURFACE ROLLING RESISTANCE #
R_S ROLLING RESISTANCE DUE TO SLOPE #
R_C MOTION RESISTANCE DUE TO SOIL COMPACTION #
H_m MAXIMUM SOIL THRUST #
$\frac{DP}{W}$ DRAWBAR PULL TO WEIGHT RATIO FOR WHEEL OR TRACK #/#
SPW SPECIFIC POWER PLANT OUTPUT KW/# MASS
E ENERGY REQ'D – FT #/MILE ~~OR KW/MILE~~
SPFC SPECIFIC FUEL CONSUMPTION – #/KW HR.
S VEHICLE RANGE – MILES
HP HORSEPOWER
n EFFICIENCY OF MOTOR & DRIVE TRAIN
f REQ'D FRICTIONAL COEFFICIENT #/#
V VEHICLE VELOCITY – FT/SEC
a VEHICLE ACCELERATION – $FT./SEC^2$

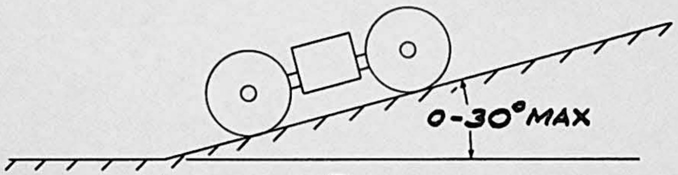
SLIDE 3

Basic Assumptions & Ground Rules

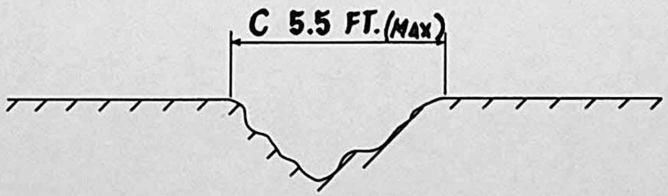
A. Surface Model – Upper Limits



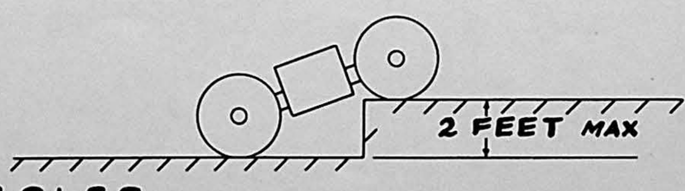
1. Traversing The Side Of A Slope



2. Drawbar Pull Requirements



3. Crevices



4. Obstacles

B. SOIL CONDITIONS

1. BOTH HARD & SOFT SOIL CONDITION'S WILL BE ASSUMED. HARD SURFACE PORTIONS WILL EXHIBT MINIMUM BEARING PRESSURE OF 6 PSI.

2. LOCOMOTION IN SOFT SOILS MAY BE EVALUATED IN TERMS OF SOIL PARAMETERS K_c, K_ϕ, C, N, & ϕ.

   ϕ = ANGLE OF FRICTION = $TAN^{-1} \frac{\text{FRICTIONAL FORCE}}{\text{NORMAL FORCE}}$
   C = COEFFICIENT OF SOIL COHESION, PSI.
   N = A FACTOR REFLECTING STRATIFICATION OF SOIL
   K_c = COHESIVE MODULUS OF DEFORMATION
   K_ϕ = FRICTIONAL MODULUS OF DEFORMATION

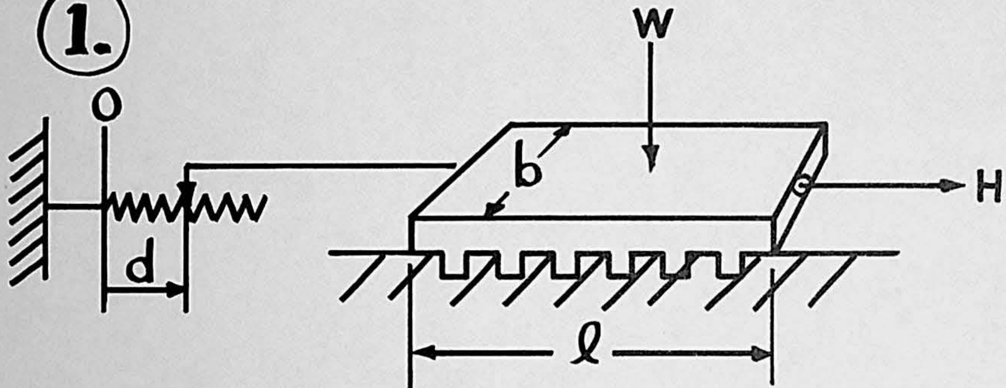
TYPICAL EARTH VALUES	DRY SAND	PLASTIC-SATURATED CLAY
C	0	3 PSI.
ϕ	40°	0

3. NO ATMOSPHERE & WATER ∴ ONLY DRY LUNAR SOILS OF A GRAVEL, SAND, OR POWDER CONSISTENCY WILL BE ASSUMED ∴ K_c=0 C=0*
   * INSUFFICIENT KNOWLEDGE IS AVAILABLE REGARDING VAN DER WAALS FORCES OF ATTRACTION BETWEEN FINE PARTICLES UNDER REDUCED GRAVITY & VACUUM. NEGLECTION OF A POSSIBLE COHESIVE COMPONENT OF LUNAR SOIL STRENGTH WILL RESULT IN CONSERVATIVE LOCOMOTION DATA.

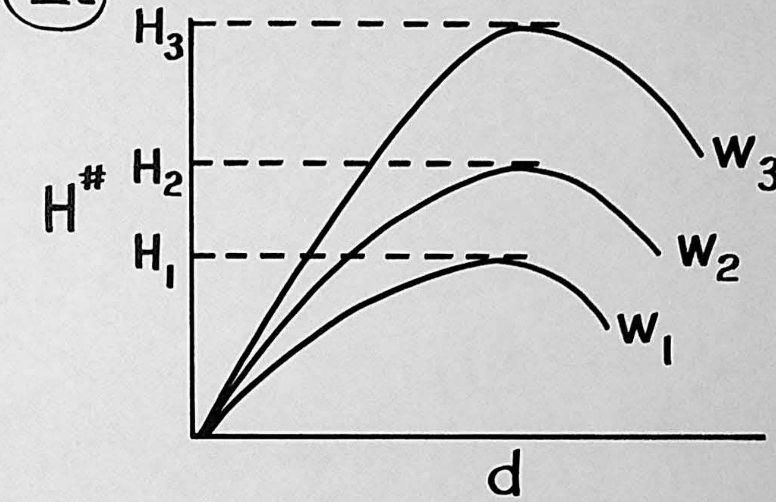
4. K_ϕ = .5 TO 3 } VARIATIONS PRODUCE SOILS RANGING FROM A MINIMUM
   N = 0.25 TO 1.25 } STRENGTH SAND TO A HARD PACKED BEACH SAND.
   ϕ = ASSUMED TO BE CONSTANT @ 32°

ESTABLISHMENT OF MAXIMUM VEHICLE THRUST IN SOIL

1.

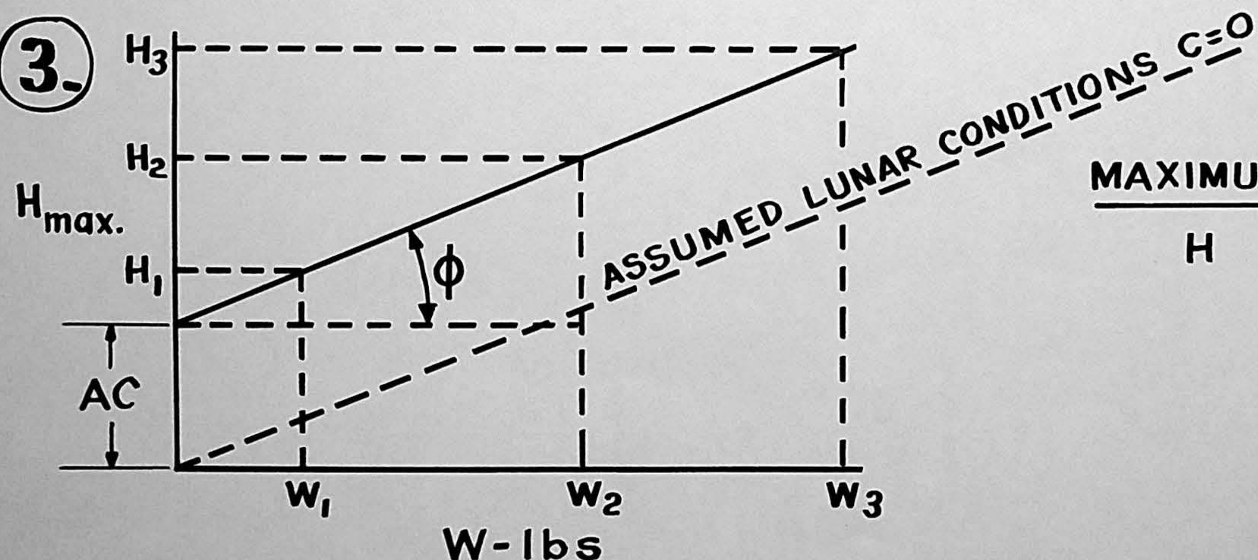


2.



A = SHEAR AREA - $(\ell \times b)\ in^2$
d = DISPLACEMENT - INCHES
W = VERTICAL LOAD - lbs.
H = PULLING FORCE - lbs.

3.



MAXIMUM SOIL THRUST EQUATION

$$H = AC + W \tan \phi$$

C. FOUR HYPOTHETICAL LUNAR MILES

PERCENT OF TIME ENCOUNTERED

PROFILE	MARIA I	MARIA NEAR SMALL CRATERS II	UPLANDS III	VICINITY OF LARGE CRATERS-UPLANDS IV
LEVEL (SOFT)	30	25	10	
5% (SOFT)	30	25	10	15
10% (SOFT)	20	20	30	25
20 FIRM	10	15	25	30
30 FIRM	10	15	20	20
40 FIRM			5	10

CREVICES, STEPS & BOULDERS

I
NO CREVICES PARTICLE SIZE-UP TO 2 CM.

II
CREVICES AROUND CRATER RIM-ISOLATED BOULDERS TO 50 CM.

