FILM TRANSPORT AND LIQUID GATE FOR AN OPTICAL DATA PROCESSING SYSTEM

A Thesis

Presented to

the Faculty of the Department of Electrical Engineering

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Electrical Engineering

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by

Linda Margaret Poole

May, 1974

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ABSTRACT

A film transport has been designed with the capability of positioning a specific five-inch segment of a 200 foot roll of 35 mm film in the input window of a coherent optical data processing system. The output of this system is the power spectrum of one of up to twenty channels of analog data pre-recorded on the film in the form of optical density variations. The optical window built into the transport is a liquid gate which functions to eliminate inherent system nonlinearities caused by irregularities in the film microstructure. Polyethylene glycol was the liquid selected for use in the liquid gate.

The desired segment of film is identified by a pre-recorded six-digit code. A fiber optic read head located to the edge of the window senses this code and transforms it into signals compatible with standard TTL integrated circuitry, which can be used for automatic microcomputer control of the system.

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I. Introduction

A system in which up to twenty possible channels of analog data are simultaneously recorded and their power spectra analyzed is currently under development for use in the processing of biomedical data.[1] In the recording system[2], each of the electrical signals to be recorded is transformed into light-intensity varying signals in a linear array of light emitting diodes (LEDs). This diode array is focused onto 35mm. film driven at a constant velocity by a camera mechanism.

After development of the film, the original temporally-varying signal appears in the form of one-dimensional tracks (one per diode) which vary spatially in density along the length of the film. The amplitude transmittance of the film at each point on the track is proportional to the amplitude of the original signal at a corresponding point in time. In the recording system, in addition to the potential twenty channels of analog data, there are up to six tracks reserved for the simultaneous recording of digital data. In this case, the LEDs are either off (Logical 0) or at maximum brilliance (Logical 1). Samples of these records are shown in Figure 1.

To optically obtain the spectra of the signals, the developed film is situated in front of a Fourier Transform lens and illuminated by a collimated laser beam. On the focal plane of this lens appears the power spectrum of the film transmittance in the form of a two-dimensional light pattern which is received by any intensity detector such as a

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1. Everett, R.L., and Anderson, W.L., "Automated Optical Data Reduction of Electroencephalographic Signals", 26th ACEMB Conf. Proc., Sept. 30-Oct. 4, 1973, Minneapolis, Minn. p400.
2. Forster, L., Everett, R.L., and Anderson, W.L., "A Photo-Optical System for recording Biomedical Signals", 25th Ann. Southwest IEEE Conf. Record 1973, p 112.

photocell or the eye. The spectrum of each track which is isolated from the others by an aperture is linearly scaled in frequency, zero frequency being centered on the optical axis. A schematic of the entire system is presented in Figure 2.

For an optimal high-fidelity system, it is essential that the film transmittance be directly proportional to the original signals. Two of the major sources of distortion are the limiting frequency response of the recording system and the nonlinear characteristics of photographic film. On recording, the system cut-off frequency is proportional to the camera speed, inversely proportional to the finite size of the LED or camera slit image projected on the film, and further modified by the modulation transfer function (MTF) of the film. Because of these effects, the system will yield an undistorted spectrum only for frequencies less than some maximum value.

Another source of nonlinearity arises from irregularities in the film structure which create optical path variations as a function of position on the film. The net result is the introduction of a phase-shifting function which is manifested in the Fourier plane. The details of this problem, which was a major design consideration in this project, are discussed in chapter II.

The primary purpose of this research was to design and construct a major component of this data processing system; the device for driving and centering the desired portion of the film in the path of the laser beam. The objectives and requirements of the film transport were:

1. to handle up to 200 ft. rolls of film
2. to read the digital information from the film and enable this to be used in a programmable controller with TTL compatible inputs
3. to be mounted and operated on a standard optical bench.

A description of the film transport and its operation is given in Chapter III.

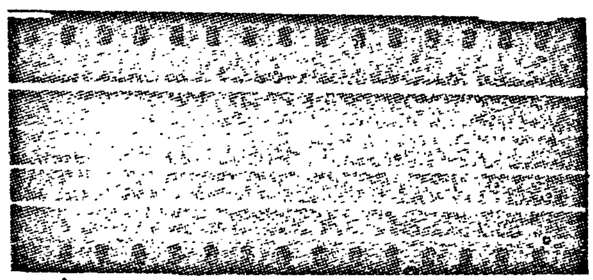

Figure 1. Sample of Recording: Two Digital Channels; Four Analog Channels with Sin Wave Recording.

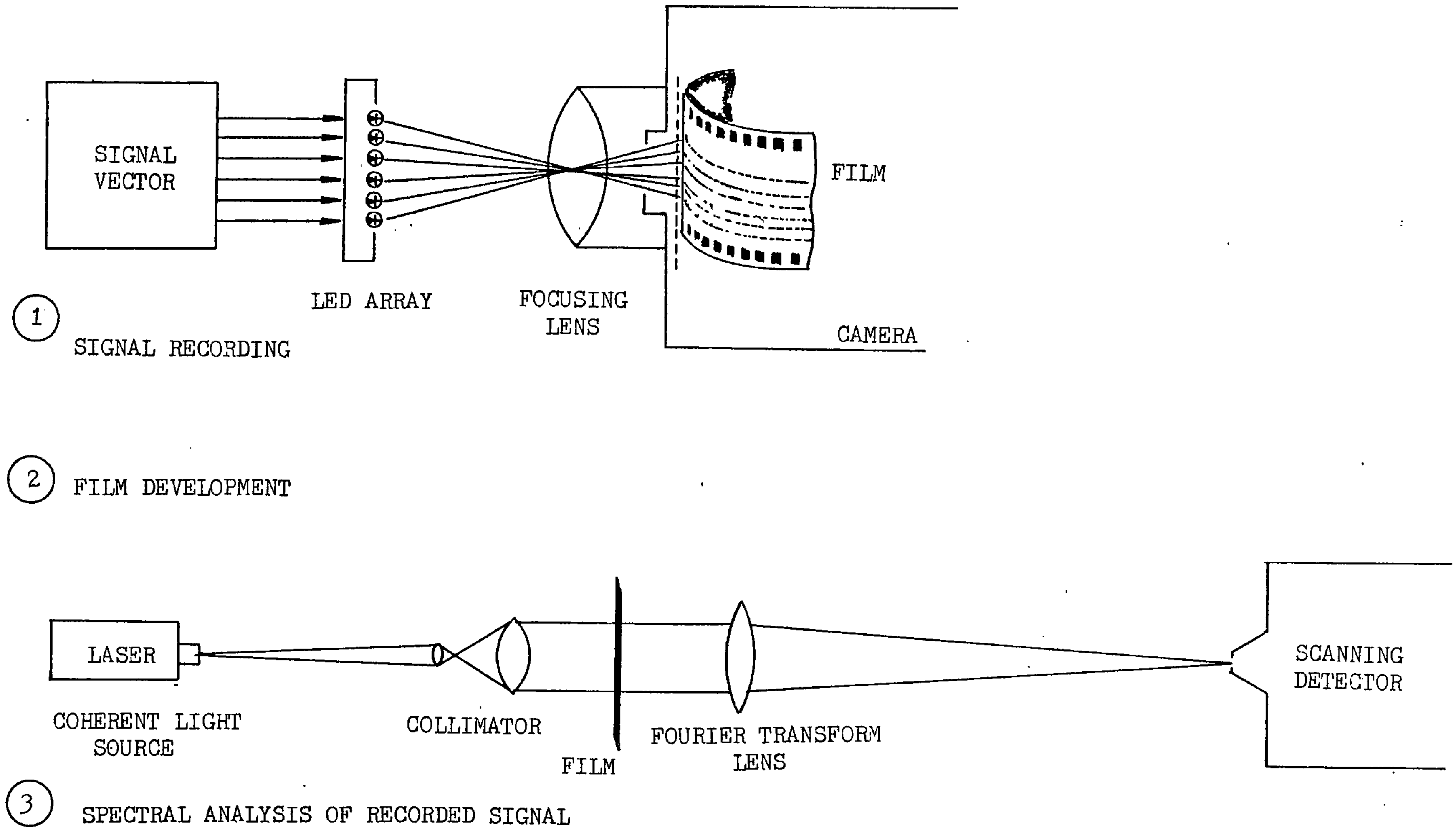

Figure 2. Fourier Optical Multichannel Analog Signal Processing System.

II. Liquid Gates in Theory and Practice

In the past, experimenters in optical systems using photographic film have discovered that irregularities in the film structure frequently cause "noisy" and distorted images. These effects may be substantially reduced by submerging the film in or coating it with a liquid medium having an index of refraction matching that of the emulsion. If the liquid were bounded by optically flat windows, the optical path variations across the aperture would essentially be nullified. Such an arrangement, as shown in Figure 3, is called a liquid gate. Based on the results of these previous investigations, a decision was made to incorporate a liquid gate into the design of the film transport. In this section, a review of the published literature and a survey of potential fluids for use in the system are presented.

Theory of the Liquid Gate Operation in the Signal Processing System

Consider the signal to be recorded, $s(t)$, in the form of a sinusoidally varying LED light intensity which is focused onto the moving film as previously described, and given by the equation:

$$s(t) = I(t) = A + m \sin \omega t \tag{1}$$

where A is the average light intensity, m is the amplitude of the modulation, and ω is the frequency in radians/sec. The mean value, A, is used to maintain the LED constantly in the "on" state, and to bias the recorded average density level on the film to the linear portion of the D - log E curve. If the frequency is within the bandpass of the recording system, the amplitude transmittance of the film is ideally:

$$\tau_s(x) = \tau_o + k \sin \omega_x x \tag{2}$$

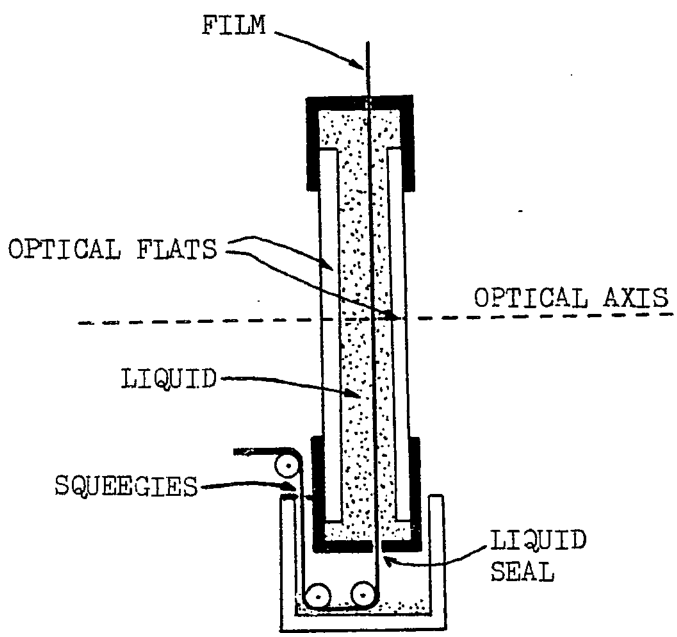

Figure 3. A Liquid Gate.

where τ_o and k are proportional to A and m of Eq.(1) respectively, and with the restriction:

$$0 \leq |\tau(x)| \leq 1.$$

As stated earlier, irregularities in the film create optical path variations which introduce a phase-shift function into the expression for the transmittance. These irregularities are reportedly caused by two independent factors; first, a differential swelling of the emulsion during the development process which creates a "relief image" or thickness variation, and second, differential variations in the refractive index of the emulsion creating an "inner image". Both of these phenomina are highly correlated with the silver density fluctuations, and have been mathematically described as linear functions of the image. Assuming these relationships, we express the actual amplitude transmittance of the film as:

$$\tau(x) = (\tau_o + k \sin \omega_x x) \exp j\phi(x) \tag{3}$$

where

$$\phi(x) = t(x) \, (n_1 - n(x)) \tag{4}$$

$t(x)$ = film thickness function
$n(x)$ = film refractive index function
n_1 = refractive index of the medium surrounding the film (constant)

and

$$t(x) = d_o + k\Delta d \sin \omega_x x \tag{5}$$
$$n(x) = n_o + k\Delta n \sin \omega_x x$$

d_o = average film thickness
$k\Delta d$ = magnitude of film thickness variations
n_o = average film refractive index
$k\Delta n$ = magnitude of film refractive index variations

If Eq.(5) is substituted into Eq.(4), the phase function $\phi(x)$ can be written:

$$\phi(x) = (d_o + k\Delta d \sin \omega_x x)\ (n_1 - n_o - k\Delta n \sin \omega_x x)$$

which reduces to

$$\phi(x) = \phi_o + \alpha \sin \omega_x x + \beta \cos \omega_x x \qquad (6)$$

$$\phi_o = d_o(n_1 - n_o) + \tfrac{1}{2}\beta$$

$$\alpha = k\ (\Delta d(n_1 - n_o) - \Delta n d_o\ )$$

$$\beta = k^2 \Delta d \, \Delta n/2$$

The first term in the expression, ϕ_o, represents a constant phase factor, which has no adverse effect in an intensity-detection system. The second term, which is the information-carrying factor in phase holograms, is the main source of distortion in our system. The third term, although an unavoidable error source, is relatively small in magnitude, and can be minimized by the choice of a "smooth" film and by careful development procedures which reduce the swelling of the emulsion.

