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750-12

PHOTOHELIOGRAPH
FILM CAMERA DESIGN

August 12, 1968

G. Bastien

Approved by: [signature]
J. Denton Allen, Task Leader,
Photoheliograph Task

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
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FOREWORD

This report covers work on one phase of the photoheliograph development task, NASA Code 945-84-00-01-00, for the period November 1967 through June 1968. The photoheliograph has been proposed to NASA for the Apollo telescope mount (ATM) by Caltech, with Professor Harold Zirin as the principal investigator and Dr. Robert Howard of Mt. Wilson and Palomar Observatories the co-investigator (see TM 33-369, November 1967). The objective of the investigation is to obtain high resolution cinematographs in white light near ultraviolet and narrow band hydrogen alpha. Because of the ATM program uncertainties, emphasis has been placed on areas of technology that are somewhat mission-independent, but the ATM spacecraft has been used to establish design constraints.

ABSTRACT

Image recording in the photoheliograph may be either by TV or photographic film. Light energy histograms in UV (1500 to 3000Å), white light (4000 to 6100Å) and Hα (6563Å) have been prepared which show that images can be recorded with reasonable exposure times (less than 1/20 sec.) and on commercially available film (i. e. Kodak SO-375). The advantages over TV are fast frame rates if required, finer resolution, and permanent record. The disadvantages are the limited total number of frames available, the need for Astronaut EVA to retrieve the film, possible radiation fogging, and the greater weight of the cameras. In an attempt to minimize these disadvantages as compared to presently available cameras, JPL undertook to design a light weight, sealed camera with the following features: maximum film load (limited by weight), 70mm film for dual track 35mm recording to reduce spool size, automatically reversible film advance mechanism.

CONTENTS

PHOTOHELIOGRAPH FILM CAMERA DESIGN

REQUIREMENTS

The functional and mission requirements and the ATM constraints together determined the following specifications for the film camera system:

(1) Full frame, 35mm format (for resolution, field of view, and for compatibility with usual editing and projection techniques).

(2) 2000 feet, (minimum) of 35mm film - or the equivalent - per load (P. I. requirement. This is with or without intermediate EVA).

(3) Film cassette to be sealed against evaporation of emulsion moisture in a prolonged (60 day) vacuum environment.

(4) Film cassette to be removable by an Astronaut during EVA for film retrieval at the conclusion of observation time. Also, mechanisms should be designed to permit replacement of cassette or film with a fresh load.

(5) Cassette weight, with film, to be less than 50 lbs. (Astronaut manipulation limitations)

(6) Three camera systems (Hα, U. V. and white light) need not be identical or interchangeable because different types of film may be used in each camera.

(7) Each of the three cameras is to be complete and able to operate indepently of the others. Each is to have its own shutter, exposure control, film advance, frame identification device, motors, and monitoring vidicon.

(8) All motors, relays, solenoids (if any) must operate on unregulated 24 to 28 volt D. C. power.

(9) All motors and controls will be operated remotely by the Astronaut in the LM.

(10) Frame rates variable from 1 frame per 20 seconds to 20 frames per second. Timing pulses will be generated in the LM console.

(11) When film is not being exposed (between frames), the light beam will be reflected to the faceplate of an adjacent vidicon. This can be done by placing a diagonal mirror on the outside of the shutter.

(12) The cameras will be located on a movable platform (for focus adjustment) along with the necessary beam splitters, filters, field stops, heat dumps, etc. in the ATM quadrant adjacent to the telescope.

(13) Cooling may be accomplished by extending the telescope liquid thermal control system to the camera cluster, or by direct radiation from the cluster to the 50°F wall of the ATM canister.

ATM CAMERA DESIGN CONSIDERATIONS

The following is a preliminary investigation of a camera which may be used on the solar telescope, and of the parameters affecting its design. Several conditions and limitations, including size, shape and weight are placed on the design which has resulted in specialized features unique to this application.

The approach has been to select the simplest system which could accomplish the mission and maintain a high degree of reliability inasmuch as the cameras will have to perform intermittently for an extended period of time in a space environment.

The three cameras will be operated independently in either single frame or cine mode which dictates a variable pulse type. Each camera will be synchronized to a separated shutter assembly and operated from the console within the spacecraft. However, the Astronaut will be required to make at least one EVA, to remove the film cassettes for return to earth. The filters and shutter assemblies will be permanently mounted on the base. The shutter itself will be a variable opening type which will allow control of exposure time.

The white light, ultra violet, and hydrogen alpha cameras are assumed to be alike for the purposes of internal mechanism design with exception of the filters and shutters. The cassette configuration may be such as to allow the reels to be placed side by side i.e., with a line from center to center perpendicular to the input light beam, or a line from center to center parallel to the input light for space conservation.

Areas of future effort will include:

(1) Further study and optimization of a film transport system.

(2) Structural design of the cassette.

(3) Latching and interfacing with the telescope.

(4) Material selection.

(5) Thermal analysis i.e., a study of the cassette heating and cooling requirements including insulatory and surface treatment requirements.

(6) A further study of motors, solenoids, clutches, and brakes which may be used in the system.

(7) A weight analysis.

DESIGN OBJECTIVES

Several factors are considered in this preliminary design. These include size of cassette, power requirements, and heat dissipation requirements. In each analysis, ballpark numbers were found for a particular configuration which do not necessarily represent the optimum or final configuration.

One particular aspect of investigation was to compare the feasibilities of two systems, i.e. a camera using 1000 feet of 70mm film with reversible feed direction and a camera using 2000 feet of 35mm film with single feed direction. The choice of either system affects the design of the upstream parts of the camera. As an example, using a bi-directional 70mm film camera necessitates a complex reversing mechanism in addition to an extra mirror which must be automatically controlled to shift the image to the other half of the film when film reverses direction. On the other hand, using a single feed direction 35mm film camera eliminates the need for a r ersing mechanism and re-imaging mirror, but the film transport and reel drive power requirements and the consequential heat dissipation problems are greater in addition to the considerably larger space required for the film cassettes on the camera platform. This latter is an important consideration because of the small packaging space available in the ATM canister. An effort has been made to reduce the number of moving parts such as gears, linkages, motors, bearings, and sprockets to conserve space and weight. Many standard cameras incorporate complex claw pull down mechanisms which necessitate a large number of moving parts. There are, however, other types of pull down mechanisms which operate on a different principle and require fewer moving parts. This is the type considered here.

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7. "Viewgraphs and Descriptions of Photoheliograph Study for the Apollo Telescope Mount," JPL Work Unit 390-40101-2-3230, NASA Presentation 15 November 1967.

8. "Motion Picture Camera Design and Selection," Journal of the SMPTE, Vol. 73, January 1964.