III
BOULDERS UP TO .5 METER ~~[illegible]~~ -ISOLATED 2-3 METERS-CREVICES AROUND CRATER RIM

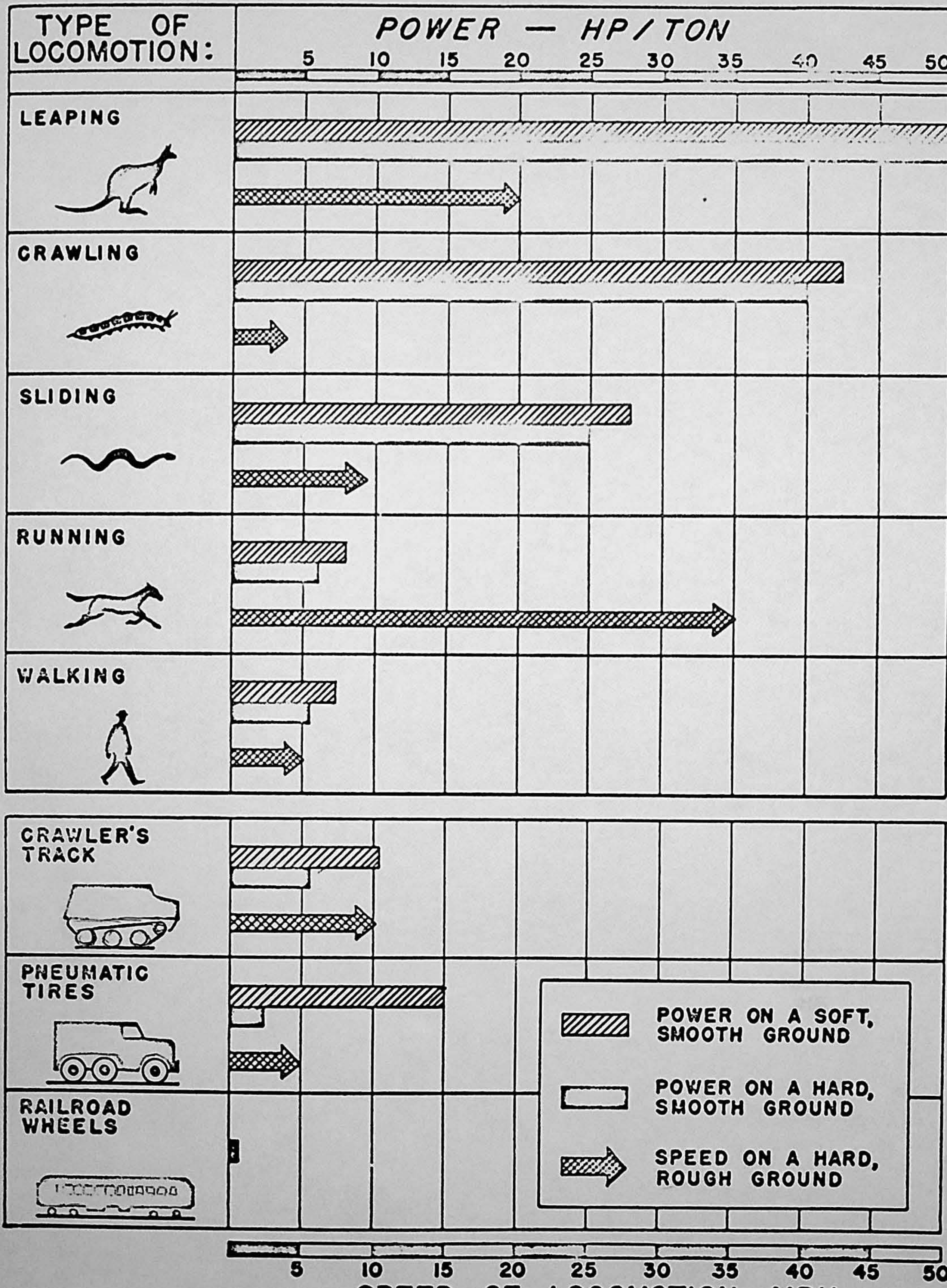
IV
BOULDERS - 5-10 METERS DIA. (TYPICAL) (IMPENETRABLE)

D. LUNAR PAYLOAD LIMITS

LANDING CPE	VEHICLE	MAXIMUM PAYLOAD
1 MILE	C1B	1,000#
67 KM.	C1B	1,800#
	C-5	15-20,000#

E. ROVING VEHICLE REQUIREMENTS

1. MUST BE CAPABLE OF LIFTING, TRANSPORTING & POSITIONING A 1500# PAYLOAD
2. LUNAR DAY AND NIGHT OPERATION IS REQUIRED
3. VEHICLE VELOCITIES UP TO 10 MPH (MANNED)
4. 150 MILES OF ROVING CAPABILITY
5. MAXIMUM AVAILABLE PAYLOAD ENVELOPE - 220"

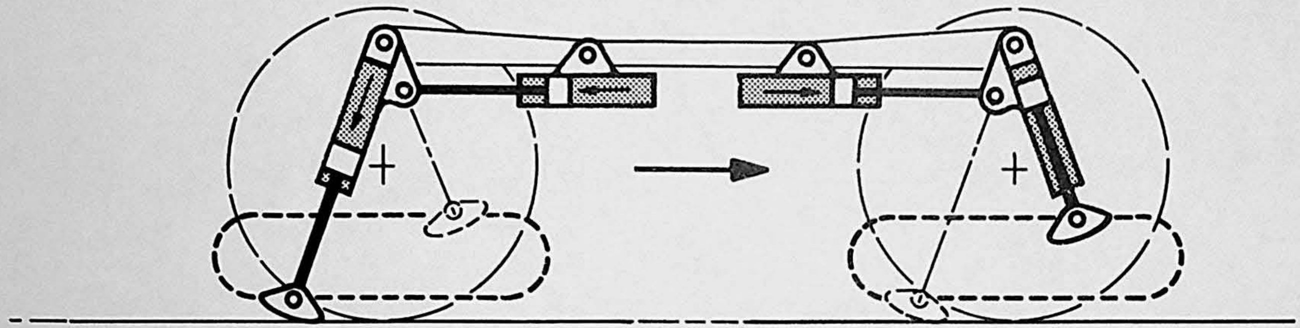


Man-made and animal locomotions.

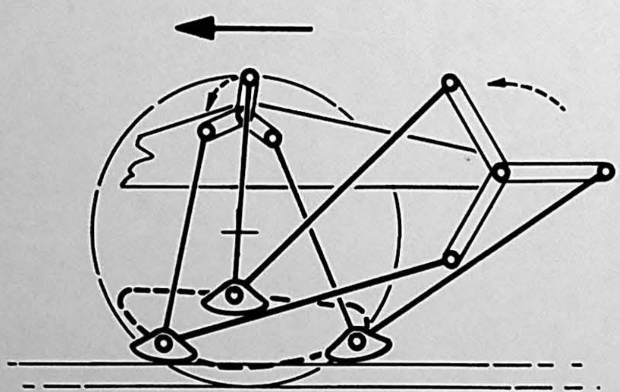
Ref. "Off-The-Road Locomotion"
by M. G. Bekker

SLIDE 9

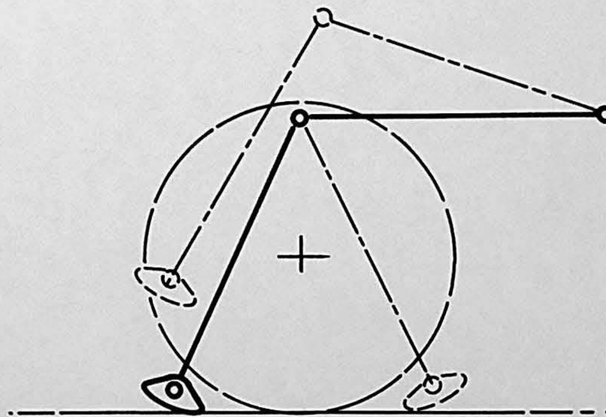
WALKING MECHANISMS PROPOSED BY VARIOUS INVESTIGATORS



MURATORI



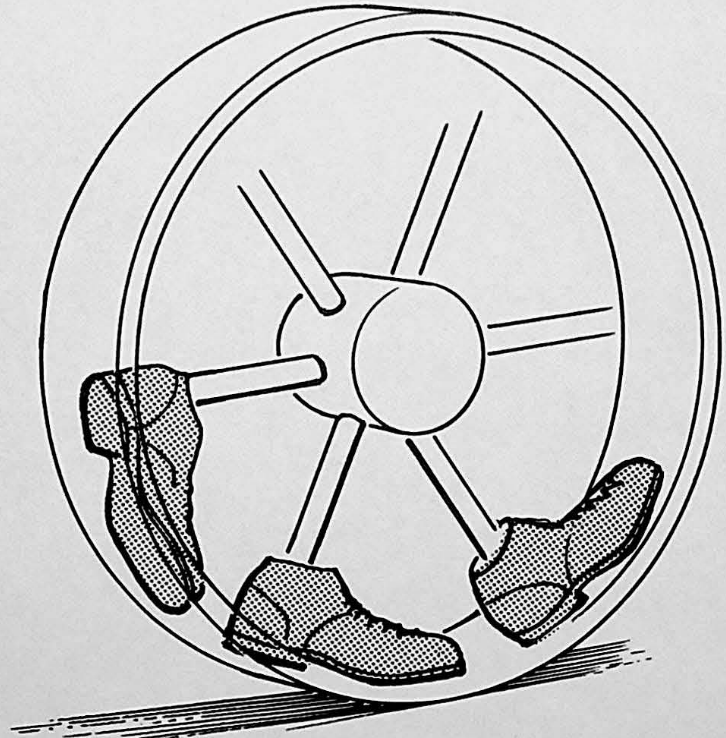
GORDON



McKENNEY

Ref. "Mechanics of Locomotion and Lunar Surface Vehicle Concepts"
By M. G. Bekker

THE WHEEL — AN IDEALIZED WALKING MACHINE



AFTER PROFESSOR J. GRAY

Ref. "Mechanics of Locomotion and Lunar Surface Vehicle Concepts"
By M. G. Bekker

MAJOR FORCES OPPOSING VEHICLE MOTION-LEVEL SURFACE

1. HARD SURFACE ROLLING RESISTANCE

RIGID WHEEL $R_{RW} = F_{RW} \frac{W}{r}$ (LOSS DUE TO BEARING FRICTION)

FLEXIBLE WHEEL $R_{FW} = F_{FW} W$ (LOSS DUE TO CARCASS FLEXURE)

TRACK $R_T = F_T W$ (INTERNAL LOSSES IN BEARINGS, LINKS, TRACK TENSION)

2. SOFT SURFACE ROLLING RESISTANCE

RIGID WHEEL $R_{TOTAL} = \left(\frac{3W}{D^{\frac{1}{2}}}\right)^{\frac{2n+2}{2n+1}} \frac{1}{(3-n)^{\frac{2n+2}{2n+1}} (n+1)(K_c + bK_\phi)^{\frac{1}{2n+1}}}$

FLEXIBLE TIRE OR TRACK $R_{TOTAL} = \frac{b}{n+1} \frac{P^{\frac{n+1}{n}}}{K^{\frac{1}{n}}}$ + HARD SURFACE ROLLING RESISTANCE

LOCOMOTION ANALYSIS

1. CRITICAL GROUND PRESSURE

$$P_c = \left[\left(\frac{W}{b}\right) \frac{n+1}{\left[\left(\frac{W}{b}\right) \frac{3}{(3-n) K D^{\frac{1}{2}}}\right]^{\frac{1}{2n+1}}}\right] \left[D - \left[\left(\frac{W}{b}\right) \frac{3}{(3-n) K D^{\frac{1}{2}}}\right]^{\frac{2}{2n+1}}\right]^{-\frac{1}{2}}$$