The second term can be eliminated by setting $\alpha = 0$, and solving for the optimal index of refraction of the surrounding medium:

$$n_m = n_o + \Delta n \, d_o/\Delta d \qquad (7)$$

dependent on the average index and thickness of the film, and the characteristic amplitude variations of these quantities. Lamberts found that for Kodak Panatomic X film, Δn and Δd are 180^o apart; the value of the average index of the film is 1.535, but the best match was made experimentally with a liquid having a refractive index of 1.49. Results of other similar experiments are summarized in Table I.

TABLE I

Authors	Film Type	Liquid Index	Application
Delwiche et. al.(1958)	Eastman Color	1.46-1.50	Optical Printing
Ingalls (1960)	unspecified	1.478±.02	Liquid Gate Design
Ripson et al. (1962)	Movie films	1.438	Projection System
Ott (1970)	Eastman Color	1.504	Optical Printing
Lamberts (1970)	Panatomic X	1.49	Fourier Transforms
Upnatnieks and Leonard (1970)	unspecified	1.497,1.618	Phase Holograms
Hannes (1967)	Agepan FF	1.66	Holography

The effects of a small mismatch between the ideal and real indices of refraction of the fluid can be theoretically predicted. Leith's (1962) presentation of this subject will be followed in the subsequent derivation. If Eq.(6) is substituted into Eq.(3) and the second harmonic term neglected, the film transmittance function is given by the expression:

$$\tau(x) = (\tau_o + k \sin \omega_x x) \exp j(\phi_o + \alpha \sin \omega_x x) \qquad (8)$$

The identities

$$\exp j\alpha \sin \omega_x x = \cos(\alpha \sin \omega_x x) + j \sin(\alpha \sin \omega_x x) \qquad (9)$$

and[1]

$$\cos(\alpha \sin \omega_x x) = J_o(\alpha) + 2\sum_{n=1}^{\infty} J_{2n}(\alpha) \cos 2n\,\omega_x x \qquad (10)$$

$$\sin(\alpha \sin \omega_x x) = 2\sum_{n=0}^{\infty} J_{2n+1}(\alpha) \sin(2n+1)\omega_x x \qquad (11)$$

where J_n is a Bessel function of order n, are used to express the transmittance in the form of a Fourier series expansion with Bessel function coefficients. In particular, the constants and first harmonic terms (see Appendix A for the detailed derivation) are:

$$\tau(x) = (\exp j\phi_o)[\tau_o J_o(\alpha) + jkJ_1(\alpha) + \sin \omega_x x\, [k(J_o(\alpha) - J_2(\alpha)) + 2j\tau_o J_1(\alpha)] + \cos 2\omega_x x(\ldots) + \ldots] \qquad (12)$$

1. Farrell, O.J. and Ross, B. Solved Problems Gamma and Beta Functions Legendre Polynomials Bessel Functions, p 284.

Recall from Eqs.(6) and (7) that

$$\alpha = k\Delta d\,(n_1 - n_m)$$

In this instance, α is a small quantity, since $(n_1 - n_m)_{max} \approx 0.5$, $k < 1$, and $d \approx 0.6\,\lambda$.[1] For small arguments, the Bessel functions may be approximated by [2]:

$$\begin{aligned} J_o(\alpha) &\approx 1 - \alpha^2/4 \\ J_n(\alpha) &\approx \alpha^n/\,2^n\, n! \qquad n = 1,2,3\ldots \end{aligned} \tag{13}$$

With these approximations, the transmittance of the film becomes:

$$\begin{aligned} \tau(x) = \exp j\phi_o\,[\,\tau_o &+ k \sin\omega_x x + j\alpha(\,k/2 + \tau_o \sin\omega_x x) \\ &- \alpha^2/4\,(\,\tau_o + 3k/2 \sin\omega_x x) + \ldots\,] \end{aligned} \tag{14}$$

The coefficients of the second harmonic term include the intermodulation factor $k^2\Delta n\Delta d/2$, the Bessel function coefficients $2\tau_o J_2(\alpha) - jkJ_1(\alpha)$ plus terms of order three and higher. The largest term in the coefficient of the third harmonic is $kJ_2(\alpha)$. The dominant effect of the phase modulation is the introduction of higher harmonics, with the diversion of power from the zeroth and first orders. The magnitude of the distortion depends on the signal, and the fact that α is not a constant, but a function of the spatial frequency and probably related to the MTF of the film.[3] If the signal of interest is modulated with a carrier frequency, α can be considered to be constant.

In practice, the adequacy of the index match is evaluated by

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1. Results from Hannes (1967) and Lamberts (1970).
2. Farrell, O.J. and Ross,B. Solved Problems Gamma and Beta Functions Legendre Polynomials Bessel Functions, p 278.
3. Goodman, J.W. Introduction to Fourier Optics, pp 225-227.

recording a pure sinusoidal signal and comparing the Fourier transforms obtianed in the cases of liquid and air immersions. The recording also may be bleached, removing all density variations and leaving the phase variations. The effectiveness of the liquid gate and the magnitude of the residual distortion is reckoned by the presence of any non-DC signal in the Fourier plane other than that of the impulse response of the imaging system. In designs of previous experiments, a mixture of two liquids, one with $n < n_o$, one with $n > n_o$, were used to assess the distortion and determine n_m. The index of the mixture is

$$n_1 = n_A + P_B(n_B - n_A)$$

where P_B is the persent by volume of ingredient B, and n_A, n_B are the refractive indicies of the two components. The consensus among the authors previously cited in Table I is that the index mismatch may be up to $\pm$ .02 before distortion becomes visibly noticable or objectionable. In particular, Ingalls found that for "average" film, the phase variation across the aperture would be within the Raleigh limit ($\lambda/4$) if the index match was within 0.02.

Therefore. a quest was made for a liquid having an index of refraction in the range 1.46 to 1.50.

Survey of Potential Liquids for Use in the Liquid Gate

Pure organic liquids range in refractive index from 1.28 to 1.75. Refractive index is correlated with polarizability which depends on the size of the atoms within the molecule and the number of valid Kekulé structures which can be assigned. Water, methanol, and ethanol are polar, but not polarizable molecules possessing indicies of refraction of 1.33. Oftentimes, a salt or sugar is dissolved in a liquid to increase its refractive index — an 85% sucrose water solution has an index of 1.50. However, water and the alcohols mentioned are undesirable for this application because of their adverse effects on film.

Liquids with refractive indices in the range of interest can be grouped into one or more of several general categories:

1. Cyclic non-aromatic hydrocarbons such as cyclohexene, indan, decalin, etc. form a homogeneous group with refractive indices from 1.43 to 1.48.
2. Benzene and its derivitives, called the aromatic hydrocarbons have refractive indices in the 1.49 to 1.56 range.
3. Relatively small molecular weight compounds with halogen substituents such as carbon tetrachloride, chloroethylenes, chloroforms, and iodides have indices from 1.43 to 1.75.
4. The heavier viscous oils such as polyunsaturated nut and vegetable oils, mineral oil and silicone-based oils have refractive indices in a fairly narrow range from 1.45 to 1.50.
5. Heavily unsaturated hydrocarbons with nitrogen (amines and amides), oxygen, or sulfur substituents especially those with conjugated double bonds are usually highly refractive.

In the process of evaluation of these fluids, several other criteria besides refractive index entered into the selection. First, the liquid must have no adverse effect on film, such as curling, mottling, swelling the emulsion, or corroding the Estar or cellulose base. Ketones, amines, and some alcohols were excluded from consideration because of these effects. Some oils, particularly those with silicone bases, mottle the film if allowed to remain and to dry on the surface.[1] (The more volatile fluids do not have this property.) Second, the liquid should be clear and colorless to prevent attenuation of the light beam, as well as being chemically stable to light and air. Compounds such as the essential oils, benzaldehyde, and some iodides will oxidize, and others such as acrylates and styrenes will polymerize and eventually solidify even if inhibitors are added to retard these reactions. Third, in consideration of operating constraints, the liquid must be non-toxic, non-odoriferous, relatively non-flammable, and non-viscous. Fourth, the liquid must not corrode or swell any material used in the construction of the liquid gate. Many of the highly refractive liquids are good solvents, used as paint thinners, varnish removers, and cleaning fluids, and are either highly toxic or corrosive. Finally, cost and availability were considered.

After a comprehensive search of the liquid gate, film cleaning and lubricating articles in the literature, and consultation of chemical reference books, a list of fluids was compiled. The substances listed alphabetically in Table II are clear (or nearly so) liquids at room temperature. The index of refraction (at 20° C, sodium D line — n_{20}^{D}) is given, along with the reference source and notes on any undesirable properties that the fluid may posess. It was impractical to experiment with a wide variety of these compounds, but several representative ones were selected and tested as to their qualities. These included toluene, methyl benzoate (derivatives of benzene), tetrachloroethylene (a dry cleaning fluid), turpentine, "Vitafilm" (a commercial film cleaner), and poly-

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1. Kolb, F.J.Jr., and Weigel,E.M. "Lubrication of Motion-Picture Film" (1965).