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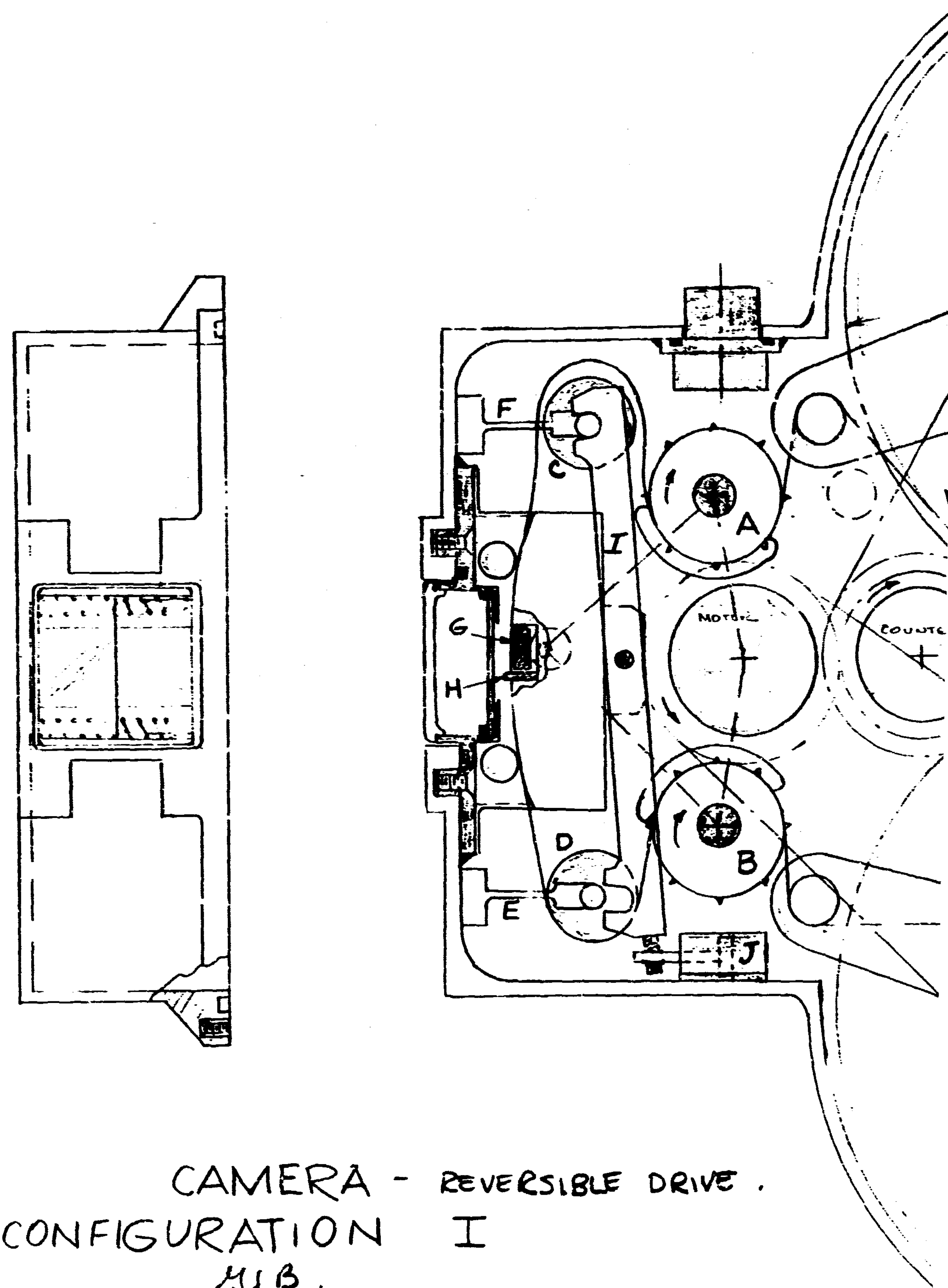
APPENDIX A

EXPLANATION OF CAMERA MECHANISM

The film is held during exposure by small rollers against a slightly curved shoe in which there is a fixed register pin (H). Sprocket (A) and (B) continuously pay out and take up film, and as sprocket (B) takes up, cantilever spring (E) moves up thus storing spring energy and putting tension in film between (D) and pin (H). Shoe (G) is pushed outwardly by a cam (gang geared to both drive sprockets) until film disengages pin (H). The stored spring energy is at this time released causing sprocket (D) to snap down until film is stopped by sprocket (C), thus placing a new frame into position ready for exposure. If camera is in cine mode, the process recycles.

The film can be exposed on its other half at the end of the reel by re-focusing the image on the other half and reversing the drive direction. This is easily accomplished by activating an actuator (J) which causes the lever (I) to engage spring (E) and disengage spring (F). The drive motor direction and the brake-clutch action of the reels are reversed, thus the take up reel becomes the feed reel and vice-versa.

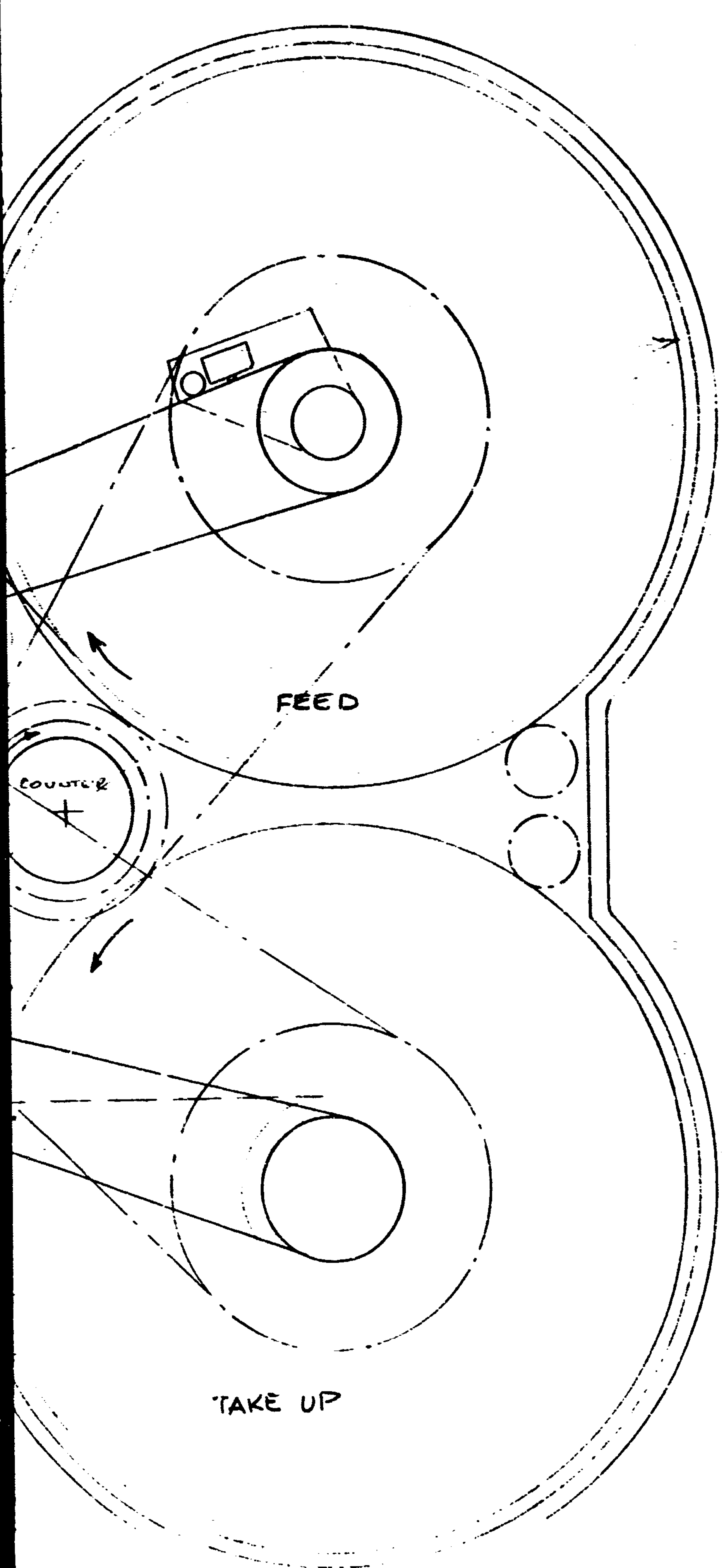
Strain relief arms are provided to limit the force on the film to a designated maximum. Limit switches are also provided to clutch and brake automatically.