ABOVE CRITICAL PRESSURE – TIRE BEHAVES AS A RIGID WHEEL

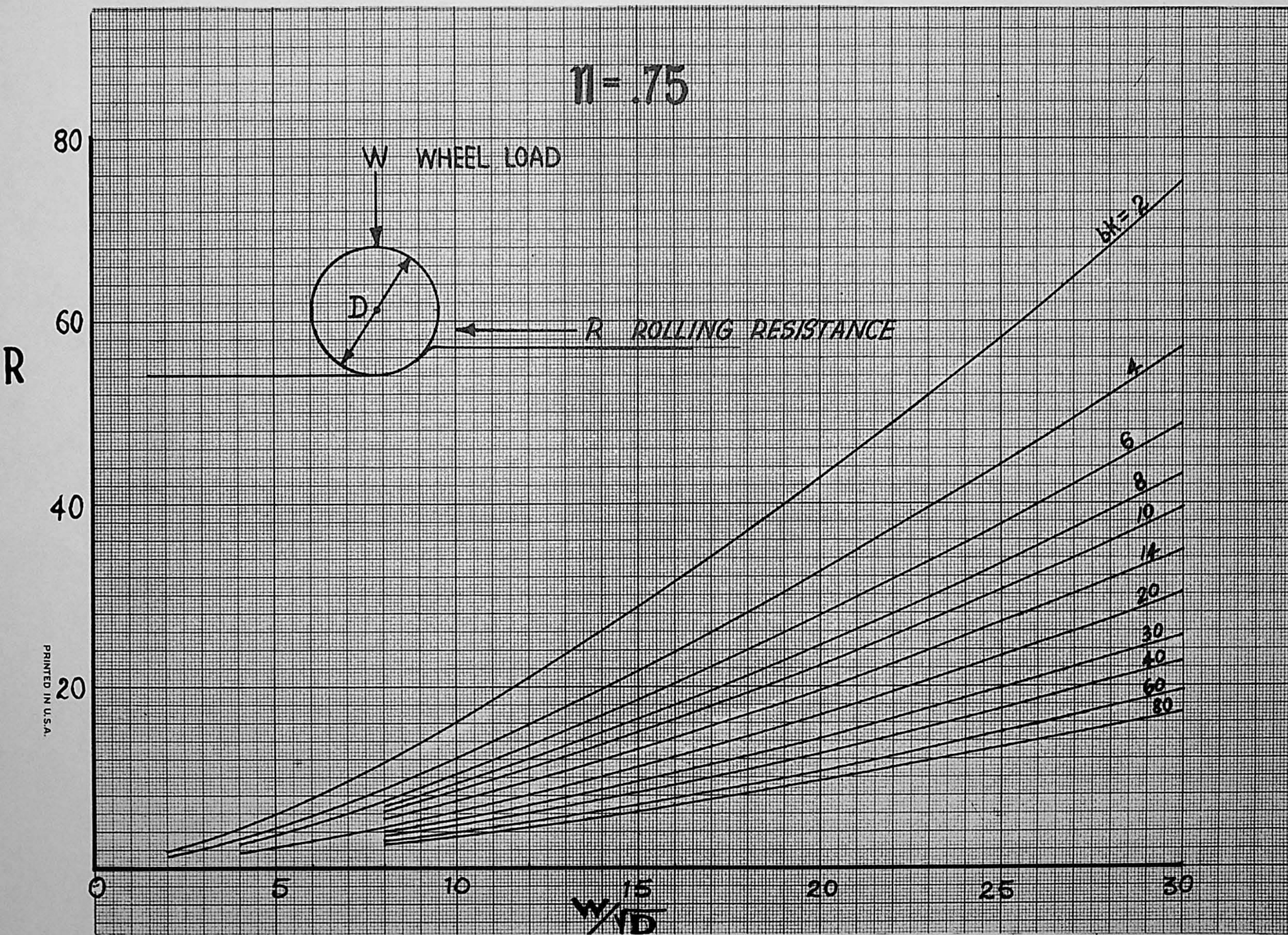
BELOW CRITICAL PRESSURE – TIRE PRODUCES FLAT GROUND CONTACT AREA

2. DRAWBAR PULL OF WHEEL OR TRACKS (DP) = MAX THRUST – ROLLING RESISTANCE

MAX THRUST = $W \tan \phi + Ac$

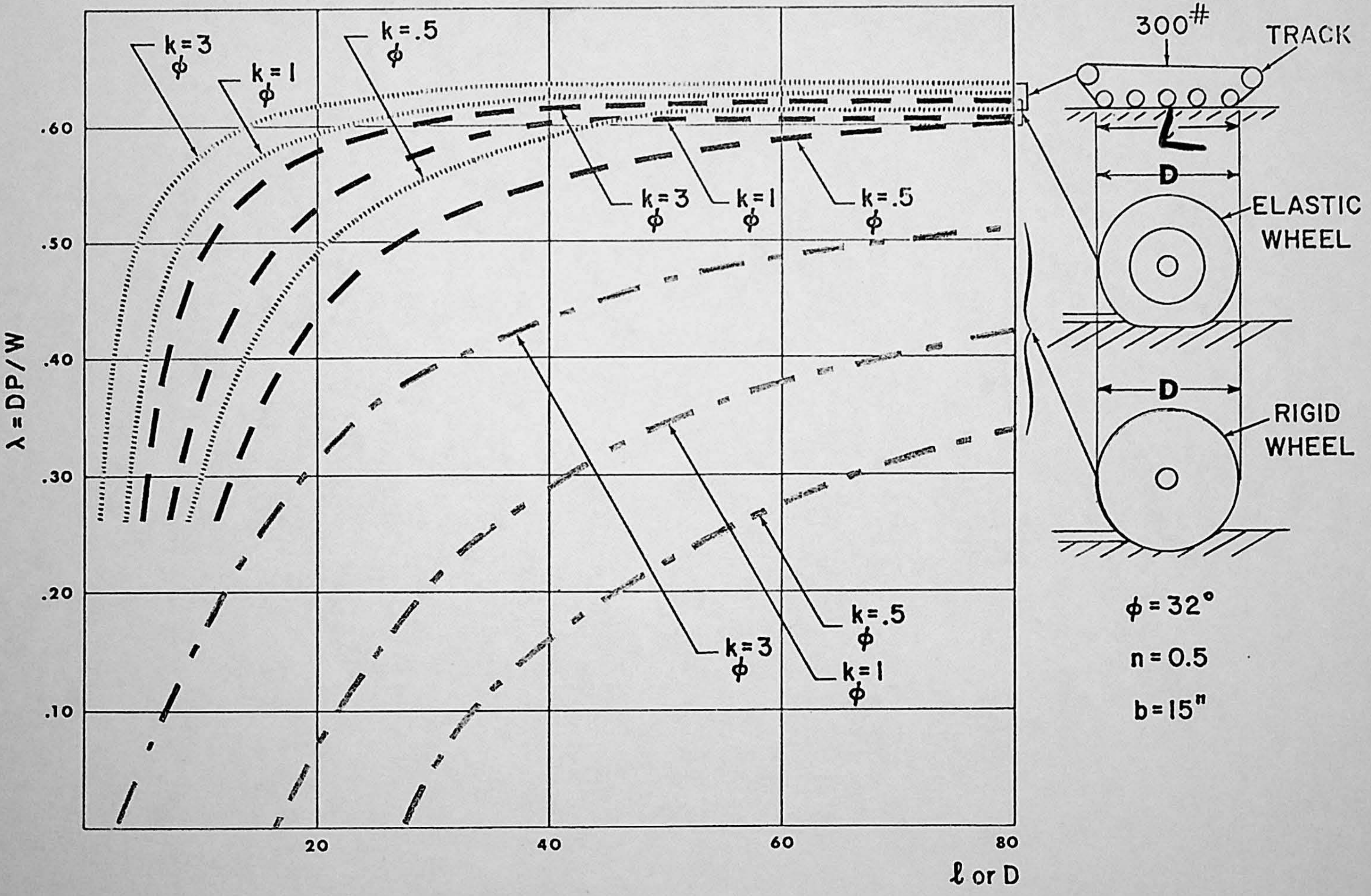
$\frac{DP}{W}$ IS HIGHLY SIGNIFICANT IN JUDGING VEHICLE PERFORMANCE, SINCE IT INDICATES THE NET THRUST REMAINING FOR PULLING, ACCELERATING AND CLIMBING

$\frac{DP}{W}$ IS APPROXIMATELY EQUAL TO THE MAX % SLOPE A VEHICLE CAN CLIMB IN A GIVEN SOIL



ROLLING RESISTANCE (R) OF HARD TIRES ON A SOFT SURFACE.

SLIDE 13

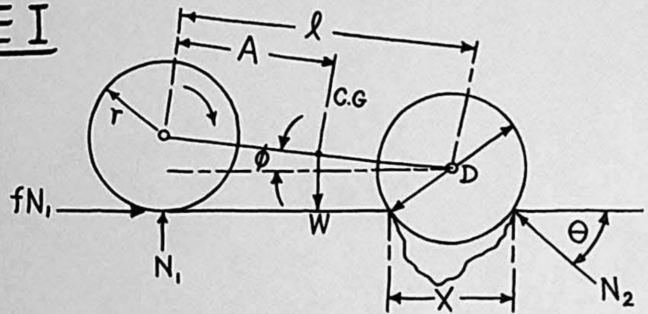


DRAWBAR PULL WEIGHT RATIO OF COMPARABLE TRACK
RIGID WHEEL AND TIRE
Ref. "Land Locomotion on the Surface of Planets"
By M. G. Bekker

SLIDE 14

TWO WHEEL DRIVE ANALYSIS

CASE I

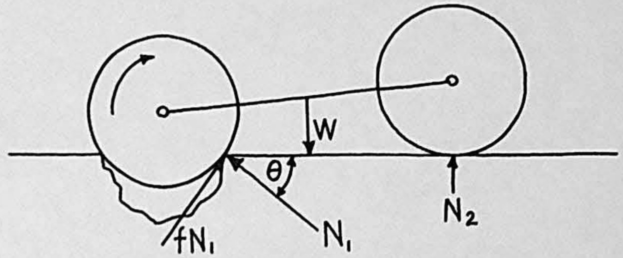


$$f = \frac{A \cos\phi \ \cot.\theta}{(\ell - A)(\cos\phi + \frac{X}{2}}$$

$$\cos\phi = \left[\ell^2 - 2r^2 + 2r\left(r^2 - \frac{X^2}{4}\right)^{\frac{1}{2}} + \frac{X^2}{4}\right]^{\frac{1}{2}}$$

$$\cos\theta = \frac{X}{D}$$

CASE II



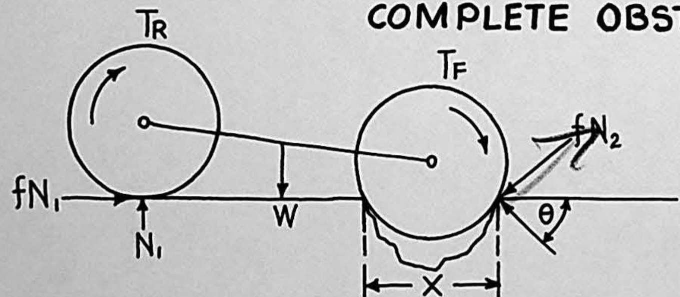
$$f = \cot.\theta$$

REAR WHEEL IS ALWAYS THE LIMITING CASE

$A/\ell \cong .5$ OPTIMUM

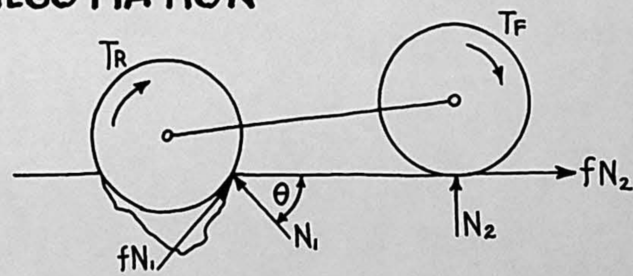
FOUR WHEEL DRIVE ANALYSIS

COMPLETE OBSTACLE NEGOTIATION



$$\frac{T_R}{DW} = f\frac{[(1 - A/\ell)\cos\phi + r/\ell \ \cos\theta]}{2[\cos\phi + r/\ell \ \cos\theta]}$$

$$\frac{T_F}{DW} = \frac{f \ A/\ell \ \cos\phi}{2(f\cos\theta + \sin\theta)(\cos\phi + \frac{r}{\ell}\cos\theta)}$$



$$\frac{T_R}{DW} = \frac{f\cos\phi \ (1 - A/\ell)}{2(\cos\phi - \frac{r}{\ell}\cos\theta)(\sin\theta + f\cos\theta)}$$

