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RESULTS OF RAM-JET
BUTTERFLY MODEL TESTS

WTM-148

Prepared by: John A. Parchem
J. A. Parchem

Approved by: W C Nelson
W. C. Nelson

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I. SUMMARY

At the UMERI Supersonic Wind Tunnel during August and October, 1949, a series of tests at Mach 1.9 was conducted on a 12" ram-jet butterfly model. This non-burning ram-jet was used for the purpose of investigating the effect on flow in and about the model by periodic disturbances internally generated by a spinning butterfly. The main sources of data were high speed Fastax Schlieren and a Massa sound pressure microphone.

With butterfly exciting frequency varied from 0 to 940 cps, the resulting bow shock pulsation and internal static pressure variation frequencies proved to be a direct function of the exciting frequency. The one exception occurred at an exciting frequency of 50 cps where no shock pulsation was observed.

Experimentally, the natural frequency of the model was seen to be approximately 270 cps which was 85% of theoretical closed tube natural frequency. Agreement between the theoretical and experimental third harmonic was poor.

An attempt to induce bow shock pulsation by choking the internal model flow with high density screens met without success.

Several tests with diverse model configurations and operating conditions produced data that showed a tendency of the internal pressure to oscillate at approximately 725 cps.

II. INTRODUCTION

Early in 1949 a program was initiated at the UMERI Supersonic Wind Tunnel to investigate the effect of internal flow disturbances upon the flow in and about a ram-jet.

In May, 1949, the first-phase testing was carried out at Mach 1.9 using a 12-inch cold model ram-jet with a 1.5-inch diameter constant area duct simulating the burner and a 1:2 subsonic diffuser. The specific test purpose was to block the internal flow by a series of plugs with sharp-edged orifices of various diameters mounted at or near the model outlet. The model became choked only when a solid plug was used, in which case the bow shock pulsated with a frequency approximately 85% of the theoretical natural frequency. No shock pulsations occurred without model in choked condition. The report of these tests is contained in Reference 1.

October, 1949, found the second phase of the test program completed. The particular test objective was twofold. Primarily, the flow was made subject to periodic disturbances generated internal to the model by means of a spinning butterfly valve. The magnitude of the disturbances was controlled by different size butterflies. Exit conditions were regulated by a series of nozzles with diverse area ratios. Secondarily, an effort was made to produce bow shock pulsation by blocking internal flow with high density screens specifically designed to choke the model. The model used in the first-phase tests was merely modified to accommodate butterflies, nozzles, and screens. The test section Mach Number throughout was 1.9. All external flow phenomenon was recorded on high speed Schlieren motion pictures. Also, a sound pressure microphone was placed just downstream of the diffuser in order to measure the frequency and magnitude of any internal static pressure variations. No other data source was provided.

This memorandum's purpose is to report the results of the second-phase tests with little attempt to explain or draw conclusions from the data gathered.

In June of this year the third-phase tests are expected to take place. The present ram-jet model has been fitted with two cone-type central body diffusers. The cone angle for each is identical. However, downstream of the cone one central body will displace a larger volume of the simulated burner than the other. This modification will permit study of flow under shock swallowing conditions as well as any effects which internal volume changes might produce. Operation of the butterfly will not be affected by this installation. Without the central body, the model reverts to its present configuration so that repetition of previous tests can be conducted. This is the intent.

It is hoped that this will lead directly to the fourth phase - wind tunnel testing of a burning ram-jet.

III. DESCRIPTION OF MODEL AND ASSOCIATED EQUIPMENT

Ram-jet Butterfly Model:

The reader is referred to Figures 1, 2, 3, 4, and 5 contained in this section for all details of the model configuration, installation and accessory parts, such as butterflies, nozzles, screens, etc. Approximate dimensions can be scaled directly from the photographs.

Western Electric Fastax 16 mm. High Speed Camera:

Made by Western Electric (Bell Telephone Laboratories, Inc.), N.Y.
Model D-163269 Serial No. 16269 Speed Range 0-8000 frames/sec.
Film spooled in 100 ft. rolls especially for Fastax by Kodak.

Installation of camera is shown in Figure 5 of this section.

Massa Sound Pressure Microphone System Model GA-1007:

Made by Massa Laboratories, Inc., Cleveland
Microphone Model M-123S Serial No. 2 Employs ADP crystals
Microphone dia. = 3/16 in. Pressure sensitivity 4 microvolts/dyne/cm^2
Frequency response range 50 cyc - 250 kc.
Microphone linear to pressure magnitudes of several million dynes/cm^2
Preamplifier Model M-114B
Power Supply Model M-116D
Special Calibration Unit built by UMERI Controls Group
Range 0.0001, 0.001, 0.01, 1.0-5 psi
Ballantine Amplifier provided by Controls Group

Installation of microphone is shown in Figures 1, 2, 3, and 4.

Dumont Dual-Beam Cathode-Ray Oscilloscope:

Made by Dumont Laboratories, Inc., Passiac, N.J.
Type 297 Serial No. 159
115/230 V Single Phase 50 - 60 cycles 300 watts

This oscilloscope is shown in Figure 5.

Fairchild 35 mm. Camera:

Made for Dumont Laboratories by Fairchild
Type 314 Serial No. 113 Two Speeds 60 in/min and 60 in/sec
Ultra Speed Ansco Film in 100 ft. rolls

This camera is shown in Figure 5.