CAMERA - REVERSIBLE DRIVE.
CONFIGURATION I

MJB.

FOLDOUT FRAME 1



FOLDOUT FRAME 2

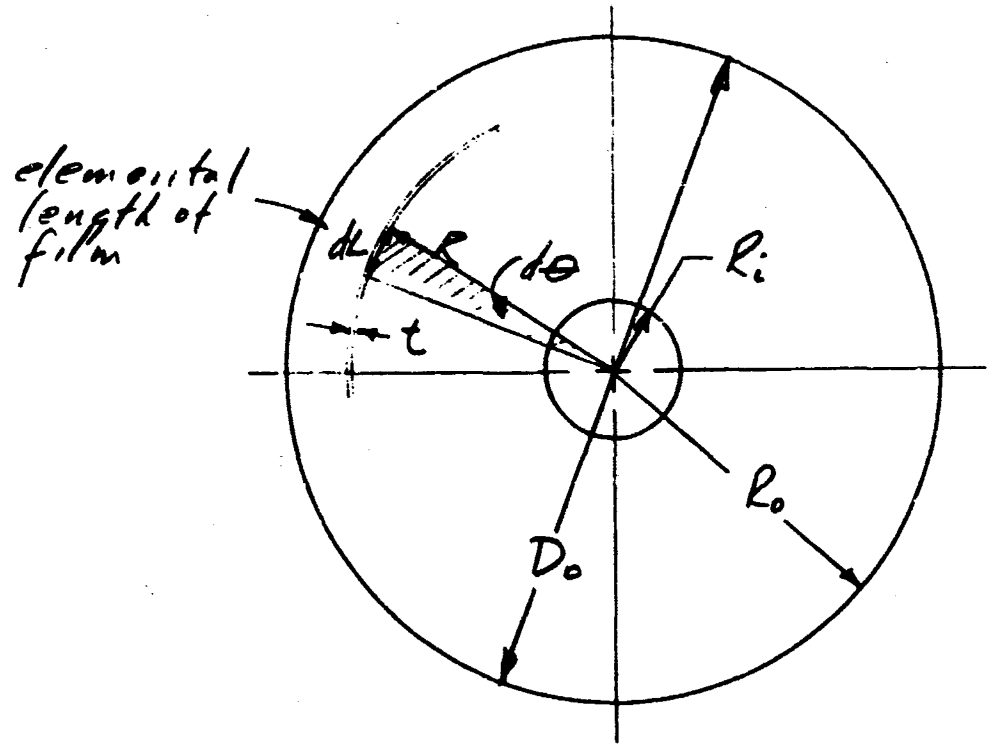
8 C - 10025004

 8

APPENDIX B

ANALYSIS OF MECHANISM

I. Determination of Outside Radius on Reel



$$L = R\theta \qquad dL = R\,d\theta$$

$$R = R_i + \frac{\theta}{2\pi} t$$

$$L_{TOTAL} = \int_0^{\theta_T} R\,d\theta = \int_0^{\theta_T} \left(R_i + \frac{\theta}{2\pi} t\right) d\theta$$

$$= R_i \theta_T + \frac{t}{4\pi} \theta_T^2$$

$$\theta_T^2 + \left(\frac{R_i 4\pi}{t}\right)\theta_T - \left(\frac{L 4\pi}{t}\right) = 0$$

$$\theta_T = \frac{-\left(\frac{R_i 4\pi}{t}\right) \pm \sqrt{\left(\frac{R_i 4\pi}{t}\right)^2 + 4\left(\frac{L 4\pi}{t}\right)}}{2}$$

$$R_o = R_i + \frac{\theta_T}{2\pi} t \quad , \quad D_o = 2R_o$$

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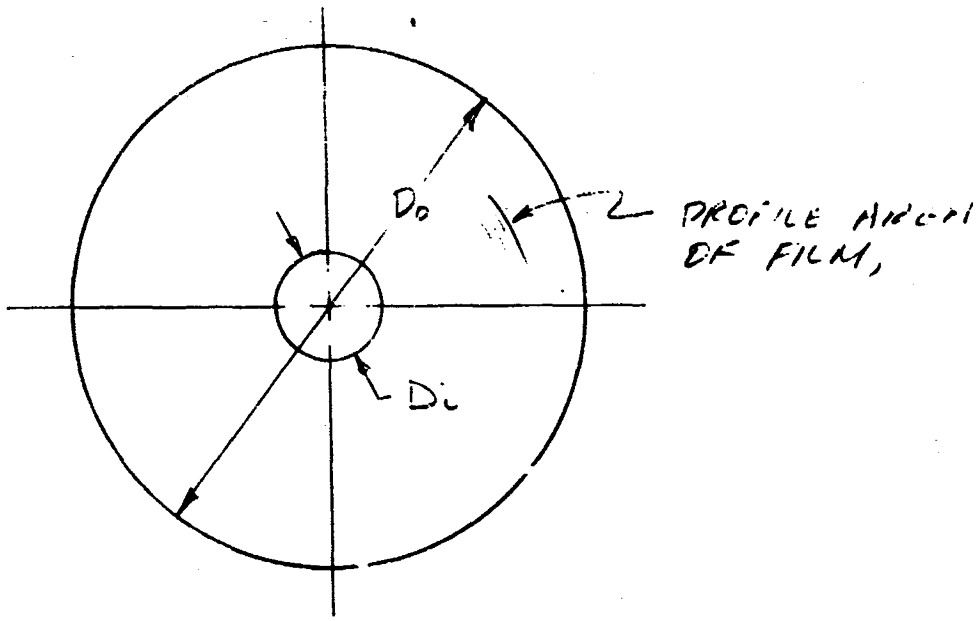
ALTERNATE FORMULATION



length of film = L
thickness of film = t

Profile Area of straight length = Lt

Profile Area of Spool = $\frac{\pi}{4}(D_o^2 - D_i^2)$

$$Lt = \frac{\pi}{4}(D_o^2 - D_i^2)$$

D_i = 2 in

Stock thickness of film : 2.5, 4.0, 5.2 mils

70 mm film · 2000 ft REQ. (35mm);

DOUBLE SIDED FILM, 1000 ft EACH SIDE.

REEL SHALL THEREFORE HAVE 1000 ft CAPACITY AND BE REVERSIBLE TO EXPOSE BOTH SIDES

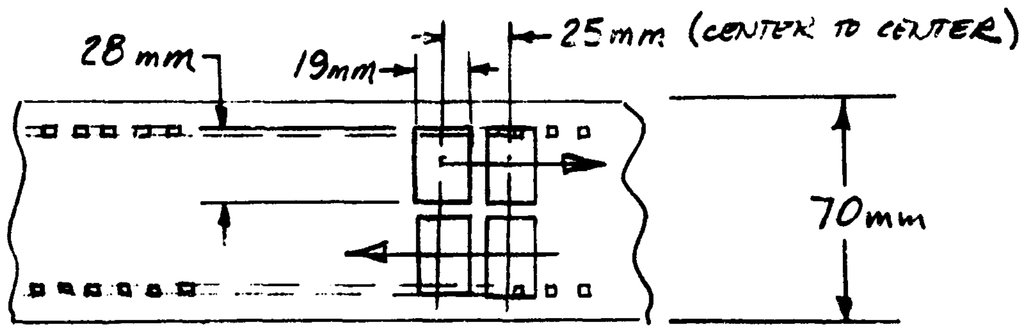
Area of film per foot = .228 ft² LENGTH = 1000'

t mils	w/ft	Wt (1000')	Do	$J(\frac{1}{2} m R_o^2)$
2.5	.00525	5.25 lb	6.5 in	.072 lb sec² in
4.0	.00775	7.75	8.1	.165
5.2	.0089	8.90	9.15	.240