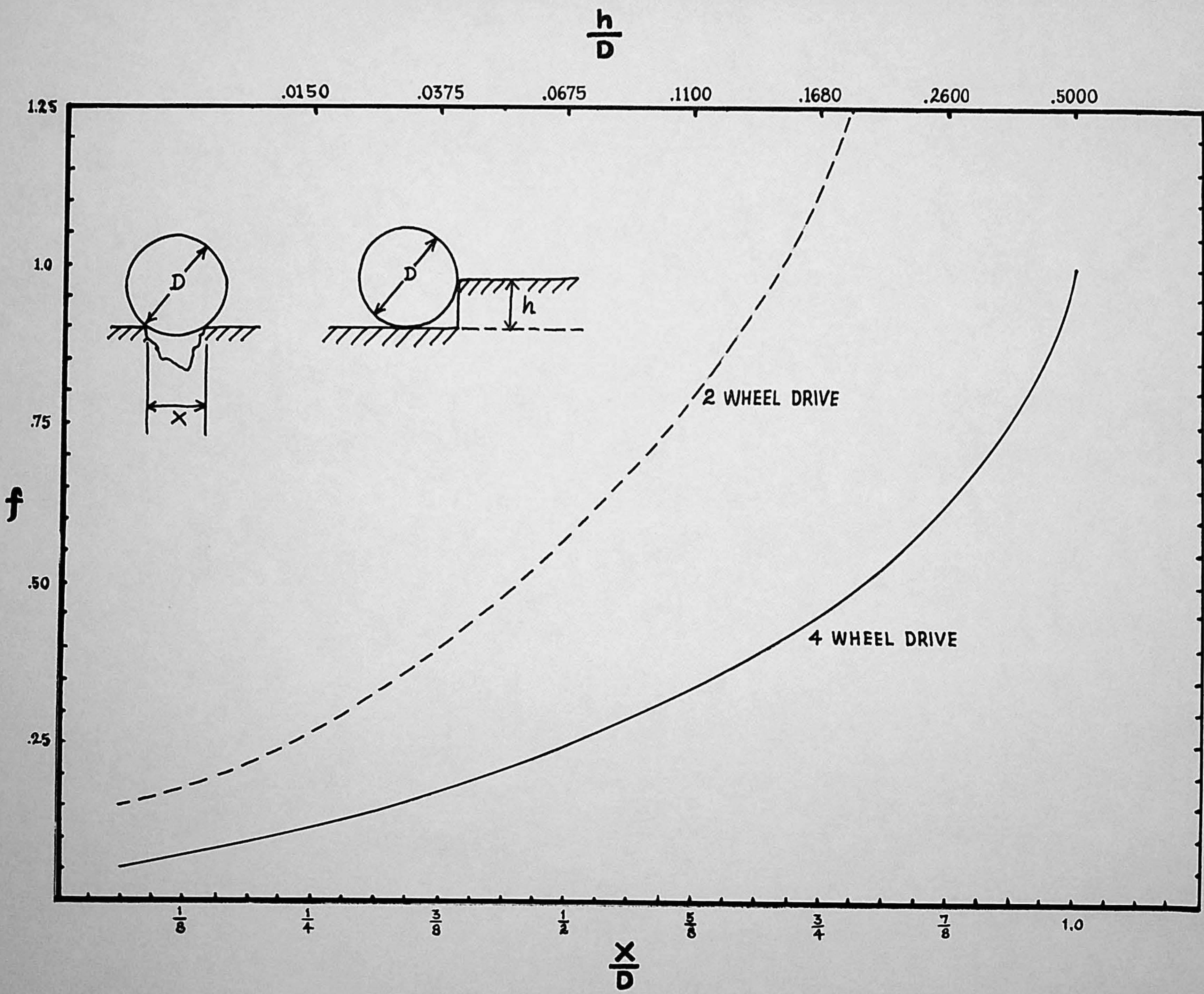
$$\frac{T_F}{DW} = \frac{f(\frac{A}{\ell}\cos\phi - \frac{r}{\ell}\cos\theta)}{2(\cos\phi - \frac{r}{\ell}\cos\theta)}$$

FRONT WHEEL IN CREVICE

$$f = \frac{-\sin\theta[\cos\phi + \frac{r}{\ell}\cos\theta] + \sqrt{(\cos\phi + r/\ell \cos\theta)^2 \sin^2\theta + 4 A/\ell \cos^2\theta \cos\phi [(1 - A/\ell)\cos\phi + r/\ell \cos\theta]}}{2\cos\theta[(1 - A/\ell)\cos\phi + r/\ell \ \cos\theta]}$$

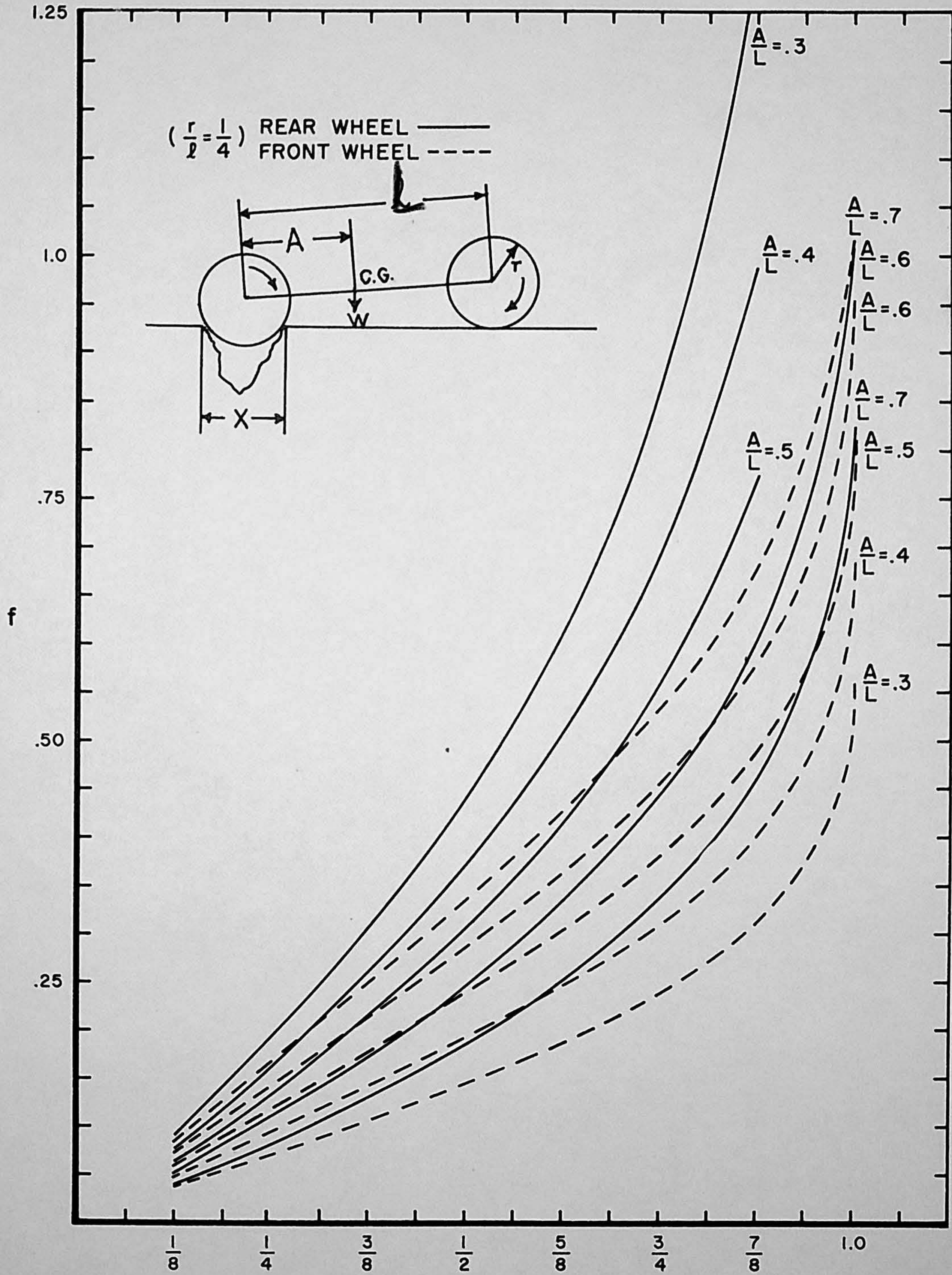
REAR WHEEL IN CREVICE

$$f = \frac{-\sin\theta(\cos\phi - \frac{r}{\ell}\cos\theta) + \sqrt{(\cos\phi - \frac{r}{\ell}\cos\theta)^2 \sin^2\theta + 4\cos^2\theta[(1 - \frac{A}{\ell})(\frac{A}{\ell}\cos^2\phi - \frac{r}{\ell}\cos\theta\cos\phi)]}}{2\cos\theta(\frac{A}{\ell}\cos\phi - \frac{r}{\ell}\cos\theta)}$$