Table II

List of Liquids Considered for Use in the Liquid Gate

Compound	Reference*	n_D^{20}	Remarks	Grade*
Acetone	1	1.36	Severe effect on film	F
Acetophenone	3	1.53	Ketone; Prob. affects film	F
Acetylenetetrabromide.	3	1.64		F
Allyl Sulfide	1	1.49	Toxic; severely affects film	F
Amylbenzene	1	1.49	Flammable, Sl. toxic	F
n-Amyl Chloride	2	1.42	High cost	F
t-Amyl Chloride	2	1.41	High cost	F
Anethole	3	1.56		D
Anisole	1	1.52		D
Aroclor 1232	5	1.62	Toxic	F
Benzaldehyde	3	1.55	Oxidizes	F
Benzene	1,2	1.50	Flammable, Sl. affects film	A
Benzacrylate	3	1.51		D
Benzylalcohol	3	1.54		F
1-Bromo-2-chloroethane	1	1.49	Severe effect on film	F
1-Bromo-1-chloropropane	1	1.48	Severe effect on film	F
2-Bromo-1-chloropropane	1	1.48	Severe effect on film	F
3-Bromofuran	1	1.50		D
t-Butyl Acetate	3	1.40		D
Butyl Alcohol	1	1.39		F
t-Butylbenzene	1	1.50		F
Butyl Bromide	3	1.44	Mod. toxic	D
n-Butyl Chloride	2	1.40		B
Carbon Tetrachloride	1,2	1.46	Toxic solvent	F
Carvacrol	3	1.52		D
Chavicol	3	1.54		D
Chlorobenzene	1	1.53	Severe effect on film	F
1-Chloro-2-fluorobenzene	1	1.50	High cost	F
1-Chloro-3-fluorobenzene	1	1.50	High cost	F
3-Chloro-1,2-propanediol	3	1.48		F

* see notes at the end of the Table

Table II (Con't)

Compound	Ref.	n_D^{20}	Remarks	Grade
Chlorotoluene	1	1.52		D
Cinnamic acid, Ethyl Ester	3	1.56		D
Cod Liver Oil	3	1.47		A
Corn Oil	3	1.47		A
Cottonseed Oil	3	1.47		A
Creosol	3	1.54	Toxic	F
Cresol	3	1.54		D
Cumene	3	1.50		C
Cuminaldehyde	3	1.53	Offensive odor	F
1,4-Cyclohexadiene	1	1.47	Mod. toxic	F
Cyclohexane	2	1.43		B
Cyclohexanone	1	1.45	Ketone; Prob. affects film	F
Cyclohexene	2	1.44	Flammable	F
Cyclohexylcarbinol	3	1.46		D
2-Cyclohexylcyclo-hexanol	1	1.50	High cost	C
Cyclopentadiene	3	1.46	Toxic	F
Cyclopentane	2	1.40		B
Cyclopentanol	3	1.46		D
Cyclopentene	2	1.42		D
Cymene	1	1.50		D
Decalin Solvent	1,3	1.48		A
n-Decyl Alcohol	3	1.44	Viscous	F
1,2-Dichloropropane	2	1.44	Severe effect on film	F
1,3-Dichloro-1-propene	1,2	1.47	Flammable	F
1,2-Dibromoethane	1	1.54	Hazardous	F
Dibromopropane	1	1.52		D
8-(3-Diethylaminopropyl-amino)-6-methoxyquinoline	3	1.59	Oily	C*
Diethylaniline	3	1.54	Severe effect on film	F
Diethylbenzene	1	1.50	Mod. toxic	F
Diethylene Glycol	3	1.45		C
1,2-Dihydrotoluene	1	1.48		D
Diisopropylbenzene	1	1.49		D

Table II (Con't.)

Compound	Ref.	n_D^{20}	Remarks	Grade
2,3-Dimethyl-1,3-butadiene	3	1.44		D
2,3-Dimethyl-1,3-dioxolane-4-methanol	3	1.44		D
1,1-Diphenylethene	3	1.61		C*
2,3-Dimethylthiophene	1	1.52	Toxic	F
1,1-Di-p-tolylethane	3			D
Dypnone	3	1.63		C*
Estragol	3	1.52	High cost	F
Ethanol	1,2	1.33	Severe effect on film	F
Ethoxyquin	3	1.57	Toxic	F
Ethyl Benzene	1	1.50	Flammable, Mod. toxic	F
α-Ethyl Benzyl Alcohol	3	1.52		D
Ethyl Cinnamate	3	1.56	Oily	C*
Ethyl Linoleate	3	1.47		C
Ethyl Selenide	1	1.48	Very toxic	F
Ethyl Thioacetate	1	1.47	Severe effect on film	F
Fenthion	3	1.57	Toxic	F
1-Fluorooctane	1	1.40		F
o-Fluorotoluene	1	1.47		F
1-α-Frenchene	1	1.47		D
Freon	1,2	1,36		B
Heptane	1,2	1.39	Flammable, Sl. effect on film	F
Hexane	2	1.38		F
3-Hexene-1-ol	3	1.48	Offensive odor	F
Isopropanol	2	1.38		B
Indan	3	1.54		C
Indene	3	1.58	Polymerizes	F
1-Iododecane	1	1.43		C
1-Iodohexane	1	1.49		C
1-Iodopentane	1	1.50		C
1-Iodo-2-methylpropane	1	1.50		C
1-Iodo-2-methylbutane	1	1.50		C

Table II (Con't.)

Compound	Ref.	n_D^{20}	Remarks	Grade
Isooctane	3	1.39	Flammable	F
Isoamylalcohol	3	1.41	Toxic	F
Isophytol	3	1.46		F
Isopropenyl Acetate	3	1.40		F
Isoprene	3	1.42	Oxidizes	F
Isopropyl Ether	3	1.37		F
Isopropyl Iodide	3	1.50	Unstable	F
Isoquinoline	3	1.62	Offensive odor, high cost	F
Isosafrole	3	1.58		C*
Lactic Acid Methyl Ester	3	1.43		F
Methylal	3	1.36		F
Methyl Benzoate	1	1.52	Affects film & plexiglass	F
Methyl-2-Furoate	3	1.49		C
Methylene Bromide	3	1.54		C
Methylene Chloride	3	1.42		F
Methylene Iodide	6	1.74	Unstable in air	F
Methyl Iodide	3	1.53	Poisonous	F
Methyl Salicylate	3	1.54	Toxic	F
Morpholine	3	1.45	Toxic	F
Methyl Chloroform	1,2,4	1.44		B
1-Methylpyrrole	1	1.49	Flammable	D
Mesitylene	1	1.50	Toxic	F
2-Methylthiophene	1	1.52	Toxic, Flammable	F
Methylcyclohexane	2	1.42		B
Methylfuran	2		High cost	D
Methanol	1,2	1.32	Severe effect on film	F
Natural Oils	3	1.46 - 1.58	Gen. unstable in air & light	F
Naphtha	2	1.39		B
Nitrobenzene	1	1.55	Poisonous	F
Nonane	1	1.40	Flammable	F
Nonylbenzene	1	1.49		D

Table II (Con't.)

Compound	Ref.	n_D^{20}	Remarks	Grade
Ocimene	3	1.49		C
n-Octylbromide	3	1.44		D
Olive Oil	3	1.47		A
Pentachloroethane	1	1.50		D
2,4-Pentanedione	1	1.45	Mod. effect on film	F
α-Phellandrene	1.	1.48		C
Phenyl Acetate	1	1.50		F
Phenylpropylmethyl-amine	3	1.51		F
2-Picoline	3	1.50		D
α-Pinene	1	1.47	Flammable, toxic	F
Piperitone	3	1.48	Ketone; Prob. affects film	F
Pristane	3	1.44		F
n-Propylbenzene	1	1.49	Flammable, Mod. toxic	F
Propyl Ether	2	1.38		F
n-Propyl Iodide	1	1.50		F
m-Propyltoluene	1	1.50		D
Propylenedibromide	3	1.52		D
Pseudocumene	1	1.50		D
Pseudoionone	3	1.53	Ketone; Prob. affects film	F
Pyridine	1	1.51	Toxic, Flammable, Offensive odor	F
Pyrrole	1	1.50	Mod. toxic, unstable in air	F
Saffrole	3	1.50	Deteriorates in air	F
Stottard Solvent	1	1.44		B
Terpinene	1,3	1.49		D
Terpinoline	1	1.48		D
Tetrachloroethane	1	1.48	Toxic, Mod. effect on film	F
Tetrachloroethylene	1,2,6	1.50	Mod. toxic, Sl. effect on film	A
Tetraethyllead	3	1.52	Poisonous	F
1,2,3,4-Tetrahydro-napthalene	1	1.54	Sl. toxic	C*
1,1,3,3-Tetramethyl-1,3-diphenylsiloxane	3	1.51		C*
Tetramethyltin	1	1.52	Poisonous, Severe effect on film	F

Table II (Con't.)

Compound	Ref.	n_D^{20}	Remarks	Grade
Thiophene	1	1.53	Poisonous	F
Toluene	1,2	1.49	Flammable, Sl. toxic	F
Trichloroethane	1	1.47		D
Trichloroethylene	1,2	1.48	Mod. effect on film	F
Triethylbenzene	1	1.50		D
Triisopropylbenzene	1	1.49		D
Turpentine	6	1.48		C
Vegetable Oil	3	1.47		A
Vinyltrichloride	3	1.47		D
Xylene	1,5	1.50		C
Water	1	1.33	swells film emulsion	F

Notes to Table II:

References Cited:

1. Delwiche et al. (1958)
2. Fassett et al. (1958)
3. Merck Index
4. Ott (1970)
5. Upatnieks and Leonard (1970)
6. Hannes (1967)

Grading System:

AA Liquid is ideal for use
A Liquid has one or more of the following drawbacks:
 1. Film requires cleaning after immersion
 2. Moderate, repairable effect on liquid gate
 3. Moderate toxicity or flammability, good ventilation required.
B Refractive index is low, otherwise suitable for use
C Good candidate for experimentation
C* Refractive index is high, candidate for experimentation
D Poor candidate for experimentation
F Rejected

ethylene glycol (Carbowax 400) used in antifreeze and as a cosmetic base and wetting agent.

No fluid was found to be perfectly satisfactory; the toluene and methyl benzoate dissolved the plexiglass digital read head, the tetrachloroethylene was toxic, the index of refraction of the "Vitafilm" was too low at 1.43, and each of these compounds adversely affected the tank sealant and film guide cement. Polyethylene glycol, with a low but acceptable refractive index of 1.4625, was inert, non-toxic, but oily and slightly viscous. If used, it would have to be removed from the film. Therefore, it was decided to incorporate a film cleaning bath separate from the liquid gate into the transport design. Thus, liquids with minor and long-term effects on the film could be used because the film could be cleaned immediately after use, and exposure to the liquid abbreviated. Alternatively, if some liquid slightly corrosive to some component of the gate proved to be the over-all "best" choice, it could be introduced into the tank immediately prior to use and drained as quickly as possible, and then the tank purged. This procedure would necessitate the refurbishment of the tank every so often, which is undesirable.

III. Film Transport and Liquid Gate Design and Operation

A basic design for the film transport system was conceived considering ease and flexibility of operation and simplicity of construction. All machine work was done by the author with help from fellow students. The subsystems of the transport: the film drive system, the digital readout system, the liquid tank assembly, and the optical system are described in the following paragraphs. The overall layout and design of the transport are shown in Figures 4, 5, 6, and 7. The photographs in this chapter were taken before the machine was painted flat black, and before final modifications were completed. Differences between the photographs and the finished product are minor, but will be indicated when applicable.

Film Drive System

The film drive system consists of three motors; two Barber-Coleman 12 volt DC reel motors and a Microswitch capstan motor with feedback tachometer. In addition to the motors, the various rollers, film guides, and squeegies determine the path of the film through the transport.