TABLE SHOWING WEIGHT, DIA., AND J FOR VARIOUS FILM THICKNESSES

DENSITY OF FILM, (TYPICAL VALUES)

THICKNESS	DENSITY
2.5 MILS	.022-.023 lb/ft²
4.0	.034
5.2	.039



35 mm film, 2000 ft REQ

SINGLE SIDED FILM; THEREFORE, REEL SHALL HAVE 2000 ft CAPACITY

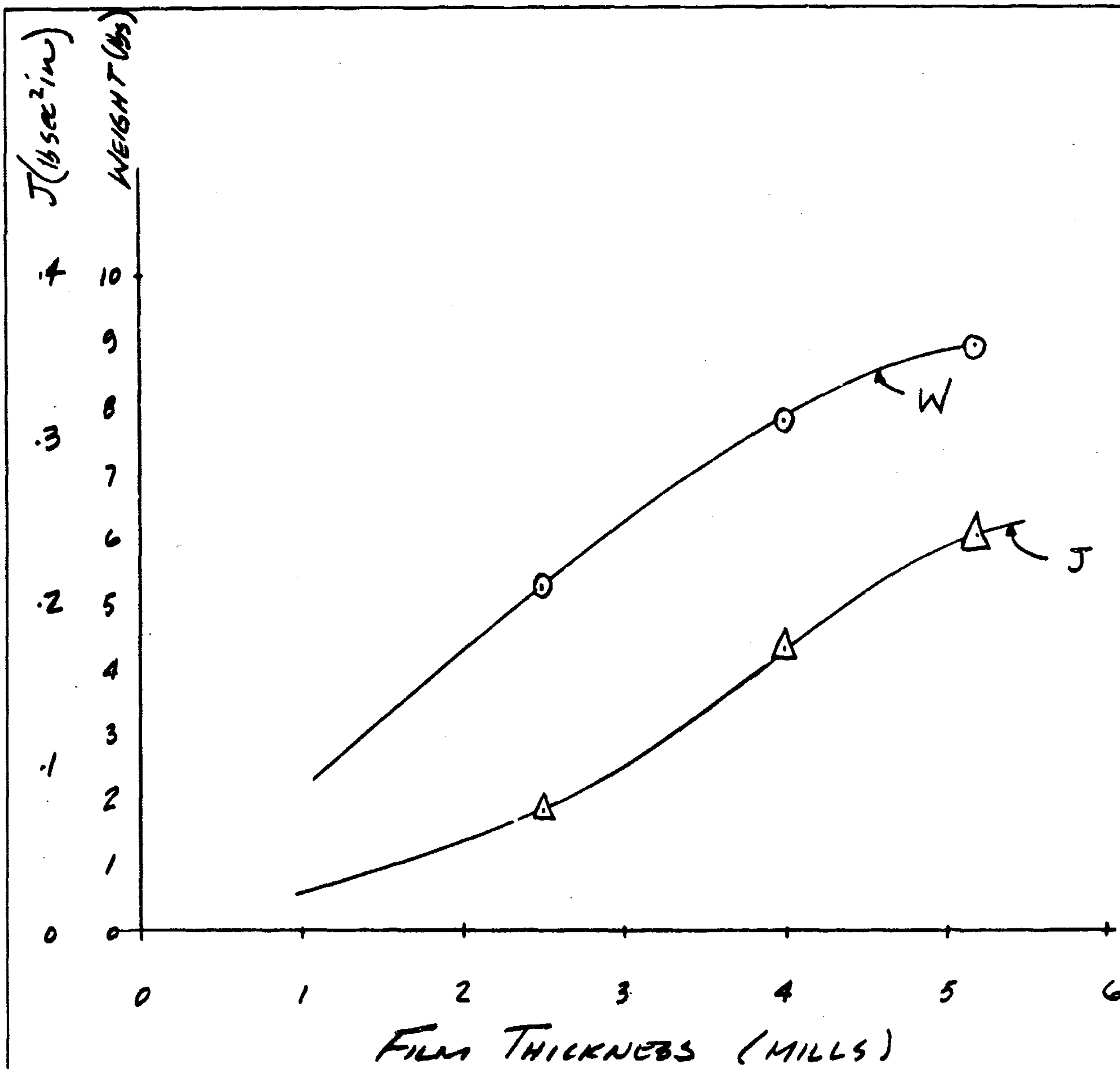
Area of film per foot = .114 ft^2 LENGTH = 2000 ft

t mils	wt/ft	Wt (2000')	Do	J (1/2 m R_o^2)
2.5	.00263	5.25 lb	8.75	.130 lb sec² in
4.0	.00387	7.75	11.20	.373
5.2	.00443	8.90	12.80	.473

TABLE SHOWING WEIGHT, DIA., AND J FOR VARIOUS FILM THICKNESSES

DENSITY OF FILM, (TYPICAL VALUES)

THICKNESS OF FILM	DENSITY
2.5 MILS	.022 - .023 lb/ft²
4.0	.034
5.2	.039

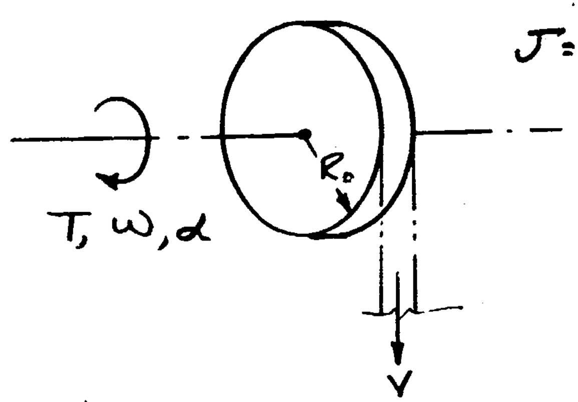


WEIGHT AND MOMENT OF INERTIA OF FILM BASED ON 70 mm × 1000 ft., VARIATION OF DENSITY INCLUDED. WEIGHT AND MOMENT OF INERTIA OF METAL REEL NEGLECTED.

II

Power required to bring a full film reel up to speed.

Assuming that the diameter of the REEL does not change appreciably initially,



Power = $T\omega$

Torque required To bring spool up to speed $\cong J\alpha$

Power = $(J\alpha)\omega$

Power Ratio P. R. $= \dfrac{(J\alpha)\omega \big]_{70\text{ mm }(1000')}}{(J\alpha)\omega \big]_{35\text{ mm }(2000')}}$

$= \dfrac{\frac{1}{2} m (R_0)^2_{70}}{\frac{1}{2} m (R_0)^2_{35}}$, since masses are equal

& $(R_0)_{70} \approx 1.4 (R_0)_{35}$

$\therefore$ P.R. $= \dfrac{R_0^2}{(1.4 R_0)^2} = \dfrac{1}{2}$

THUS IT CAN BE SEEN THAT THERE IS A DISTINCT ADVANTAGE, FROM A POWER STANDPOINT, IN USING A 70 mm - 1000 ft REEL AS COMPARED TO A 35 mm - 2000 ft REEL. THIS DOES NOT NECESSARILY RULE OUT THE USE OF THE 35 mm REEL, BUT IN A SYSTEM WHERE POWER IS AT A PREMIUM, TWICE THE POWER MUST BE CONSIDERED A HEAVY WEIGHING FACTOR.