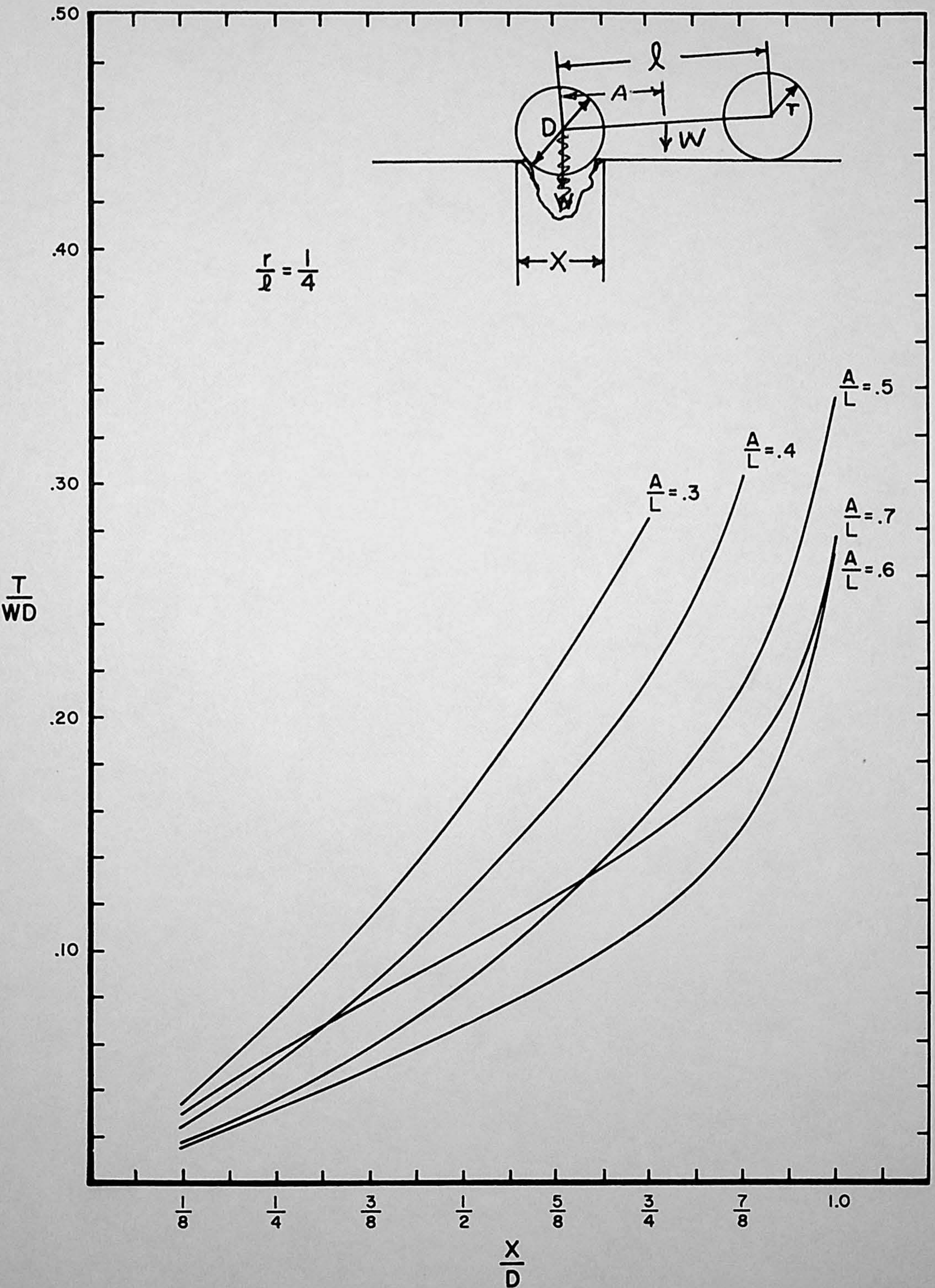


FRICTION REQUIREMENTS FOR CREVICE AND STEP NEGOTIABILITY

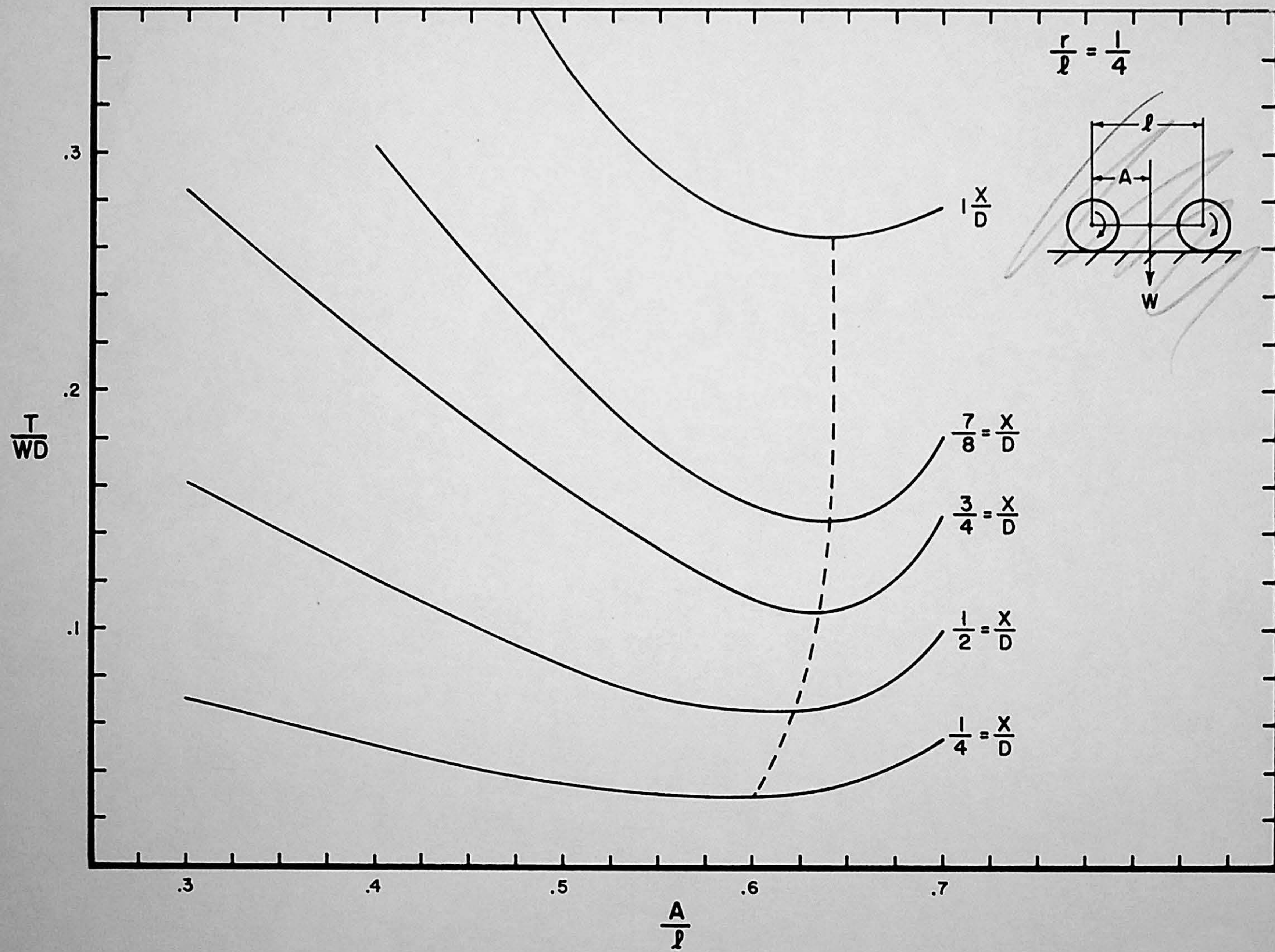
SLIDE 16



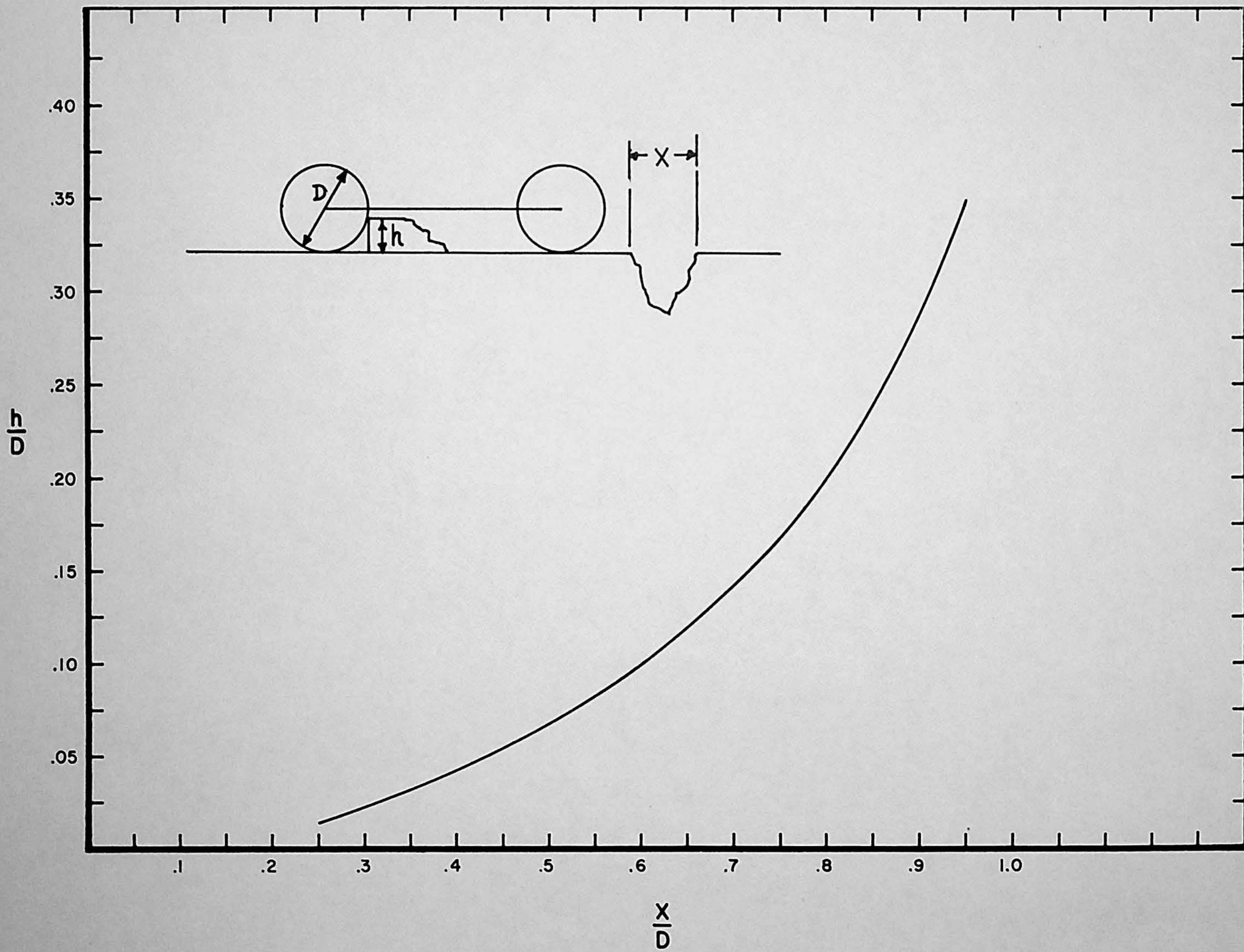
FRICTION REQUIREMENTS FOR FOUR WHEEL DRIVE VEHICLE NEGOTIATING A CREVICE.



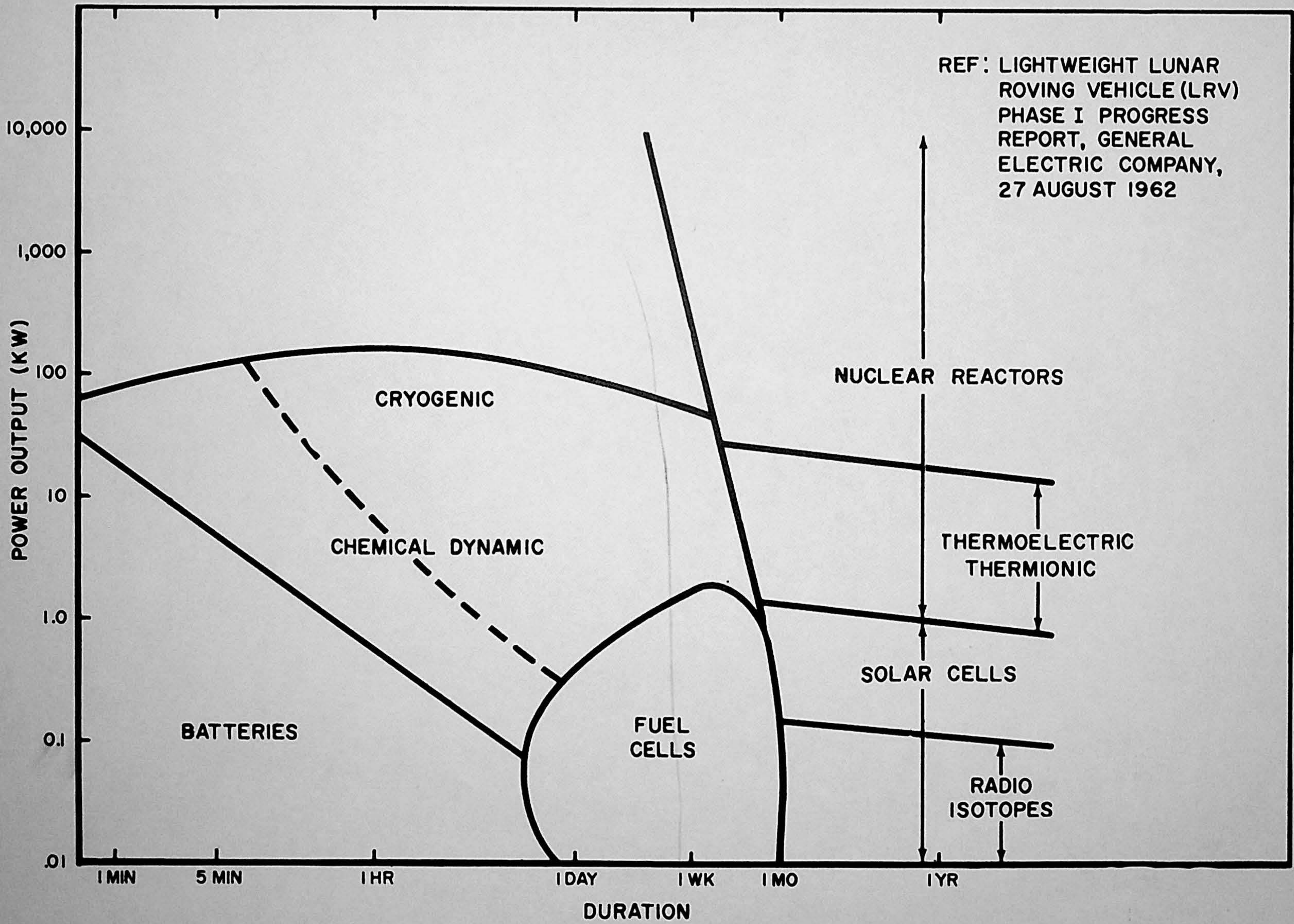
MAXIMUM AXLE TORQUE REQUIREMENTS FOR FOUR WHEEL DRIVE VEHICLE NEGOTIATING A CREVICE.