Each reel drive motor is controlled by an amplified reference voltage which is proportional to the tension in the film near the take-up reel. A movable roller constructed of 1" diameter polyvinylchloride (PVC) tubing senses the tension in the film by its vertical position, which is determined by a balance between the forces exerted by gravity, the tension in the film, and the tension in a pull-down watchspring. As illustrated in Figure 8, the watchspring is mounted in a pulley casing connected to the tension-sensing roller by a line. This line, a nylon

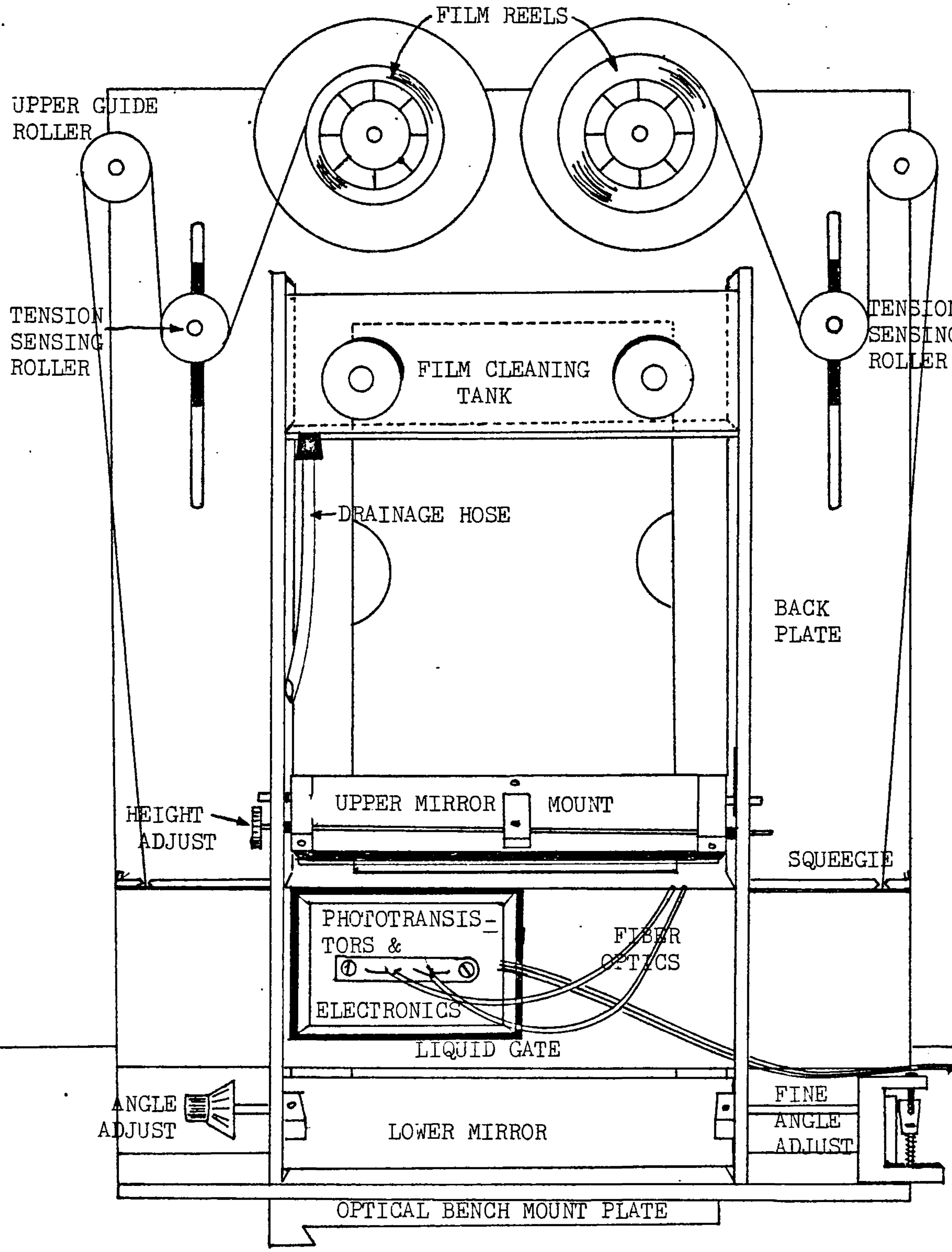


FIGURE 4. Schematic Diagram of Film Transport - Front Side

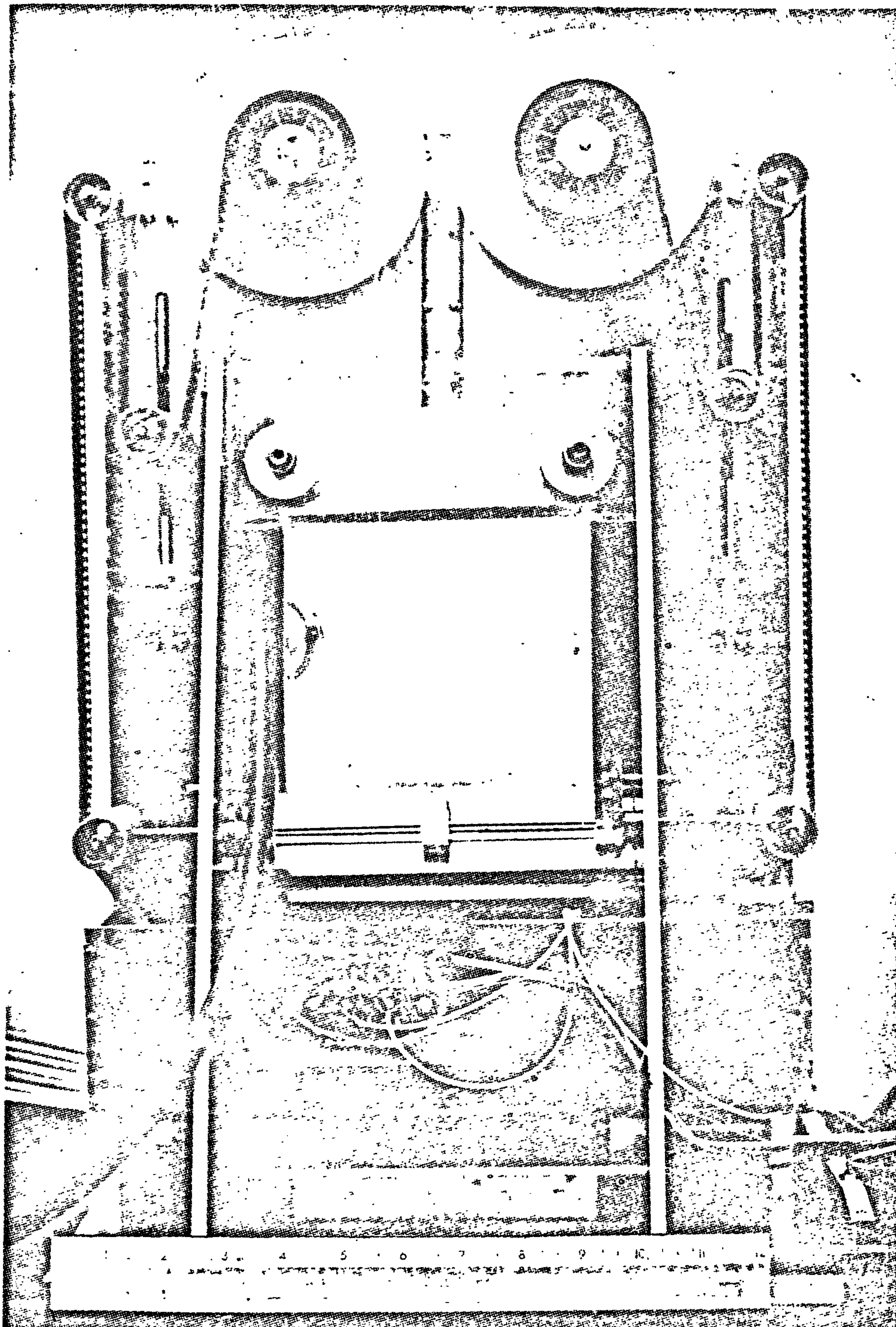


Figure 5. Front View of Film Transport.