A LIST OF ADVANTAGES AND DISADVANTAGES OF USING EITHER SYSTEM IS SHOWN TO INDICATE OTHER WEIGHING FACTORS WHICH SHOULD BE CONSIDERED IN FUTURE EVALUATIONS.

Advantages of using 35mm - 2000ft REEL (unidirectional)

1. The primary advantage is that only one direction of film feed is required. i.e., film will not be required to feed in reverse direction, thereby eliminating complex reversing mechanism.

Disadvantages (relative to 70mm - 1000 ft)

1. Approximately 40% greater diameter spool required, therefore 40% larger cassett required in area where space is a premium.
2. Approximately twice the power required to bring spool up to speed.
3. Approximately 50% greater size of motors, brakes, and clutches required to operate this size spool.
4. Cassett size and weight greater by 40%, therefore 40% greater storage space required.

Advantages of using 70 mm - 1000 ft REEL
(Bi directional)

1. The disadvantages of the 35 mm - 2000' REEL become the Advantages of the 70 mm - 1000' REEL
i.e.,
40% smaller diameter Reel
50% less power required to accelerate Reel
50% Smaller motors, clutches, and brakes to operate this size Reel.
cassett size and weight 40% less.
40% less storage area required.

Disadvantages

1. The primary disadvantage is that film feed direction must be reversed at end of reel to take pictures on other half of film thus necessitating complex reversing mechanisms.

IV.

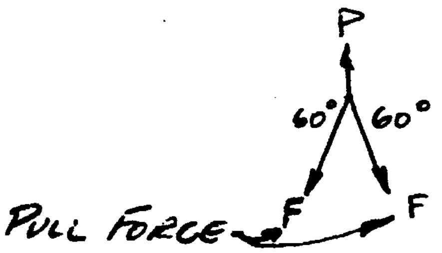
DETERMINATION OF FORCE ON FILM AND TIME FOR REEL TO COME UP TO SPEED.

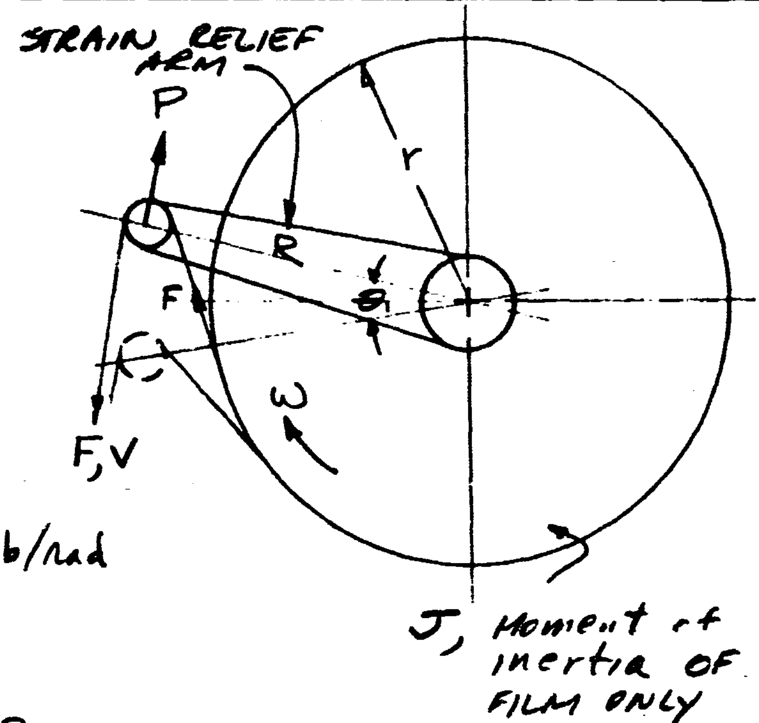
A STRAIN RELIEF ARM IS INCORPORATED TO LIMIT THE AMOUNT OF FORCE ON THE FILM i.e., A HELICAL SPRING IN THE ARM GRADUALLY TRANSFERS THE RETARDING FORCE OF THE INERTIA OF THE REEL ONTO THE FILM. THIS REDUCES THE SUDDEN FORCE (JERK) APPLIED TO THE FILM AND BRINGS THE REEL UP TO SPEED. SINCE ONLY BALLPARK NUMBERS ARE NEEDED AT THIS POINT, AN APPROXIMATE ANALYSIS FOLLOWS.

IT IS ASSUMED THAT :

1. THE REEL IS FULL AND THEREFORE THE RADIUS $\underline{r}$, THE MASS $\underline{m}$, AND THE MOMENT OF INERTIA $\underline{J}$ ARE AT MAX. CONDITIONS AND DO NOT CHANGE.
2. THE PULL FORCE $\underline{F}$ DUE TO THE PULL ANGLE REMAINS CONSTANT.

FIND ω vs t





$$2F \sin 60^\circ = P$$

$$F \quad .58P$$

$$P = K\,\theta_1 \qquad K = \text{lb/rad}$$

$$\therefore\ F = .58K\,\theta_1$$

$$\theta_1 = \left(1 - \frac{r\omega}{V}\right)\theta_{max}$$

$$F \times r = J\frac{d\omega}{dt}$$ Torque Req. to accelerate Reel

$$.58K\theta_m r\left(1 - \frac{r\omega}{V}\right) = J\frac{d\omega}{dt}$$

$$a = .58Kr\theta_m$$

$$b = \frac{r}{V}$$

then

$$\int dt = \int \frac{J\,d\omega}{a(1-b\omega)}$$

$$t = -\frac{J}{ba}\ln(1-b\omega) + C$$

i.e., $t=0,\ \omega=0 \quad \therefore C=0$

$$\omega = \frac{1}{b}\left(1 - e^{-\frac{ba}{J}t}\right)$$ Angular Speed vs time

$$F = \frac{J}{r}\frac{d\omega}{dt} = \frac{J}{r}\frac{k}{k}\frac{a}{J} e^{-\frac{ba}{J}t} = \frac{a}{r} e^{-ba/J\, t}$$

$$F_{max} = \frac{a}{r} = \frac{.58 K r \theta_m}{r} = \underline{\underline{.58 K\theta_m}} \quad @ \; t = 0$$

F_{max} = Maximum Force on film

$$\theta_1 = \left[1 - \left(\frac{r}{V}\cdot\frac{1}{b}\right)\left(1 - e^{-ba/J\, t}\right)\right]\theta_m$$

θ_1 max @ $t=0$ = θ_m

$$\theta_1 = \theta_m e^{-ba/J\, t}$$

THE REEL WILL COME UP TO 63% OF ω_{max} AT <u>ONE</u> TIME CONSTANT WHERE THE TIME CONSTANT IS GIVEN BY,

$$T_c = \frac{J}{ab} = \frac{J\,V}{.58\, K r^2 \theta_m} \cong \frac{m\, V}{2\, F_m}$$

NOTE V = FILM SPEED $\cong$ 10 in/sec

FOR 70 mm FILM,

t (thickness of film) = 5.2 MILS

r (RADIUS OF Reel) = 4.55 in

J (MOMENT OF INERTIA) = .240 lb sec² in

SINCE SPACE IS LIMITED, θ_m SHOULD BE RESTRICTED TO $\theta = \frac{X}{R} = \frac{1.0}{6} = .166$ rad. (9.5°)

THE MAXIMUM FORCE ON THE FILM SHOULD NOT EXCEED 16 oz (1 lb).

$$\therefore K = \frac{F_m}{0.58\,\theta_m} = \frac{1 \text{ lb.}}{0.58\ (.166)\text{ rad.}} \cong 10 \text{ lb/rad.}$$

THE RESULTING TIME CONSTANT IS,

$$T_c = \frac{(.240)\ 10}{0.58\,(10)\,(4.55)^2\,(.166)} = .120 \text{ sec}$$

UNITS $\frac{\text{lb sec}^2 \text{ in. in}}{\frac{\text{lb}}{\text{rad}}\ \text{in}^2\ \text{sec}}$ rad $\rightarrow$ sec

ω WILL BE APPROX 96% OF ω_{max} IN APPROX $4T_c$ OR .480 sec.