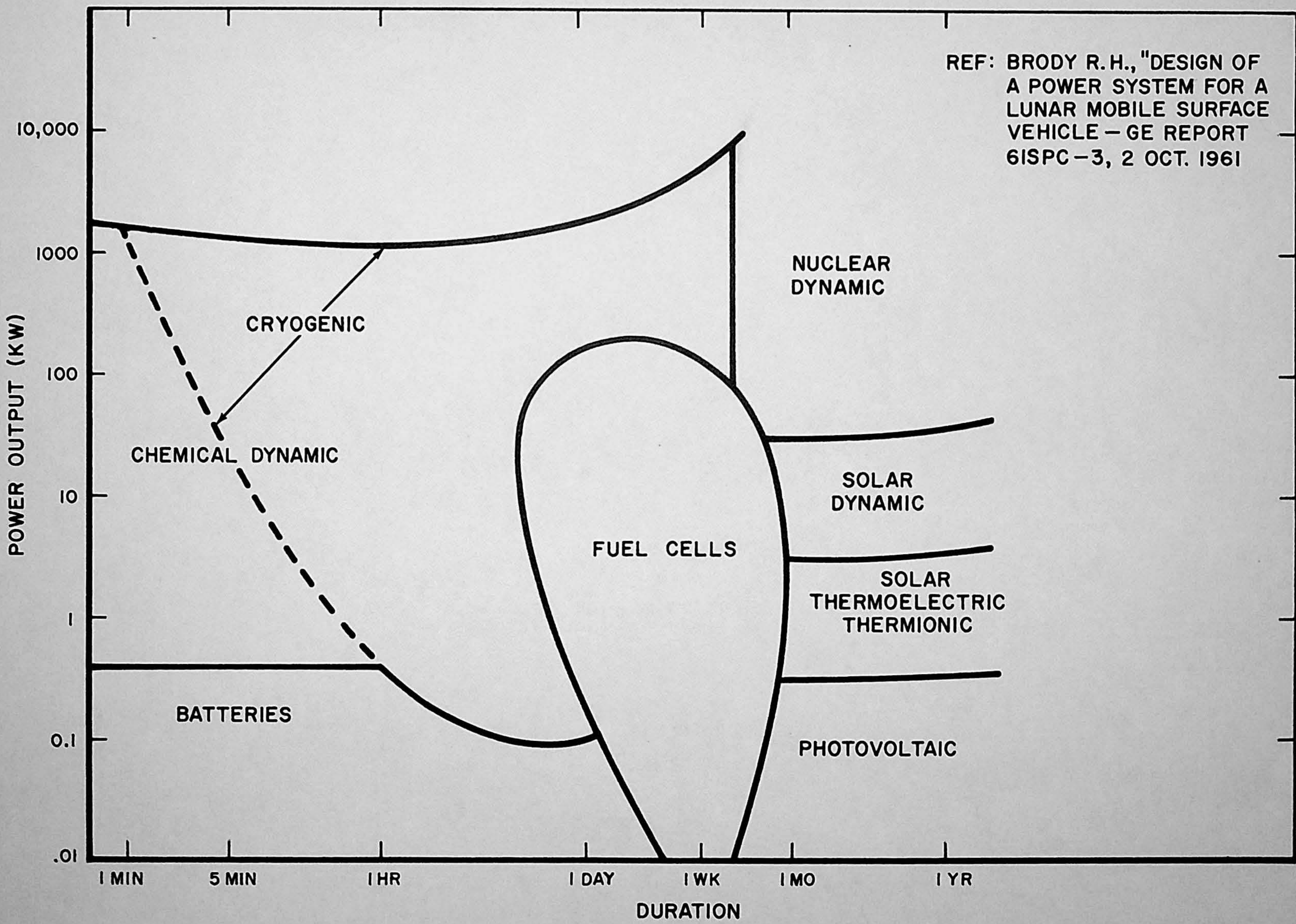
VEHICLE C.G. LOCATION FOR MINIMUM TORQUE & MAXIMUM OBSTACLE NEGOTIABILITY



CREVICE WIDTH CONVERTED TO OBSTACLE HEIGHT OF EQUAL NEGOTIABILITY



POWER SYSTEMS
1962 AREAS OF OPTIMUM APPLICATIONS



POWER SYSTEMS FORECAST FOR 1966

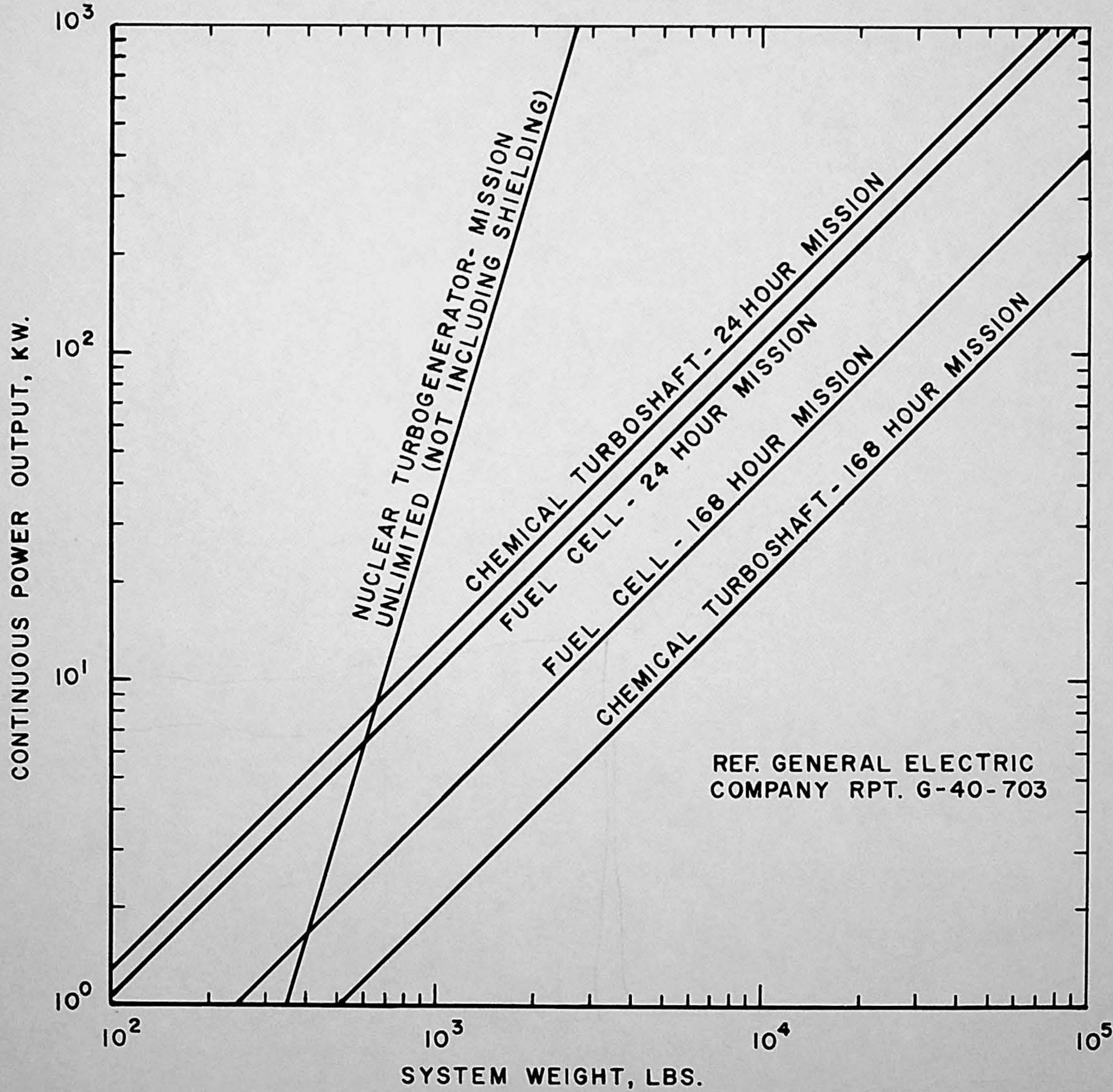
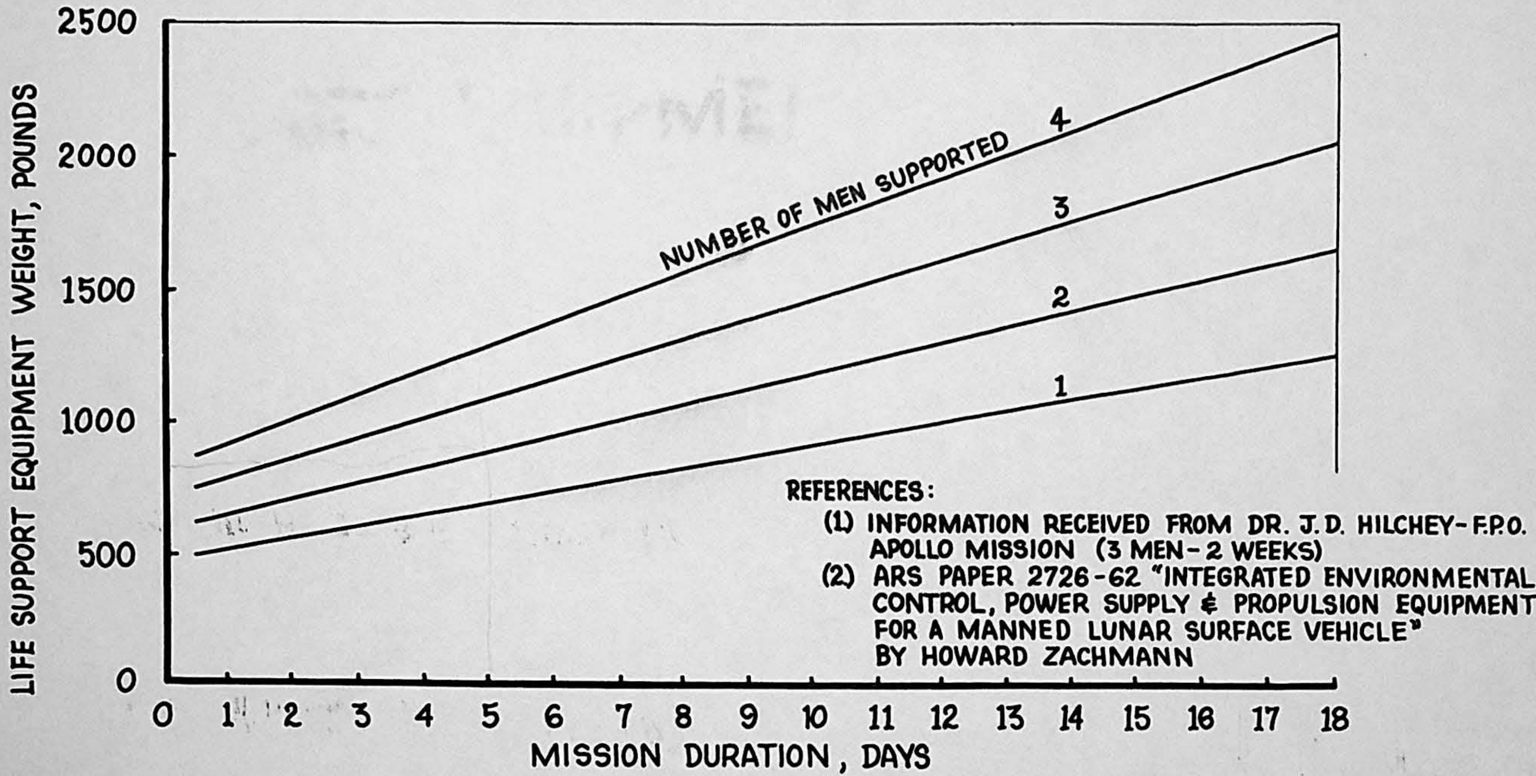


FIG. POWER SYSTEMS WEIGHT

SLIDE 23

LIFE SUPPORT EQUIPMENT WEIGHT



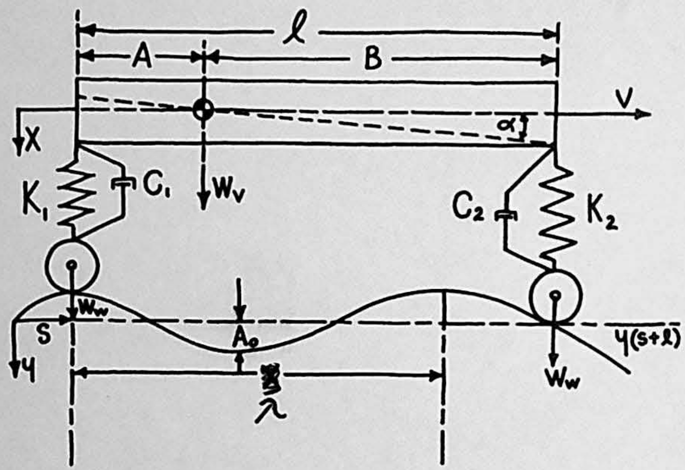
ENVIRONMENTAL CONTROL, SYSTEM EQUIP. & EXPENDABLES APOLLO MISSION (3 MEN 2 WKS.)