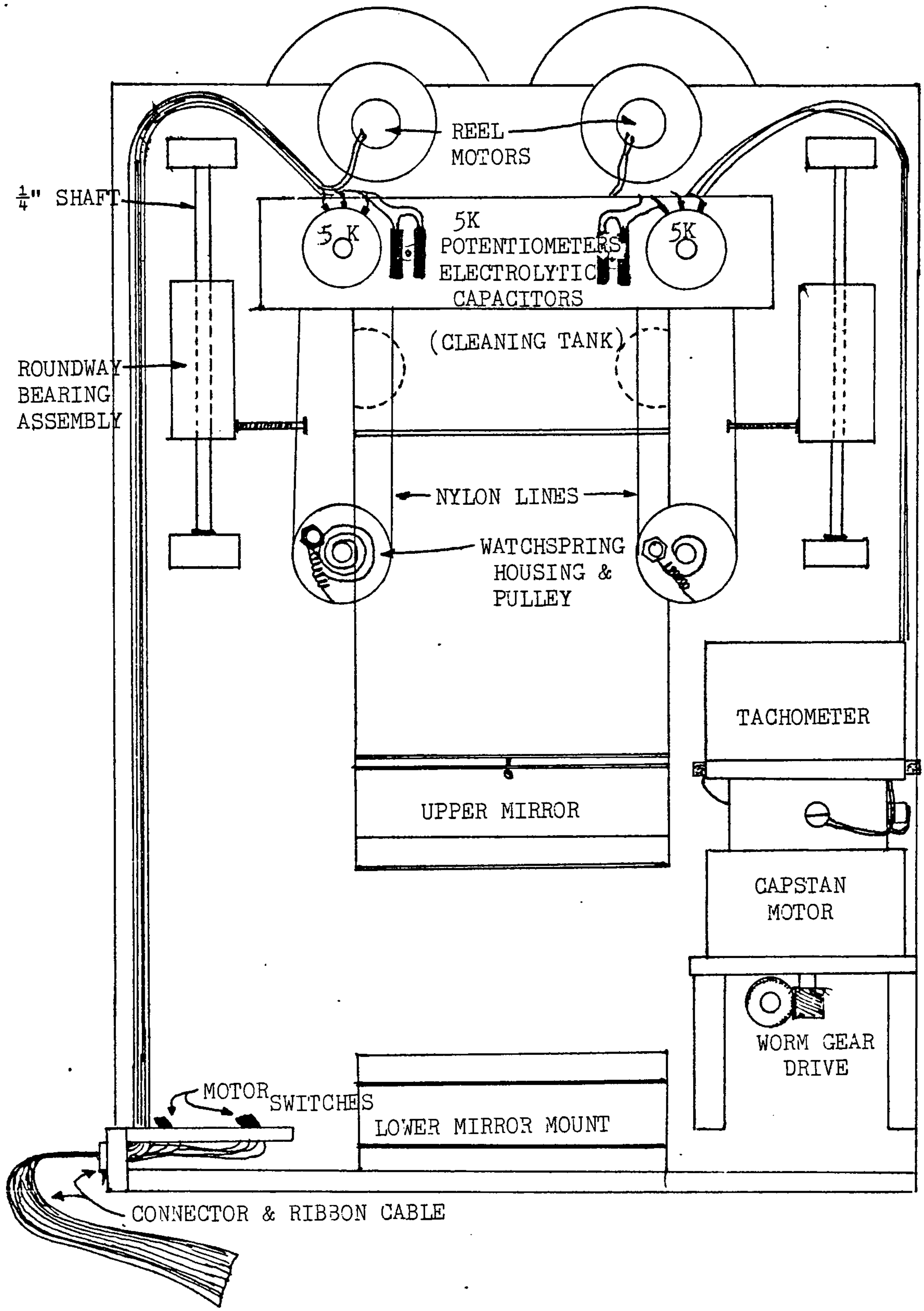


FIGURE 6 Schematic Diagram of Film Transport- Back Side

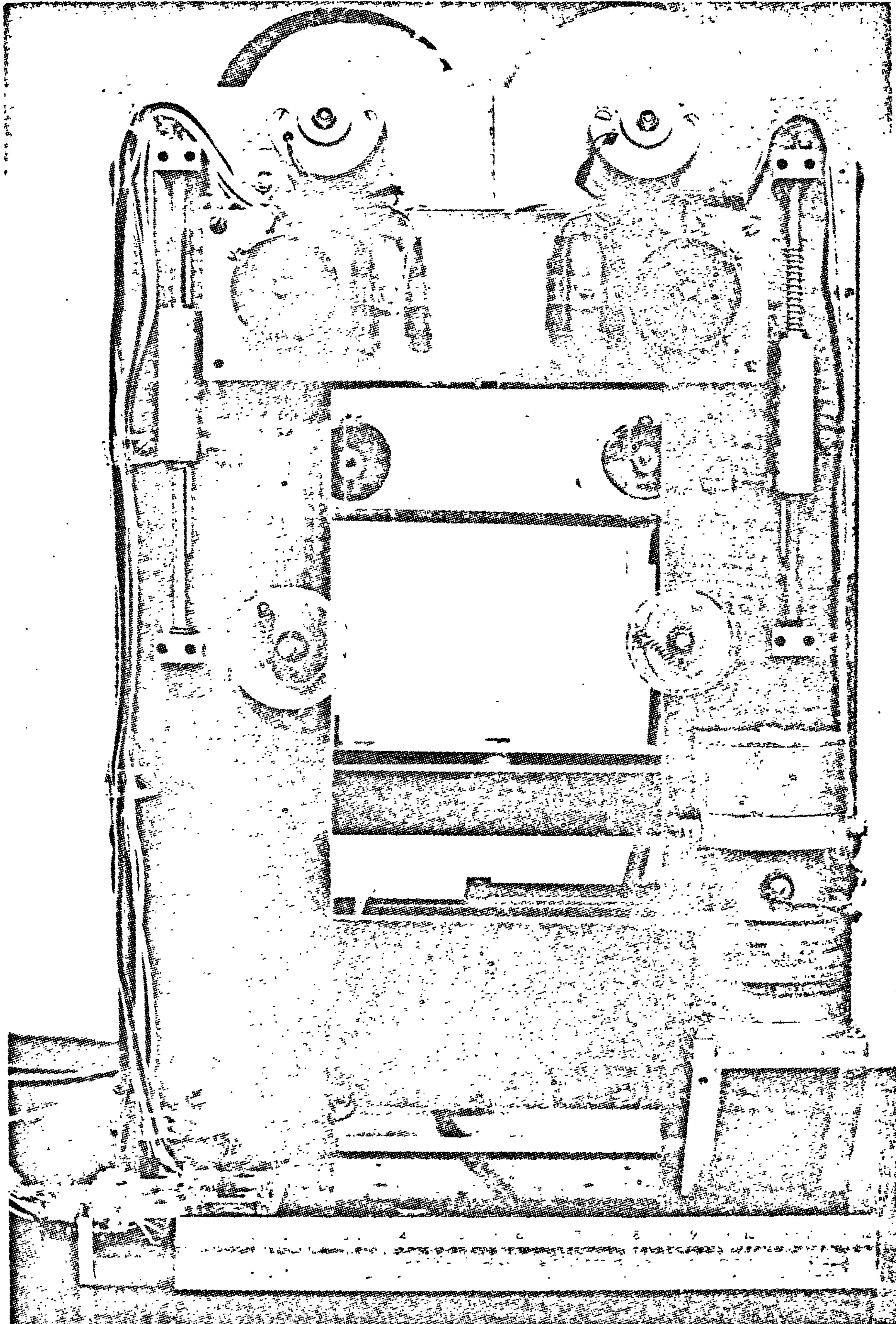


Figure 7. Back view of Film Transport.

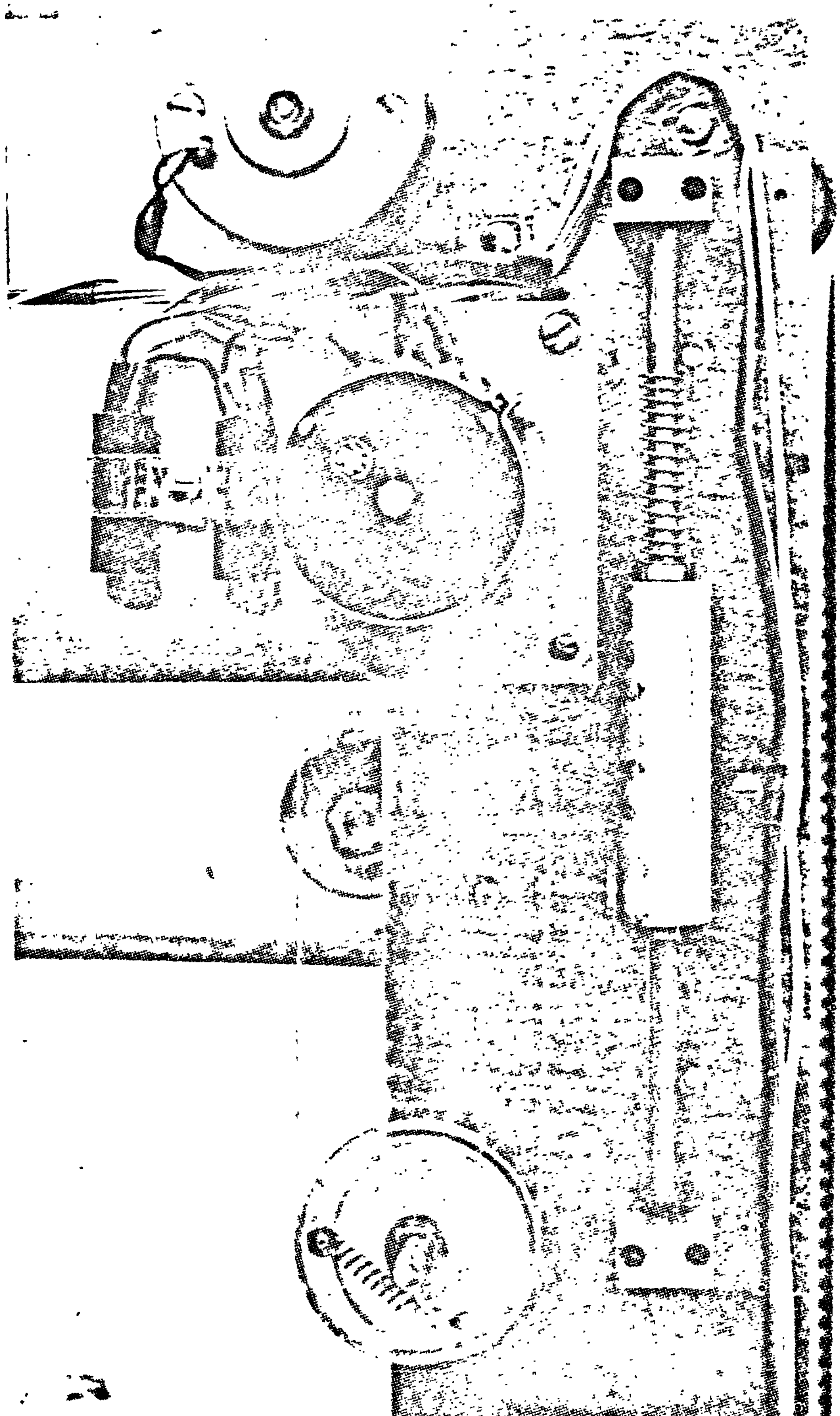
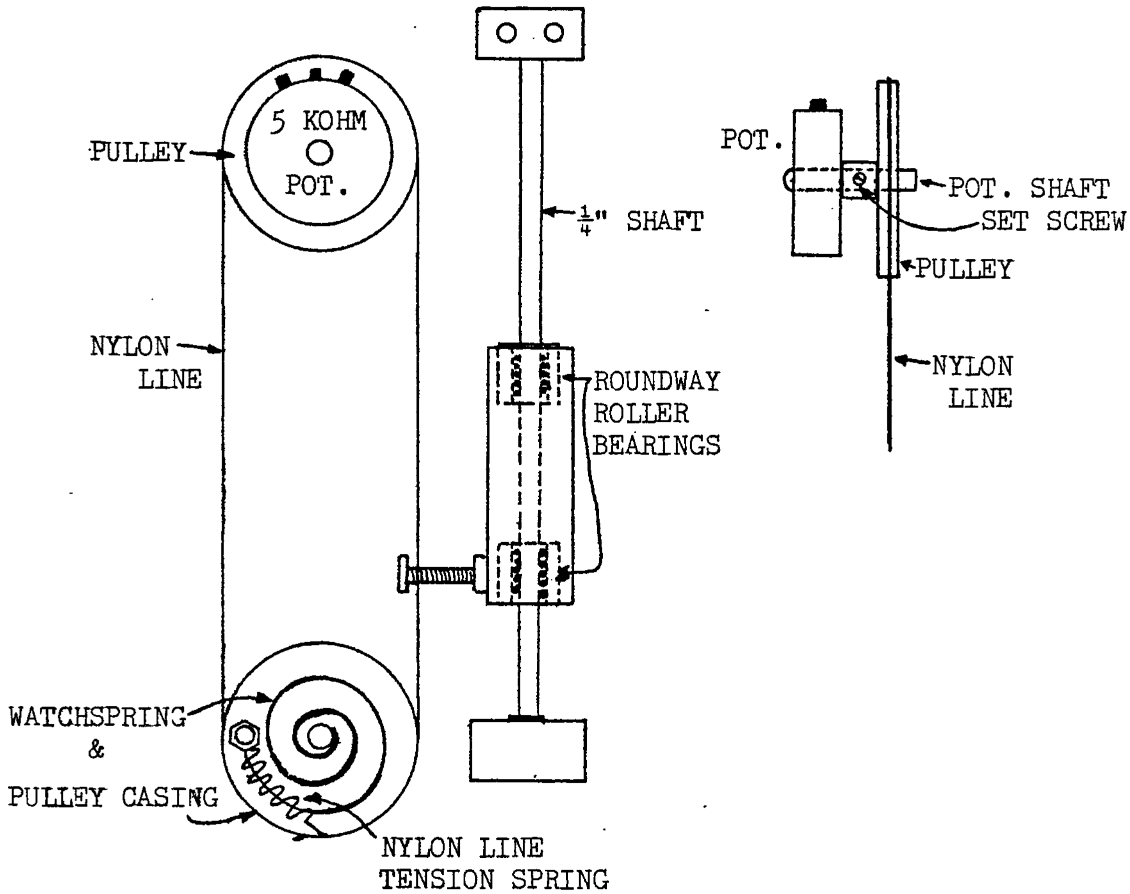


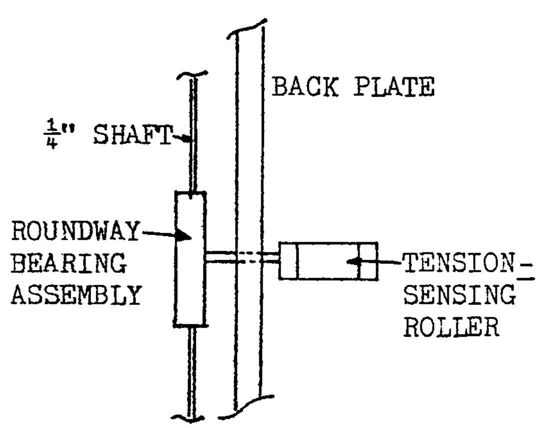
Figure 8. Film Tension Feedback Control System.

monofilament fishing line, is wound around a second pulley mounted on the shaft of a 5 K ohm precision potentiometer. (See Figures 9 and 10). As the film tension increases, the roller is elevated, and the shaft of the potentiometer is rotated. Across the potentiometer is a bipolar reference voltage such that when the roller, and thus the slider, is in its median position, the output voltage is zero. As the film tension eases or tightens, the output voltage becomes increasingly positive or negative. This is used as the reference voltage to drive the reel motors in a negative feedback sense - i.e. when the tension in the film is too slack, the motor acts to take up the film, and when the film tension is too great, the reel motor plays out film. The time response is limited to prevent oscillations by 100 μf capacitors across the slider terminal and the positive side of the potentiometer to ground. The static film tensions on either side of the liquid gate are individually set in two manners. First, a gross adjust is provided by the amount of winding present in the watchspring, and second, a fine adjust can be made by setting the null position of the tension-sensing roller. Care must be taken to insure that the discontinuity in the single-turn potentiometer is not traversed as the roller moves the length of its excursion. The speed of the motor for a given offset is determined by the gain in the power amplifier shown in Figure 11. A gain of 10 was experimentally found to be satisfactory.

The Microswitch capstan motor, rated at 18 volts, 5 amps. and with a torque of 3.75 oz. in. / sec., provides the film drive and speed control through the liquid gate. The brass sprocket drive roller and the rubber pinch roller are immersed in the liquid (See Figure 12.). A worm gear drive, selected because of uniformity of motion, connects the motor



(a) Back View



(b) Side View

Figure 9. Schematic Diagram of Film-tension Feedback Control System.