SOME TIME CONSTANTS FOR OTHER FILM THICKNESSES ALL OTHER FACTOR BEING EQUAL.

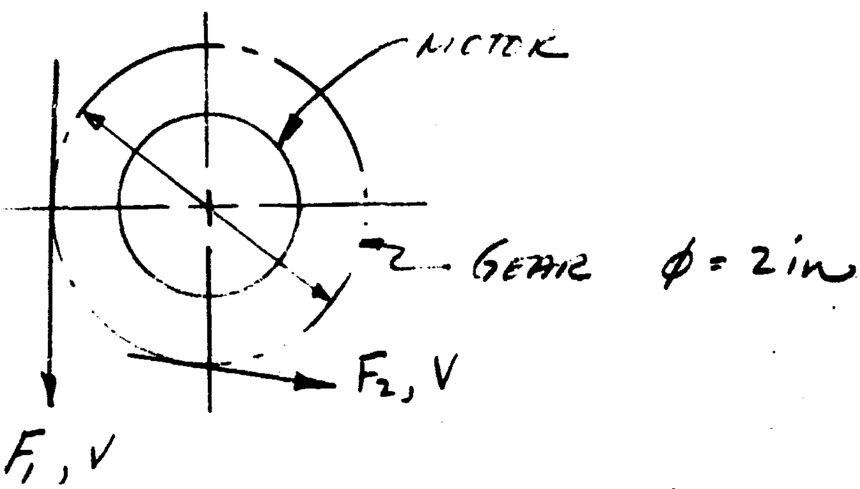
FILM THICKNESS	T_c
4.0 MILS	.100 SEC
3.5	.092
3.0	.081
2.2	.029

V. POWER REQUIREMENT FOR MOTOR

F_1 (FILM FORCE)
F_2 (DRAG)

$F = F_1 + F_2$

$F_1 = 1\ lb$
$F_2 = 1\ lb$
(ESTIMATED)



$V = \frac{10}{12}\ ft/sec.$

$$\text{HORSE POWER}\Big]_{REQ.} = \frac{FV}{550} = (2)\frac{10}{12}\cdot\frac{1}{550} = .003\ HP$$

$$= 2.2\ watts.$$

$$\text{TORQUE}\Big]_{REQ.} \approx R \times F = 1\ in \cdot 2\ lb = 2\ in\,lb$$

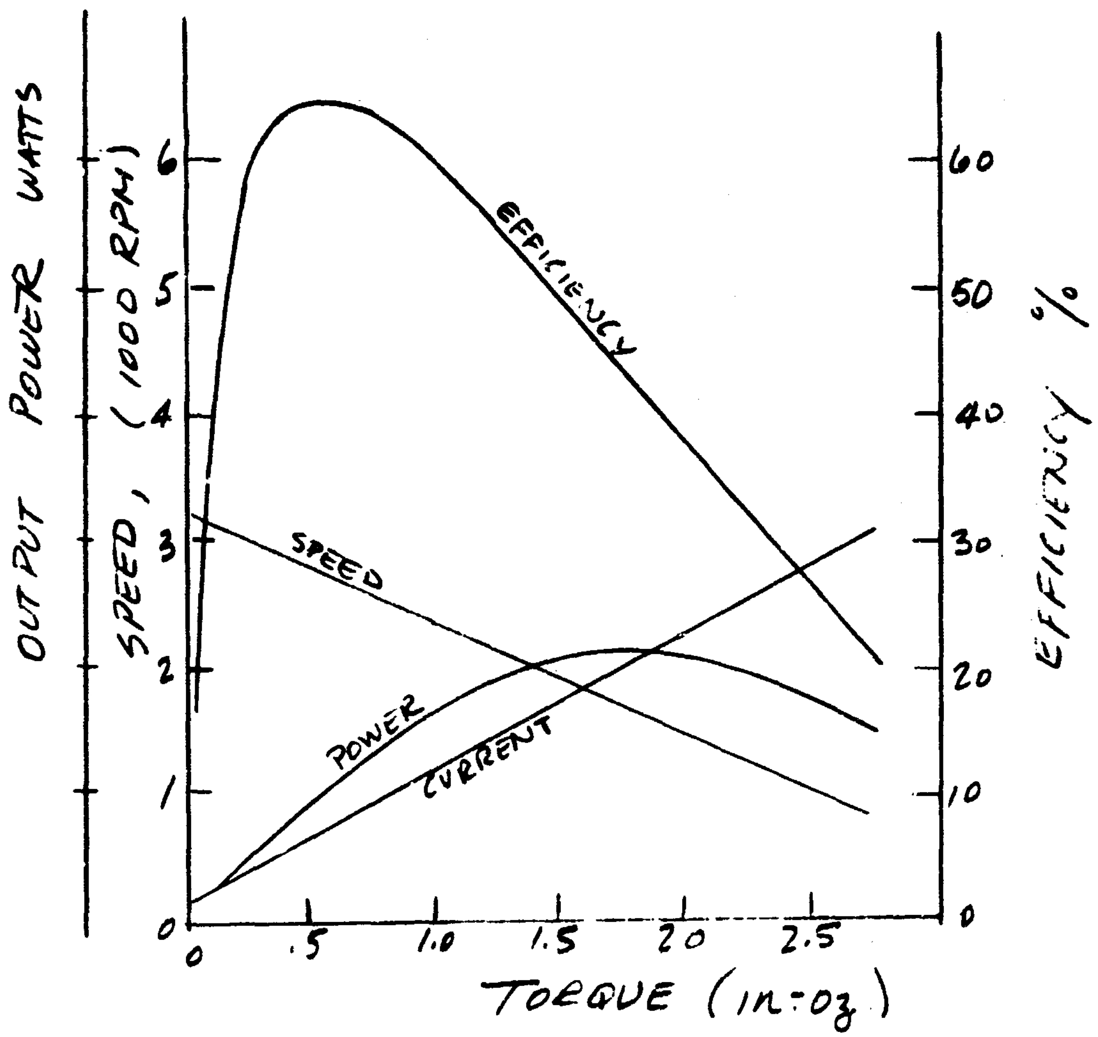
TYPICAL D.C. TORQUE MOTOR CURVES INDICATE THAT EFFICIENCY VARIES FROM 20% TO 50% FOR MAX POWER.

$$\text{MOTOR OUTPUT SPEED} = \frac{10\ in}{sec} \times \frac{1}{1\ in} \times \frac{REV}{2\pi\ rad} \times \frac{60\ sec}{MIN}$$

$$= 96\ RPM$$

OPERATING AT $T_m = 1.5\ in\text{-}oz$ $S = 2000\ RPM$.