	SYSTEM	HARDWARE	EXPENDABLES
1.	OXYGEN SYSTEM	200#	150#
2.	NITROGEN SYSTEM	200#	150#
3.	TEMP. CONTROL	250# (150# PLUS 50# /ADDITIONAL MAN)	
4.	FOOD, WATER & CONTAINERS		50#/MAN
5.	HUMIDITY CONTROL	250# (150# PLUS 50# /ADDITIONAL MAN)	
6.	CONTAMINANTS	25#	

	SYSTEMS	HARDWARE	EXPENDABLES
7.	WATER MANAGEMENT	50# (40# PLUS 5# /ADDITIONAL MAN)	
8.	SEATS	100#/MAN	
9.	SANITATION	10#/MAN	
10.	SURVIVAL KITS	50#/MAN	
11.	BIOMEDICAL	2#/MAN	
12.	CO_2 ABSORBERS	150# (100# PLUS 25# /ADDITIONAL MAN)	

VEHICLE DYNAMICS

I VEHICLE VIBRATIONS:



ASSUMPTIONS:

- y - COSINE WAVE FORM
- W_w - NEGLECTED WEIGHT OF WHEELS
- V - CONSTANT

SYMBOLS & PARAMETERS:

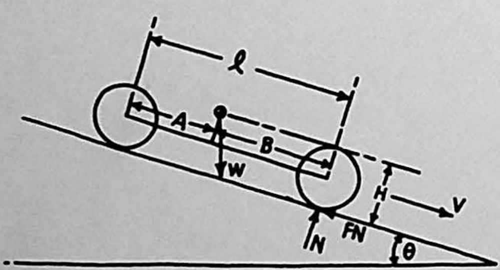
- X = VEHICLE BOUNCE FROM STATIC POSITION
- α = VEHICLE PITCH ANGLE
- λ = WAVE LENGTH
- A_0 = MAX. WAVE AMPLITUDE
- W_v = WEIGHT OF VEHICLE
- S = HORIZONTAL GROUND DISTANCE = $\int V\,dt$
- K = SPRING CONSTANTS
- C = DAMPENING CONSTANTS
- ℓ = LENGTH OF VEHICLE

BASIC EQUATIONS DERIVED FROM:

(A) Σ FORCES = MASS × ACCELERATION. (B) Σ MOMENTS = MASS MOMENT OF INERTIA.

A HIGH-SPEED DIGITAL COMPUTER WILL BE UTILIZED TO INVESTIGATE THE INFLUENCE OF THE SYSTEM PARAMETERS UPON THE MOTION OF THE VEHICLE. FUTHER INVESTIGATION OF MORE COMPLEX ASPECTS OF THE VEHICLE DYNAMICS WILL BE ACCOMPLISHED WHERE NECESSARY.

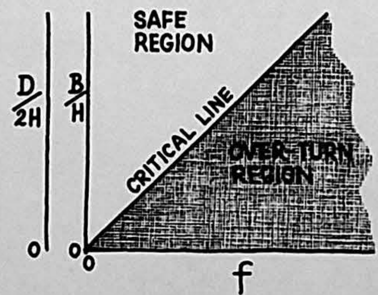
II. CRITICAL CASE OF BRAKING:



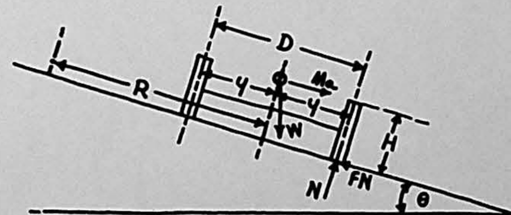
$f = \frac{B}{H}$

CRITERIA FOR SLIDING

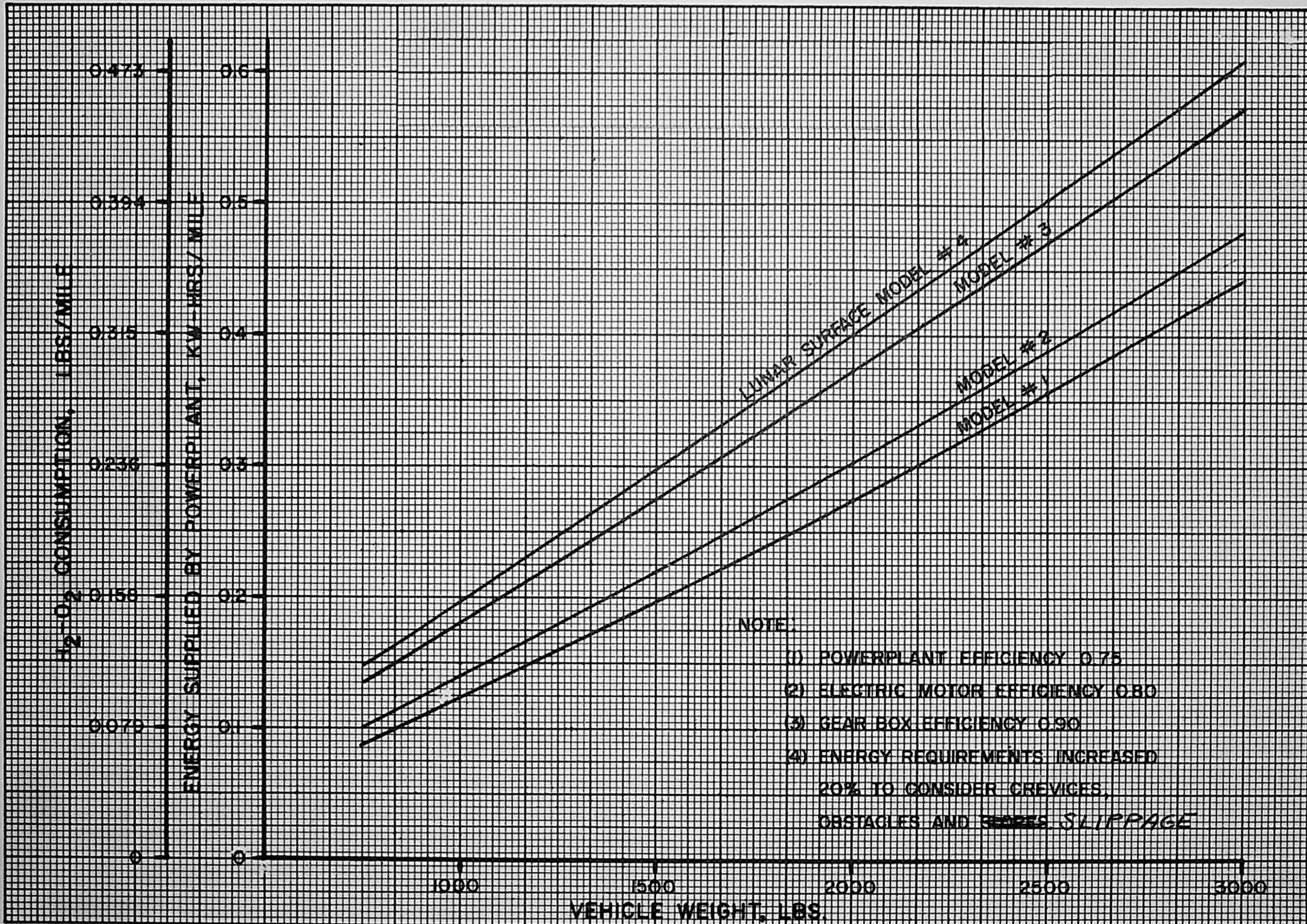
$f < \tan\phi + \frac{a}{g\cos\theta}$



III CRITICAL CASE OF OVERTURNING: (TURNING CURVE ON A SLOPE).



$f = \frac{D}{2H}$



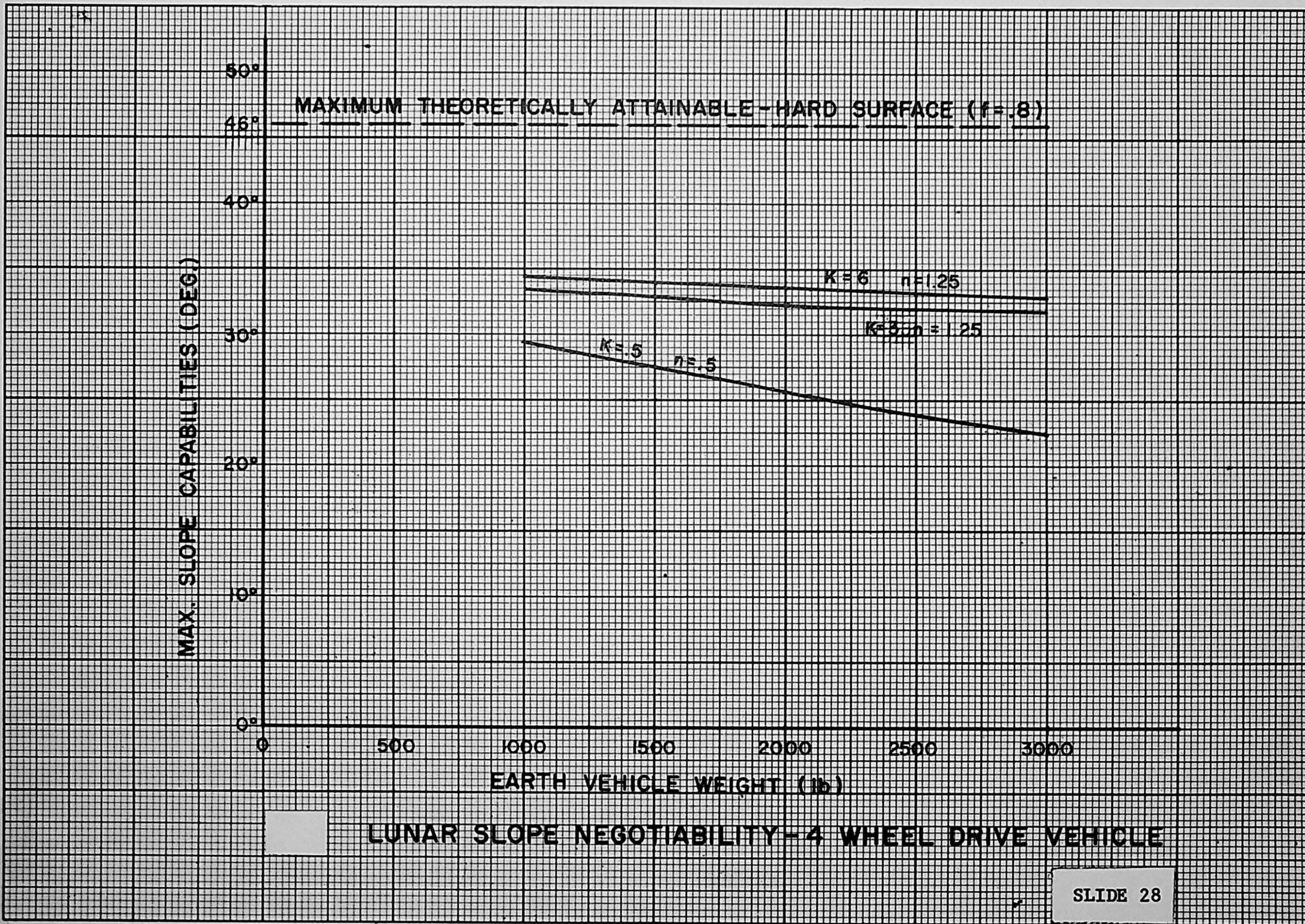
ENERGY & PROPELLANT REQUIREMENTS FOR LRV MOBILITY OVER FOUR ASSUMED LUNAR PROFILES.