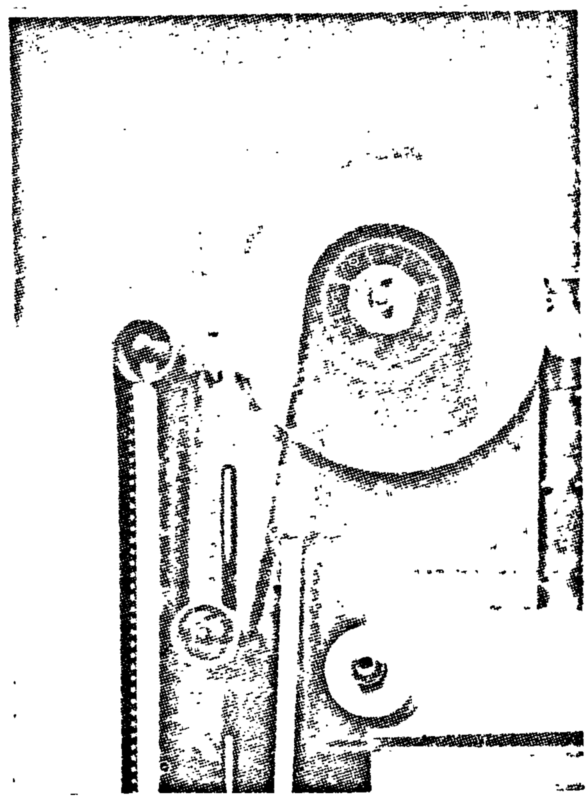


Figure 10. Film Tension-Sensing Roller Showing its Relation to the Film Reel.

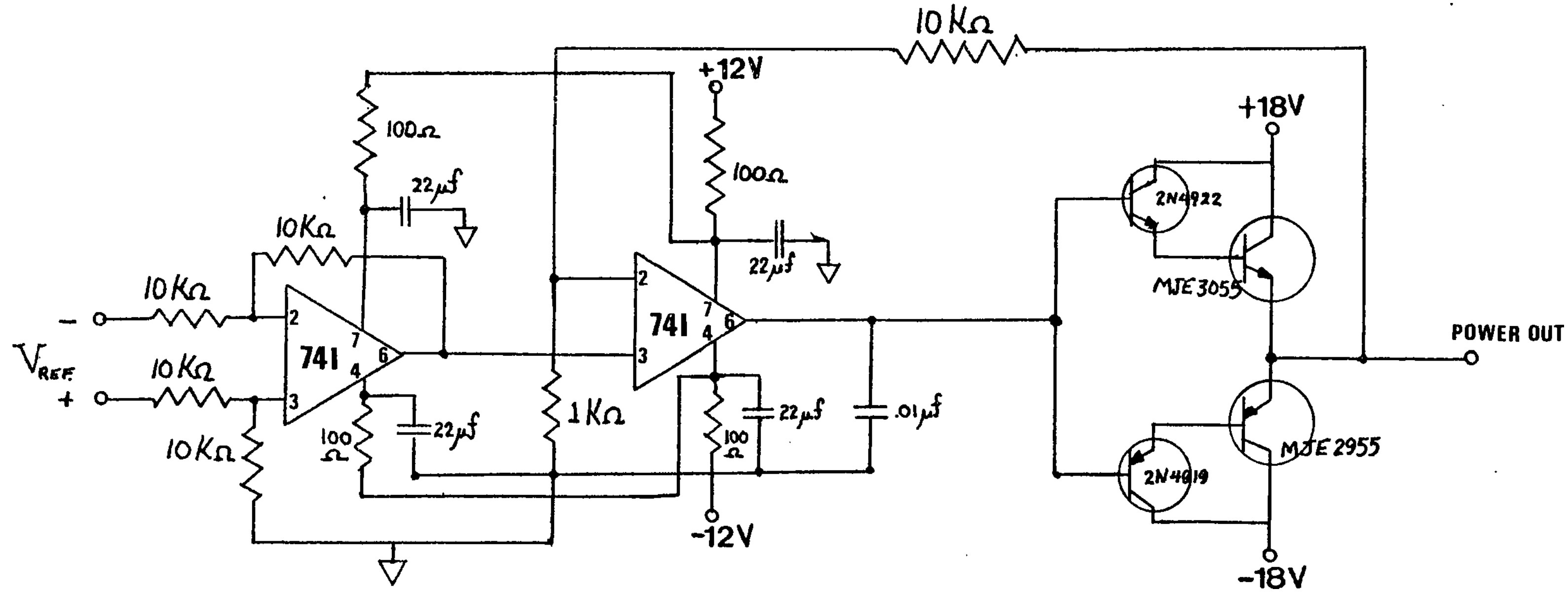


Figure II. Reference Voltage Power Amplifier

Figure 12. Film Drive Roller Assembly.

shaft to the drive roller shaft which penetrates the liquid tank through a ball bearing, shown in detail in Figure 15. The speed of the motor is controlled by an amplified reference voltage, which may be set positive or negative, depending on the direction of motion desired, and maintained constant by a voltage feedback servo loop using the output voltage of the tachometer connected to the motor shaft. Switches of the reverse side of the transport provide ON-OFF control for each of the three motors.

Digital Readout System

The digital readout system consists of a miniature light source, a fiber optic read head, and an electronic light sensor and amplification unit. The system schematic is shown in Figure 13. The miniature light bulb, obtained from Edmund Scientific, rated at 5 volt, 120 mA., is located on the underside of the liquid gate. Its light, which is nearly collimated by a 6 mm. lens with a 7.6 mm focal length, passes through the lower glass plate and the film and falls onto the fiber optic read head, which projects through the upper glass plate of the liquid gate. The read head is constructed of plexiglass embedded with a linear array of 10 mil diameter plastic fiber optics. Each of the six channels consists of two adjacent fibers with a single fiber separating it from the next channel, as shown in Figure 14. The fibers held in two three-channel cables emerge from the top of the inner tank and are abutted against six phototransistors (TI LS600) located in an electronics box (See Figure 15). The emitters of the phototransistors are the inputs to Darlington-type amplifiers which become saturated when the film is transparent to light and cut off when the film occludes the light source. In these two states,

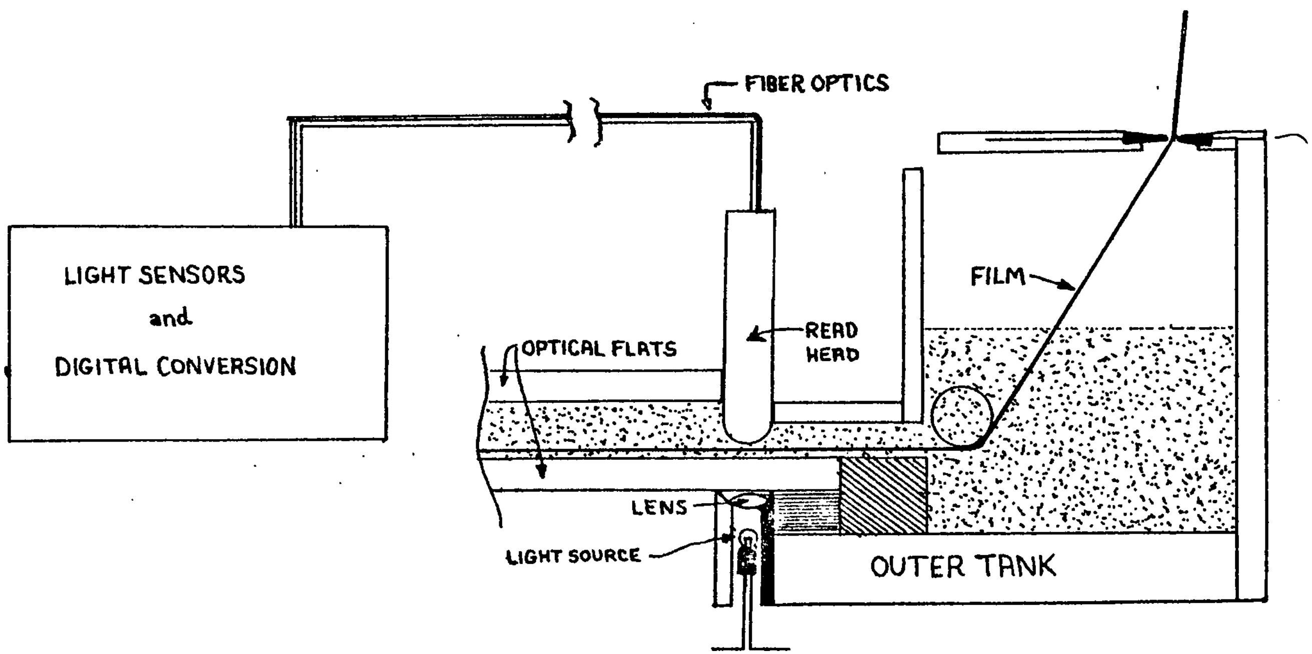
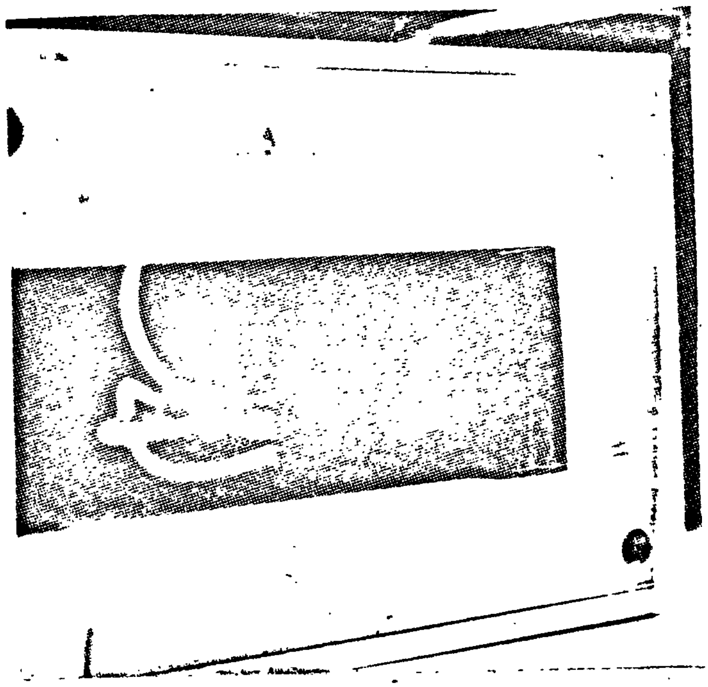
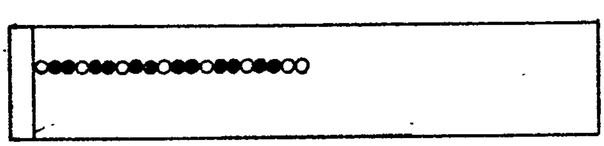


Figure 13. Schematic Diagram of Digital Readout System.





Detail of Digital Read Head

Figure 14. Lower Surface of Inner Tank Showing Fiber Optic Read Head.