GEAR DOWN RATIO $= 21$ $T_{OUT} = 2\ in\ lb$ OK



TYPICAL D.C. TORQUE MOTOR CURVES

POWER INPUT REQUIRED FOR MOTOR IS THEREFORE,

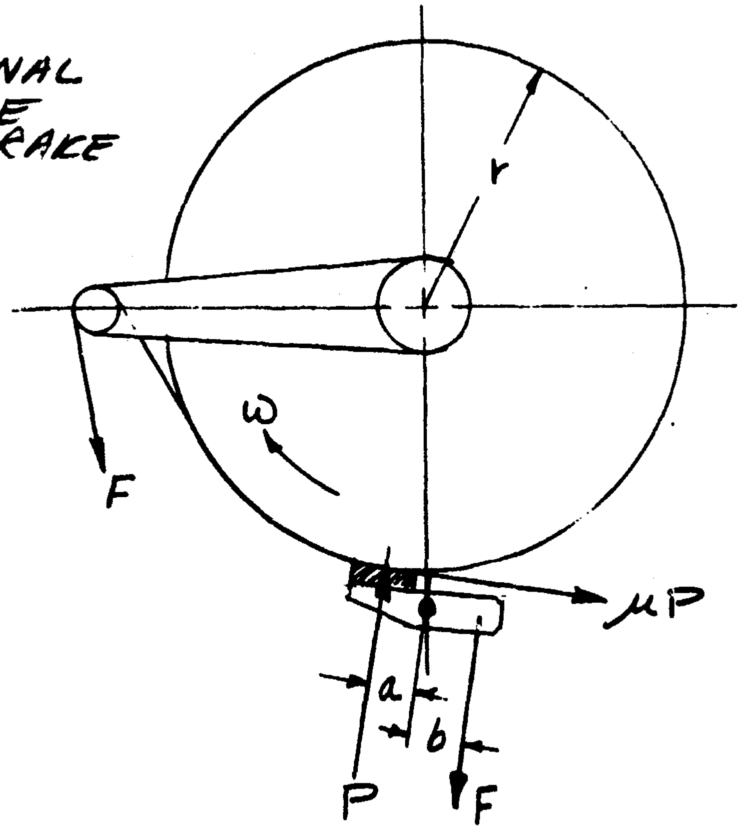
$$P_{in} = \frac{2.2 \text{ watts}}{Eff._{NOM}} = \frac{2.2}{.40} = 5.5 \text{ watts}$$

SURGE POWER $\cong$ 0.4 AMPS × 27 VOLTS $\cong$ 11 WATTS

VI.

BRAKE DESIGN OF REEL

1. EXTERNAL SHOE BRAKE



IMPULSE MOMENTUM EQUATION

$$\int M\,dt = J\omega$$

ENERGY EQUATION

$$T = \int M\,d\theta = \int J\ddot{\theta}\frac{d\theta}{dt}\,dt = \tfrac{1}{2}J\omega^2$$

IT IS ASSUMED THAT;

1. REEL IS FULL i.e., r, J, AND MASS ARE MAXIMUM AND CONSTANT.

FROM IMPULSE EQN.

$$r \mu P t = J(\omega_1 - \omega_2)$$

$$t_s = \frac{J(\omega_1 - \omega_2)}{r \mu P} \text{, STOP TIME}$$

THE ANGLE θ THROUGH WHICH THE REEL ROTATES IN COMING TO A STOP CAN BE FOUND FROM THE ENERGY EQN.,

$$\theta_s = \tfrac{1}{2} \frac{J(\omega_1^2 - \omega_2^2)}{r \mu P} \text{, COASTING ANGLE}$$

APPOX. μ FOR BRAKE SHOE MATERIAL ; $\mu = .45$

STOP TIME, BASED ON 70mm - 1000 ft REEL

FILM THICKNESS = 5.2 MILS

$J = .240$ lb sec^2 in

$r = 4.55$ in

$$t_s = \frac{.240(2 - 0)}{4.55(.45)P} = \frac{0.23}{P}$$

COASTING ANGLE,

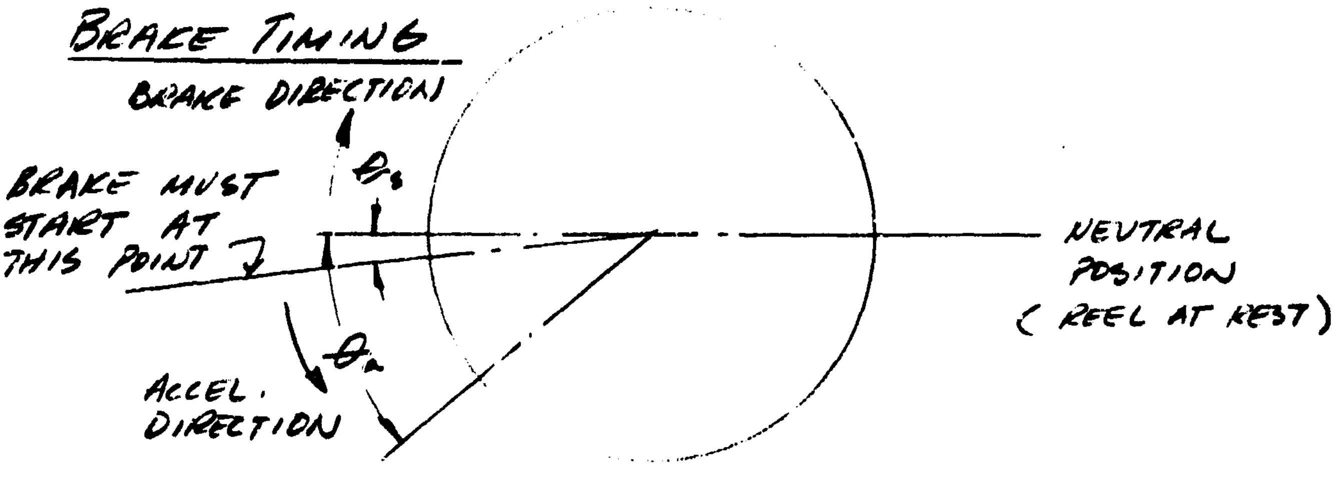
$$\theta_s = \frac{.240(2^2 - 0)}{2(4.55)(.45)P} = \frac{.23}{P}$$

ASSUME BRAKE FORCE $\underline{P}$ IS IN THE ORDER OF 10 lb i.e., P = 10 lb

$$t_s = \frac{0.23}{P} = .023 \text{ sec} \quad (23 \text{ ms})$$

$$\theta_s = \frac{0.23}{P} = .023 \text{ rad} \quad (1.3^\circ)$$

BRAKE TIMING



θ_a = ACCELERATION TIME = 9.5°

θ_s = STOP TIME = 1.3°

$$\frac{\theta_s}{\theta_a} = \frac{1.3^\circ}{9.5^\circ} = .137$$

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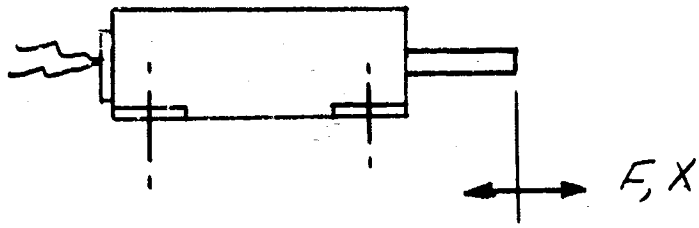
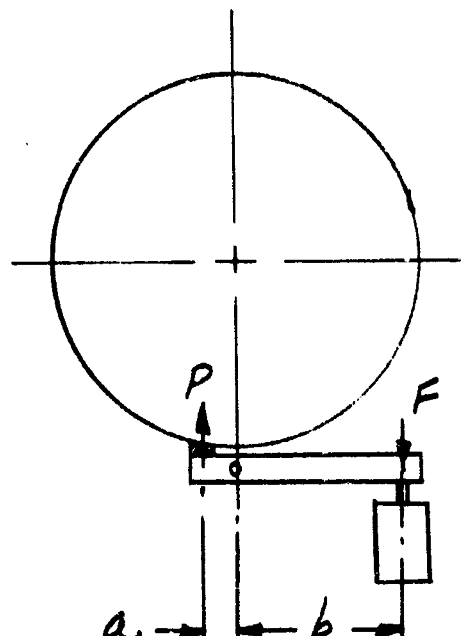
SOLENOID BRAKING POWER LOAD