VEHICLE		LEVEL K = 0.5 n = 0.5	5° SLOPE K = 3.0 n = 1.25	10° SLOPE K = 3.0 n = 1.25	20° SLOPE HARD SURFACE	30° SLOPE HARD SURFACE	40° SLOPE HARD SURFACE	WHEEL TORQUE FOR MAXIMUM NEGOTIABLE CREVICE
1000#	WHEEL TORQUE FT.-LBS.	17.3	20.7	31.6	43.6	63.5	77.5	106.0
	VEHICLE POWER K W.	0.38	0.46	0.70	0.96	1.40	1.71	
1500#	WHEEL TORQUE FT.-LBS.	31.3	32.6	48.8	65.4	95.0	120.0	159.0
	VEHICLE POWER K W.	0.69	0.72	1.08	1.44	2.10	2.65	
2000#	WHEEL TORQUE FT.-LBS.	48.2	45.0	66.7	87.1	127.0	160.0	212.0
	VEHICLE POWER K W.	1.06	0.99	1.47	1.92	2.80	3.53	
2500#	WHEEL TORQUE FT.-LBS.	66.5	58.0	85.0	108.5	163.5	200.0	265.0
	VEHICLE POWER K W.	1.47	1.28	1.88	2.40	3.49	4.42	
3000#	WHEEL TORQUE FT.-LBS.	86.5	72.2	104.6	131.0	190.0	239.0	318.0
	VEHICLE POWER K W.	1.91	1.60	2.31	2.89	4.20	5.29	

NOTE: POWER REQUIREMENTS BASED ON VEHICLE SPEED OF 5 M.P.H.

VEHICLE POWER AND WHEEL TORQUE REQUIREMENTS

SLIDE 27


MAXIMUM THEORETICALLY ATTAINABLE - HARD SURFACE (f = .8)
50°
46°
40°
30°
20°
10°
0°
MAX. SLOPE CAPABILITIES (DEG.)
K = 6 n = 1.25
K = 3 n = 1.25
K = .5 n = .5
0
500
1000
1500
2000
2500
3000
EARTH VEHICLE WEIGHT (lb)
LUNAR SLOPE NEGOTIABILITY - 4 WHEEL DRIVE VEHICLE
SLIDE 28

GENERAL CONCLUSIONS

1. FOR FIRST GENERATION LUNAR ROVING VEHICLES, WALKING, JUMPING & CRAWLING MECHANISMS ARE IMPRACTICAL FROM THE STANDPOINT OF RELIABILITY, SIMPLICITY & POWER REQUIREMENTS.

2. AS A VEHICLE BECOMES LIGHTER IN WEIGHT & LARGER IN PHYSICAL DIMENSIONS, IT BECOMES MORE MOBILE OVER ROUGH TERRAIN.

3. FOR OBSTACLE NEGOTIABILITY & MINIMUM ROLLING RESISTANCE, LARGE DIAMETER NARROW TREAD WHEELS OR LONG NARROW TRACKS ARE MOST EFFICIENT.

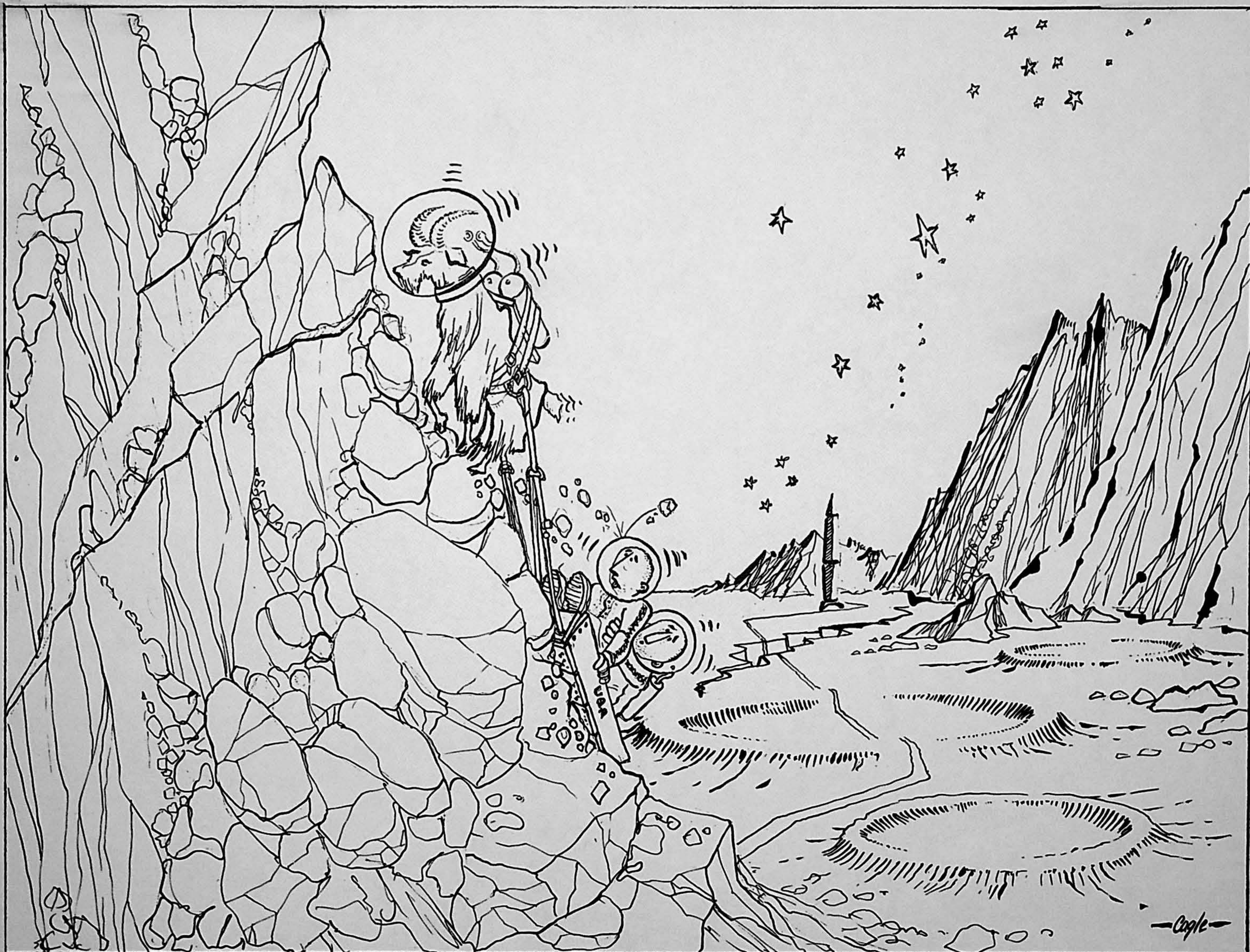
4. WHEN COMPARED UNDER AN EQUIVALENT SIZE OR EQUAL LOAD BASIS, REASONABLE WHEEL DIAMETERS MAY BE SELECTED THAT WILL APPROACH THE PERFORMANCE OF A TRACK. THE SLIGHT DIFFERENCE IN PERFORMANCE IS OFFSET BY THE WHEEL'S INHERENT SIMPLICITY, RELIABILITY & LOWER WEIGHT REQUIREMENTS.

5. THE PERFORMANCE GAINS EXHIBITED BY SOFT PNEUMATIC TIRES ON THE LUNAR SURFACE ARE NOT SIGNIFICANT ENOUGH TO WARRANT THEIR USE. RELIABILITY IS POOR COMPARED TO A RIGID WHEEL.

6. A GIVEN VEHICLE ON EARTH WILL EXHIBIT A MUCH GREATER DP/W ~~DRAWBAR PULL~~ ON THE MOON BECAUSE THE RESISTANCE TO MOTION REDUCES AT A MUCH GREATER RATE THAN THE AVAILABLE SOIL THRUST.

GENERAL CONCLUSIONS (CONT.)

7. VEHICLE DYNAMICS CONSIDERATIONS RENDER A COMPLETELY RIGID WHEEL UNDESIRABLE. A SEMI-RIGID WHEEL CAPABLE OF WITHSTANDING THE EXTREMES OF LUNAR ENVIRONMENT IS DESIRED.
8. FOUR WHEEL DRIVE VEHICLES ARE FAR SUPERIOR TO TWO WHEEL DRIVE IN OBSTACLE NEGOTIABILITY.
9. FOR FOUR WHEEL DRIVE VEHICLES, A C.G. LOCATION SLIGHTLY FORWARD OF THE MIDWAY POINT ($A/\ell = .6$) WILL PROVIDE MINIMUM TORQUE REQUIREMENTS AND EQUAL FRICTION REQUIREMENTS FOR BOTH FRONT & BACK WHEELS.
10. RADIUS OF WHEEL TO WHEELBASE RATIOS (r/ℓ) BEYOND 1/4 DO NOT PROVIDE ANY SIGNIFICANT IMPROVEMENT IN OBSTACLE NEGOTIABILITY.
11. A 1500# VEHICLE APPEARS MARGINAL AND LIMITED IN USEFULNESS FOR MANNED LUNAR ROVING APPLICATIONS.



SLIDE 31

RECOMMENDATIONS

1. NON-INFLATED FLEXIBLE WHEELS ARE RECOMMENDED FOR LUNAR APPLICATION
2. FOR THE FIRST LUNAR VEHICLE A FOUR WHEEL INDIVIDUALLY POWERED DRIVE SYS. IS RECOMMENDED.
3. IN ADDITION TO THE 150 MILE ROVING CAPABILITY THE INITAL LUNAR ROVING VEHICLE SHOULD INCLUDE AN ENVIRONMENTALLY CONTROLLED CABIN WITH LIFE SUPPORT EQUIPMENT CAPABLE OF SUPPORTING 2 MEN FOR AT LEAST 5 DAYS IN THE EVENT OF A VEHICLE MALFUNCTION AT SOME DISTANCE AWAY FROM THE BASE SHELTER.
4. THE CURRENTLY PROPOSED 1500# FOR VEHICLE WEIGHT IS NOT SUFFICIENT TO COVER THE REQUIREMENTS FOR POWER PLANTS AND LIFE SUPPORT EQUIP. AND STILL PROVIDE A VERSATILE AND USEFUL VEHICLE.
5. THE ROVING VEHICLE SHOULD BE OF A MODULAR DESIGN. A STANDARD BASIC SELF SUPPORTING LOCOMOTIVE CARRIER MODULE SHOULD BE DESIGNED COMPLETE WITH RUNNING GEAR SYS., CHASSIS SYS, POWER PLANT SYS., & PROPELLANT TANK SYS. ADD-ON MODULES COULD INCLUDE THE FOLLOWING: (A) REMOTE CONTROL MODULES, (B) MANNED CONTROL MODULES, (C) MISSION MODULES
6. ALL MODULES SHOULD BE INTERCHANGEABLE ON THE SAME BASIC CARRIER.
7. ALL CARRIERS SHOULD BE CAPABLE OF MOVING SINGULARLY OR IN A TRAIN.

FOLLOW-ON STUDY REQUIREMENTS

1. PERFORM DETAILED ANALYSIS OF VEHICLE DYNAMICS TO ESTABLISH RELATIONSHIPS BETWEEN LUNAR SURFACE WAVE FORMS, VEHICLE SUSPENSION SYSTEM CHARACTERISTICS, (TRANSMISSIVITY, SPRING CONSTANTS, DAMPING,) AND VEHICLE CRITICAL VELOCITIES.
2. THOROUGHLY REVIEW & REFINE AVAILABLE DATA ON POWER PLANT & LIFE SUPPORT SYSTEMS APPLICABLE TO THE LUNAR ROVING VEHICLE.
3. PROVIDE DETAILED DESIGN CRITERIA AND PRELIMINARY DESIGN OF A PROPOSED LUNAR ROVING VEHICLE.
4. EVALUATE MATERIALS PROBLEMS TO BE EXPERIENCED IN THE HARSH LUNAR ENVIRONMENT.