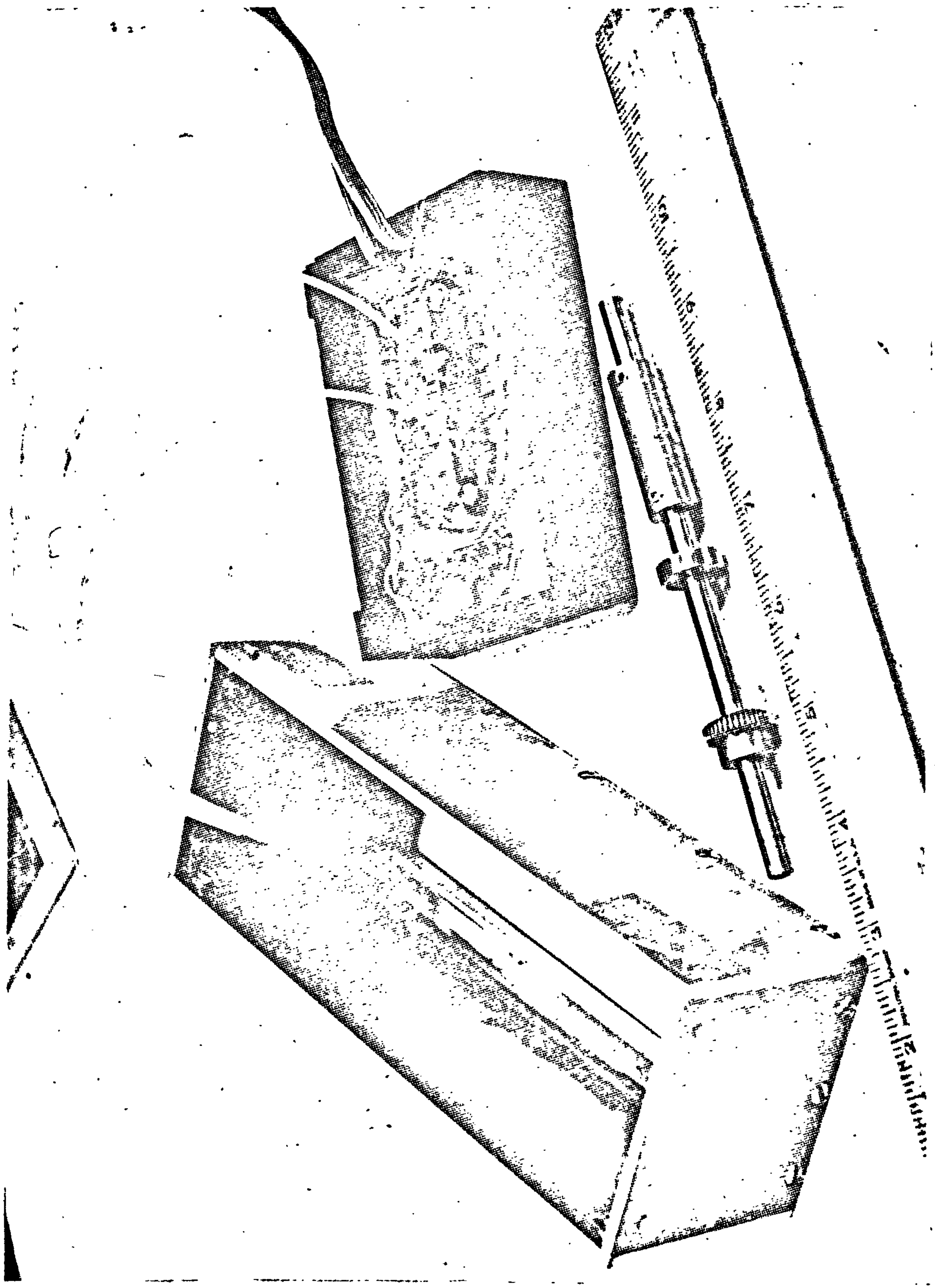


Figure 15. Digital Read Head in the Inner Tank, Showing Fiber Optic Cables and Amplifier Electronics.

the output voltage is either 0.3 V (saturated) or V_{CC} = 5 V, which is compatible with standard TTL digital integrated circuitry. The circuit is shown in Figure 16. The test pattern shown in Figure 17 was generated to verify the operation of the system. It was found that a high contrast between digits recorded on the film as well as minimal room light was necessary for good operation. Illumination of the liquid gate had no effect on the outputs. The sensitivity of the sensors, and the film transmission value at output level transitions are easily regulated by controlling the intensity of the miniature lamp.

In order to determine the exact position of the six digital channels on the film, light was applied to the free ends of the inter-channel fibers as unexposed film was driven through the gate. After development, it was easy to measure the channel positions,as shown in Figure 18. Pulsing the light to the fibers and observing the recorded pattern gives a clear indication of the resolution of the read head and the minimum digit dimension required for a discrete level switch.

Liquid Tank System

There are two liquid tanks in the film transport; one forms the liquid gate system and consists of two nesting aluminum boxes, the other is a plexiglass container for the film cleaning fluid. Each tank has a one-holed rubber stopper plugged into the bottom of the tank with an inserted piece of glass tube connected to a rubber hose which can be clamped or unclamped for drainage purposes. The inner tank of the liquid gate pictured in Figure 15 is screw-and-spring mounted at three places to the lower tank with the capability of aligning the upper glass flat parallel to the lower glass flat, and separated by approximately

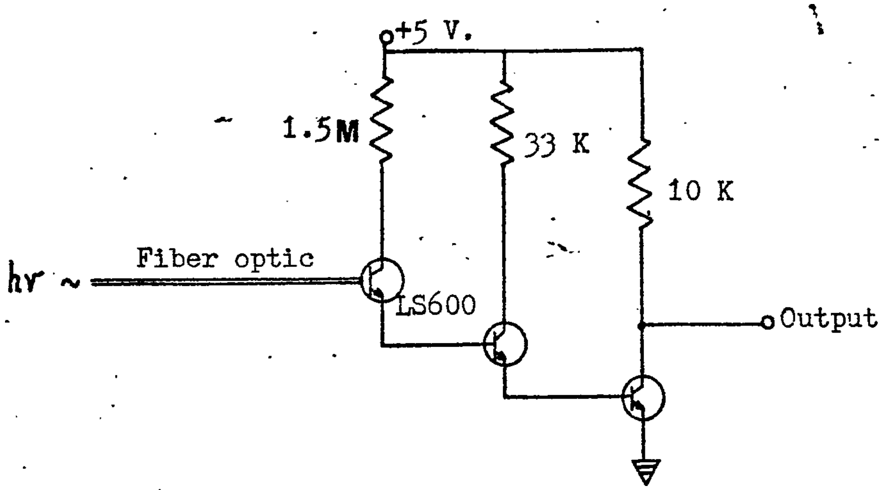


Figure 16. TTL Compatible Light-to-Voltage Transducer Electronics.
(Single Channel)

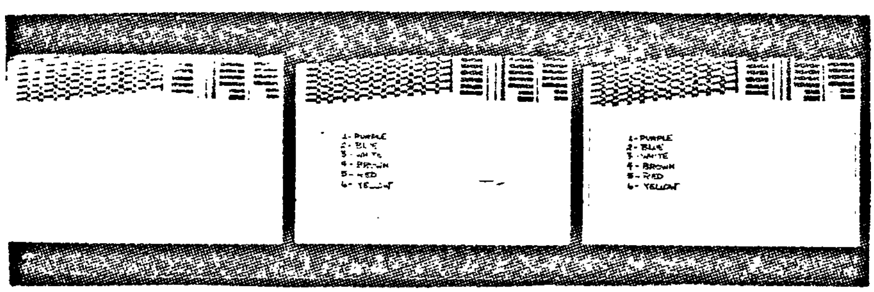


Figure 17. Test Pattern for Digital Output.

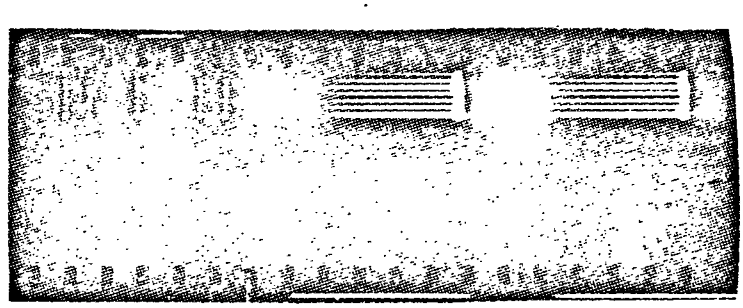


Figure 18. Test Film for Location of Digital Channels.

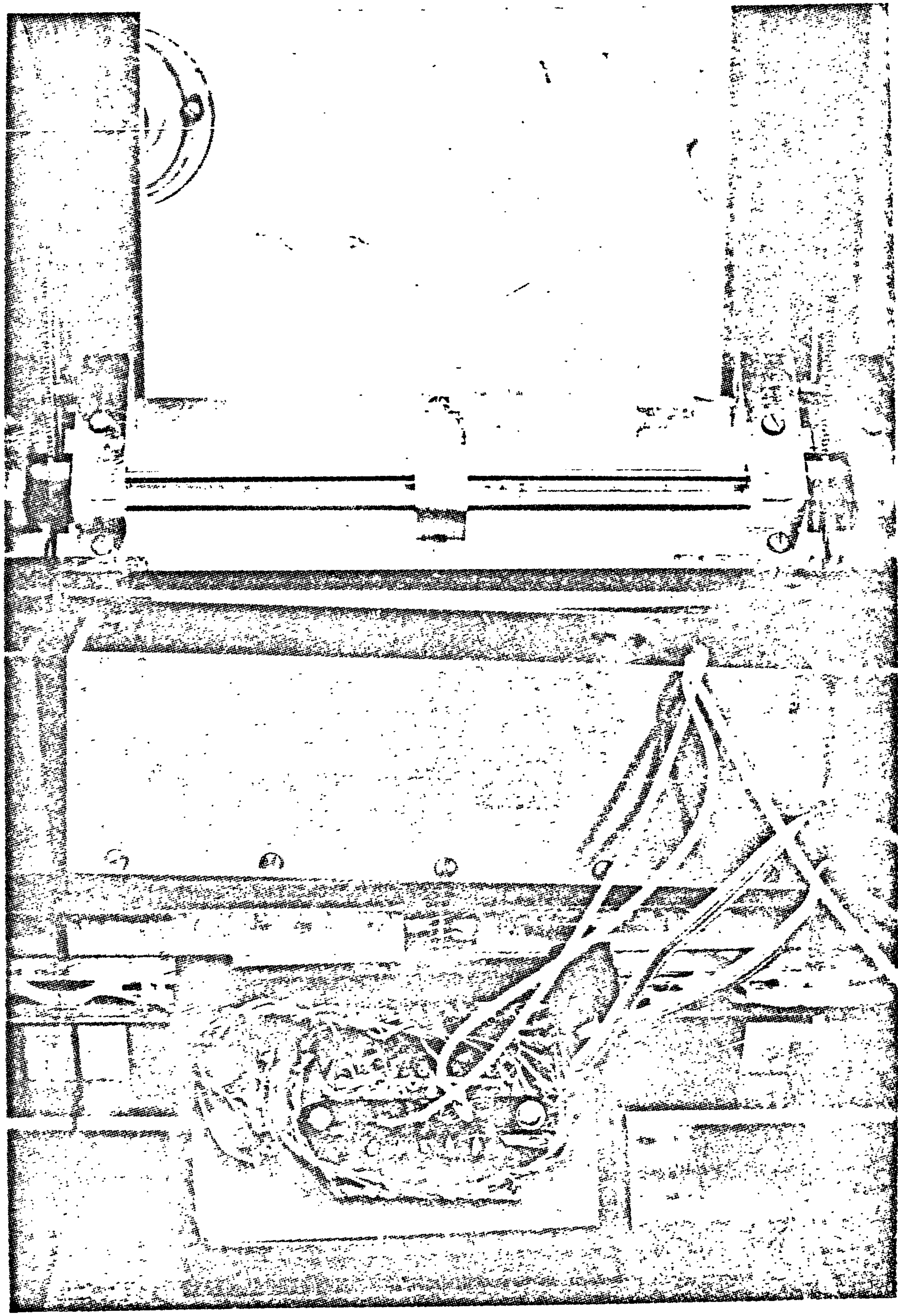


Figure 19. Inner Tank Mounted to the Floor of Outer Tank.

0.35". The edges of the film in the liquid gate are held against 8-mil feeler gauge stock spaced on either side of the gate by exactly the width of the film. The film is pressed flat against the lower glass plate by 2-mil feeler gauge stock which covers the film sprocket holes, and is affixed to the 8-mil feeler gauge stock by silicone sealer. A picture of the film in the optical window of the liquid gate with the inner tank removed is shown in Figure 20.

The film enters the lower tank through a set of wiper blade squeegies, passes between the drive and pinch rollers, through the film guides previously described, under a brass guide roller at the other side of the window (this brass roller can be seen in Figure 21), through a symmetric set of squeegies, and out of the tank. The tanks are made liquid-tight by coating all joints with silicone sealant just prior to final assembly. This method of sealing permits dissassembly.

The film cleaner tank contains "scrubber" roller made of wooden spools covered with terry cloth. A commercial film cleaner, "Vitafilm", is used to remove the polyethylene glycol from the film, and may be left of the film indefinitely.