VOLTAGE INPUT = 27 VDC





LET:

$P = 10$ lb

$b = 6$ in

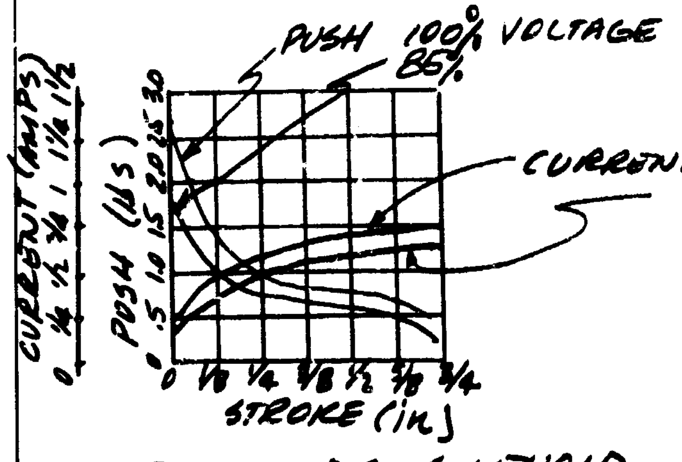
$a = 0.5$ in

$$F \times b = P \times a$$

$$F = \frac{P\,a}{b} = \frac{10(.5)}{6} = 0.83 \text{ lb}$$

ASSUME 85% VOLTAGE

i.e., V = 23 VOLTS



TYPICAL D.C. SOLENOID

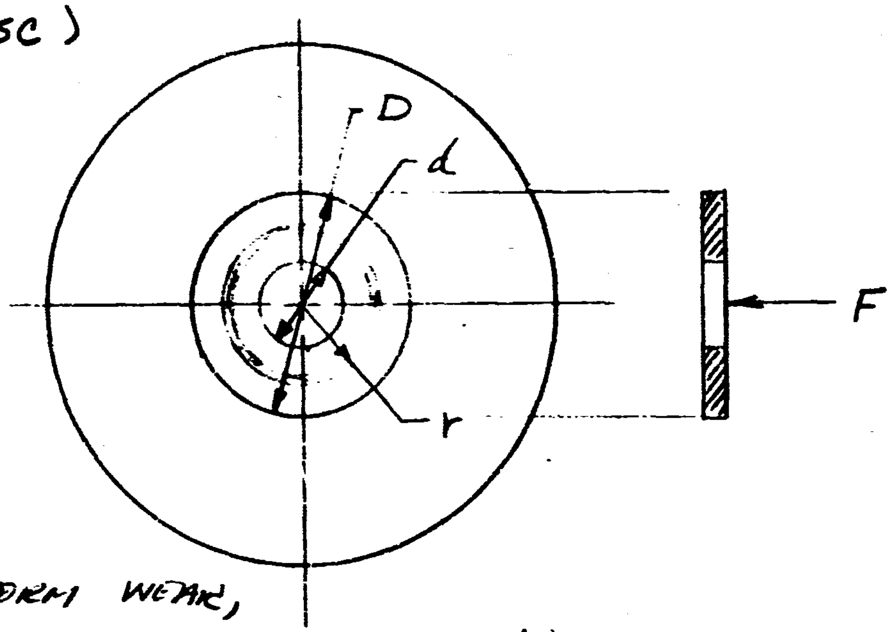
CURRENT LOAD = .37 AMPS

AVAILABLE STROKE = 1/8 in

POWER LOAD = 8.5 WATTS

JPL 0999-1-8 MAR 63

7. DISK BRAKE
(FOR ONE DISC)



BASED ON UNIFORM WEAR,

GREATEST PRESS. AT $r = d/2$ FOR UNIFORM WEAR, P_a = MAX. PRESSURE

$$p r = p_a \frac{d}{2} \quad \text{or} \quad p = p_a \frac{d}{2r}$$

$$F = \int_{d/2}^{D/2} 2\pi p r\,dr = \pi p_a d \int_{d/2}^{D/2} dr = \frac{\pi p_a d}{2}(D-d)$$

$$T = \int_{d/2}^{D/2} 2\pi \mu p r^2\,dr = \frac{\pi \mu p_a d}{8}(D^2-d^2)$$

OR $T = \frac{\mu F}{4}(D+d)$ / DISC

FROM IMPULSE EQN.,

$$t_s = \frac{4J(\omega_1 - \omega_2)}{\mu F(D+d)}, \quad \text{STOP TIME}$$

$$\theta_s = \frac{2J(\omega_1^2 - \omega_2^2)}{\mu F(D+d)}, \quad \text{COASTING TIME}$$

ASSUME,

1. $D = 4$ in, $d = 2$ in
2. $\mu = .45$
3. $J = .240$
4. $\omega_1 = 2$ rad/sec

$$t_s = \frac{4(.240)(2-0)}{(.45)(4+2)F} = \frac{.71}{F}\left(\frac{1}{N}\right)$$

$$\theta_s = \frac{2(.240)(2^2-0)}{(.45)(4+2)} = \frac{.71}{F}\left(\frac{1}{N}\right)$$

WHERE N = NO. OF DISCS

THUS 3 DISCS ARE REQUIRED FOR EFFECT COMPARABLE TO EXTERNAL SHOE BRAKE.

VII DETERMINATION OF HEAT GENERATION OF BRAKE.

IN BOTH CASES OF BRAKING

$J = .240 \text{ lb sec}^2 \text{ in}$

$= .02 \text{ slug - ft}^2$

$T = J\alpha$

$$T = \frac{12 J \, 2\pi n}{60 \, t}$$

n = RPM

t = BRAKE TIME (SEC)

BRAKE ENERGY E_K,

$$E_K = \left(\frac{2\pi T}{12}\right)\left(\frac{1}{2}\frac{n}{60}t\right) = \frac{2\pi T n t}{1440} = \frac{\pi^2 n^2 J}{1800}$$

$$n = 2 \frac{\text{rad}}{\text{sec}} \times \frac{\text{Rev}}{2\pi \text{ rad}} \times 60 \frac{\text{sec}}{\text{MIN}} = 120 \text{ RPM}$$

$$E_K = \frac{\pi^2 (120)^2 (.02)}{1800} = 1.53 \text{ ft} \cdot \text{lb}$$

$$\text{POWER} = \frac{1.53}{.02} \frac{\text{ft - lb}}{\text{sec}} \cdot \frac{1}{550} = .14 \text{ HP}$$

$.14 \text{ HP} = 102 \text{ WATTS}$

HEAT GENERATED IN FRICTION PER CYCLE (H),

$H = .102 \text{ KW} \times 56.9 = 5.69 \text{ BTU/MIN}$