Optical System

The optical system associated with the film transport consists of two diagonal mirrors and the optical flats forming the liquid gate. The flats were selected by observing the interference pattern betweeen different pairs of flats illuminated with a collimated laser light source. The best pattern of lines in the interference pattern were straight and regular, indicating a good match between the flats. Two other flats were selected an aluminized in a vacuum chamber to serve as the diagonal mirrors.

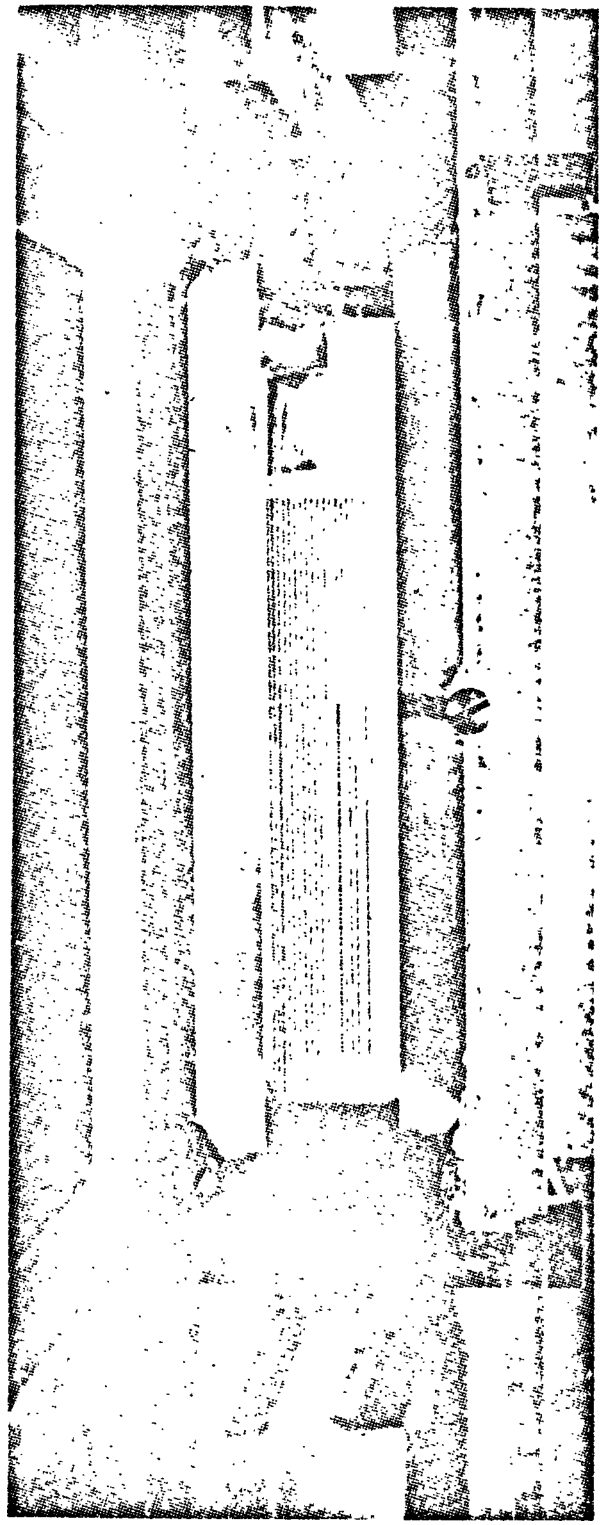


Figure 20. View of Film in the Guide of the Lower Tank Taken from Upper Mirror. The Inner Tank has been Removed. Note three point Mounting for the Inner Tank and the Miniature Lamp for the Digital Readout System.

Since the coating on these mirrors is very fragile, the mirrors were the last items to be installed on the transport. The lower mirror is mounted on a rotating plate below the liquid gate. Both gross and differential adjustments may be made to the angle of this plate, as illustrated in Figure 21. By using the fine angle adjust, the spectrum may be accurately centered on the slit of the automatic Fourier Transform scanner.[1]

The upper diagonal mirror is rack-and-pinion mounted so that its height may be varied. This arrangement provides for either a focus adjust by changing the optical path length, of a means for centering the mirror in the laser beam. Also an independent angle adjustment is built into the design by a three-point spring-and-screw mounting as shown in Figure 22.

The entire transport is screwed onto an aluminum optical bench mount, which is easily snapped into place on a standard optical bench.

1.. Forster, L. Master's Thesis, University of Houston, 1974.

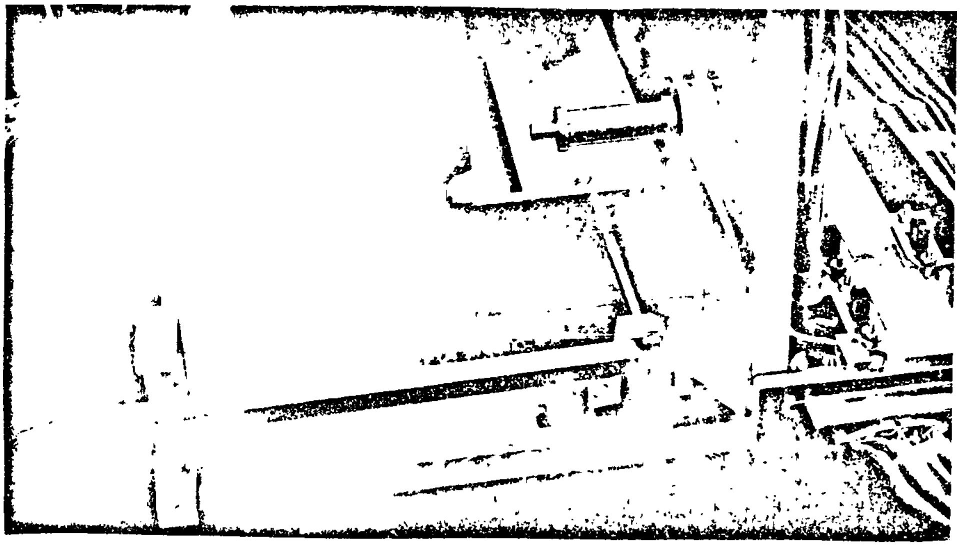


Figure 21. Lower Mirror Mount with Differential Angle Adjustment. Note the Motor Switches and Ribbon Cable Connector on Back Side.

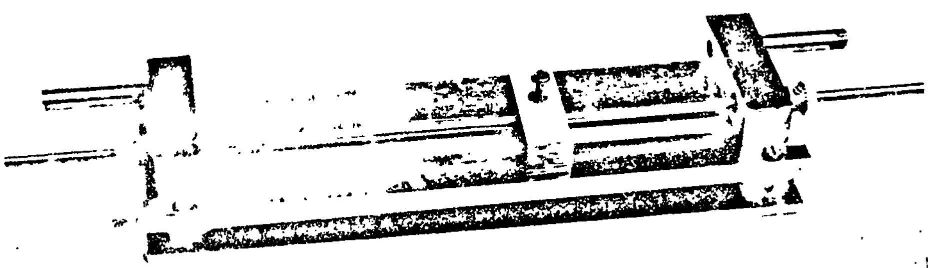


Figure 22. Upper Mirror Rack-and-Pinion Mount with Three-Point Angle Adjustment.

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APPENDIX A

Details of Derivation

$\tau(x)$

We have from Eq.(8) an expression for $\tau(x)$:

$$\tau(x) = (\tau_o + k \sin \omega_x x) \exp j(\phi_o + \alpha \sin \omega_x x) \qquad \text{A-1}$$

The identities in Eqs. (9), (10), and (11) :

$$\exp(j\alpha \sin \omega_x x) = \cos(\alpha \sin \omega_x x) + j\sin(\alpha \sin \omega_x x)$$

$$\exp(j\alpha \sin \omega_x x) = J_o(\alpha) + 2 \sum_{n=1}^{\infty} J_{2n}(\alpha) \cos 2n\,\omega_x x \qquad \text{A-2}$$
$$+ 2j \sum_{n=1}^{\infty} J_{2n+1}(\alpha) \sin(2n+1)\omega_x x$$

are used to expand the exponential expression in a Fourier series.

The substitution of Eq. (A-2) into Eq. (A-1) results in the expression:

$$\tau(x) = e^{j\phi_o} (\tau_o + k \sin \omega_x x)\big(J_o(\alpha) + 2J_2(\alpha) \cos 2\omega_x x +$$
$$+ 2 J_4(\alpha) \cos 4\omega_x x + \ldots + 2j(J_1(\alpha) \sin \omega_x x +$$
$$+ J_3(\alpha) \sin 3\omega_x x + \ldots) \big)$$

$$\tau(x) = e^{j\phi_o} (\tau_o J_o(\alpha) + \sin \omega_x x \, (k J_o(\alpha) + 2\tau_o j J_1(\alpha))$$
$$+ 2kJ_2(\alpha) \sin \omega_x x \cos 2\omega_x x + 2j J_1(\alpha) k \sin^2 \omega_x x$$
$$+ 2\tau_o J_2(\alpha) \cos 2\omega_x x + \ldots)$$

$$\tau(x) = e^{j\phi_o}(\tau_o J_o(\alpha) + \sin \omega_x x \, (k J_o(\alpha) + 2j J_1(\alpha)) +$$
$$+ 2k J_2(\alpha) \sin \omega_x x \, (1 - 2 \sin^2 \omega_x x) + 2jk J_1(\alpha) \left\{ \frac{1-\cos 2\omega_x x}{2} \right\}$$
$$+ 2\tau_o J_2(\alpha) \cos 2\omega_x x + \ldots)$$

$$\tau(x) = e^{j\phi_o} \Big(\tau_o J_o(\alpha) + jk\, J_1(\alpha) + \sin\omega_x x \,(k\, J_o(\alpha) + 2j\tau_o\, J_1(\alpha) + 2\,k\, J_2(\alpha)) - 4k\, J_2(\alpha) \sin^3\omega_x x + \cos 2\omega_x x \,(2\tau_o J_2(\alpha) - jkJ_1(\alpha)) + \ \ldots \Big)$$

$$\tau(x) = e^{j\phi_o} \Big(\tau_o J_o(\alpha) + jk\, J_1(\alpha) + \sin\omega_x x \,(k\, J_o(\alpha) + 2j\tau_o\, J_1(\alpha) + 2kJ_2(\alpha)) - 4kJ_2(\alpha) \big(\tfrac{1}{4}(3 \sin\omega_x x - \sin 3\omega_x x)\big) + \cos 2\omega_x x \,(2\tau_o J_2(\alpha) - jkJ_1(\alpha)) + \ \ldots \Big)$$

$$\tau(x) = e^{j\phi_o} \Big(\tau_o J_o(\alpha) + jkJ_1(\alpha) + \sin\omega_x x \,(k\, J_o(\alpha) + 2j\tau_o J_1(\alpha) - k\, J_2(\alpha)) + \cos 2\omega_x x \,(2\tau_o J_2(\alpha) - jkJ_1(\alpha)) + \sin 3\omega_x x \,(k\, J_2(\alpha) + \ldots) + \ldots \Big) \qquad \text{A-3}$$

Eq. (A-3) corresponds to Eq. (12) in the text.

APPENDIX B

WIRE COLOR CODING

1. Shielded Wires:

   1.- Tachometer terminals

   2.- $+V_{REF}$; Ground to capacitors

2. Colored Wires

   A. Left Reel Drive;

      1. Green & Yellow to Motor
      2. Blue $-V_{REF}$ to Potentiometer terminal
      3. Purple to Potentiometer Slider terminal

   B. Right Reel Drive:

      1. Brown & Black to Motor
      2. Red $-V_{REF}$ to Potentiometer terminal
      3. Orange to Potentiometer Slider terminal

   C. Capstan Motor Terminals:

      1. Grey & White
      2. Purple & Blue

3.. Digital Readout System:

   1. Miniature light - Red & Yellow
   2. Orange - V_{CC}
   3. Grey - Ground

4. Output Channels:

#1	Purple
#2	Blue
#3	White
#4	Brown
#5	Red
#6	Yellow