120 Cycle Pulser Unit:

This unit was designed and built by the UMERI Controls Group. It is used in conjunction with the Fastax camera and Dumont oscilloscope. In the Fastax camera is an argon timing light. The unit supplies voltage pulses of 120 cps (derived from the 60 cycle power line frequency) causing the argon light to pulse and in turn produce a short pip on the sound track of the film. Simultaneously, the pulse was sent to the oscilloscope on one of the beams to be recorded as a pip on the oscilloscope film. The width of the pulses is 1/11 of distance between pulses. Thus, a time reference is established. See Reference 2.

Butterfly Tachometer and Shaft Pulser:

This unit was also designed and built by the UMERI Controls Group. In operation it is similar to the 120 Cycle Pulser Unit. In this case, the voltage pulses from the butterfly shaft commutator (Figure 1) cause the same argon light to produce a pip on the Fastax film sound track simultaneous with a pip on the oscilloscope film. These pulses or pips have a ratio of width to distance between pulses of 1/20. The butterfly position was carefully coordinated with the commutator so that appearance of a pip indicates that the butterfly was fully closed (face of butterfly normal to the flow). Thus, there are two pips per revolution. In relation to the 120 cps pips the position and speed of rotation of the butterfly are known from two sources. See Figures 8 and 12 for reproduction of timing pips.

The pulser contains an electronic tachometer which is used for indicating nominal butterfly speeds. It proved quite inaccurate.

Figure 5 shows these pulser units. Reference 2 carries a complete description of the units as well as operation instructions and wiring diagrams.

Butterfly Motor:

Made by General Industries Co., Elyria, O.
Model 61400 D.C. (Universal) Series 24 V 7 amp
1/8 hp 8500 rpm (1 minute)

The motor was driven from a.c. current. It can be seen in Figure 1.

Powerstat (Variac):

Made by Superior Electric Co., Bristol, Conn.
Type 116 Prim. V 115 50 - 60 cyc 7.5 max. output

Two were used, one to control butterfly motor speed and the other to control Fastax camera speed. Their relation to the other equipment is to be seen in Figure 5.

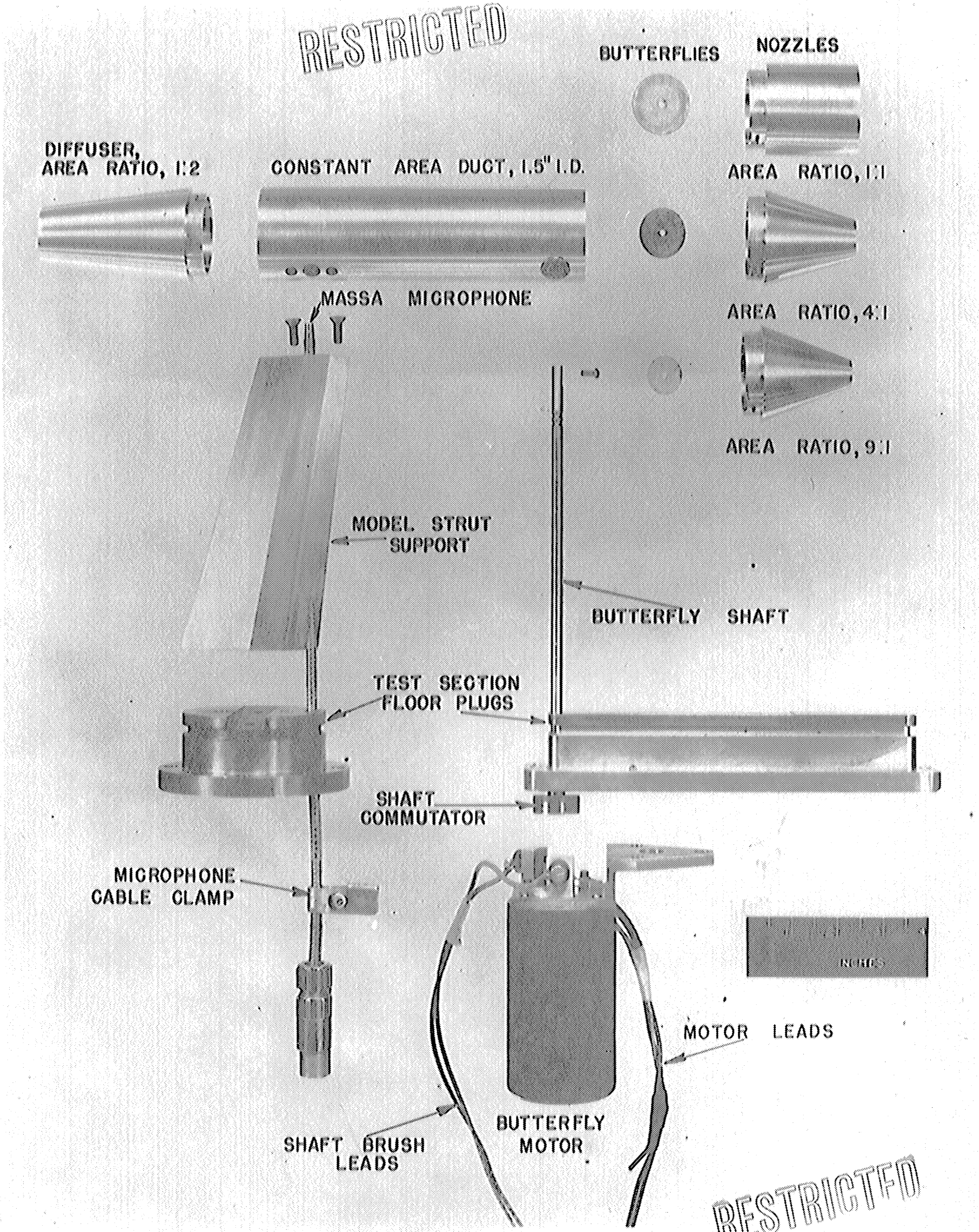
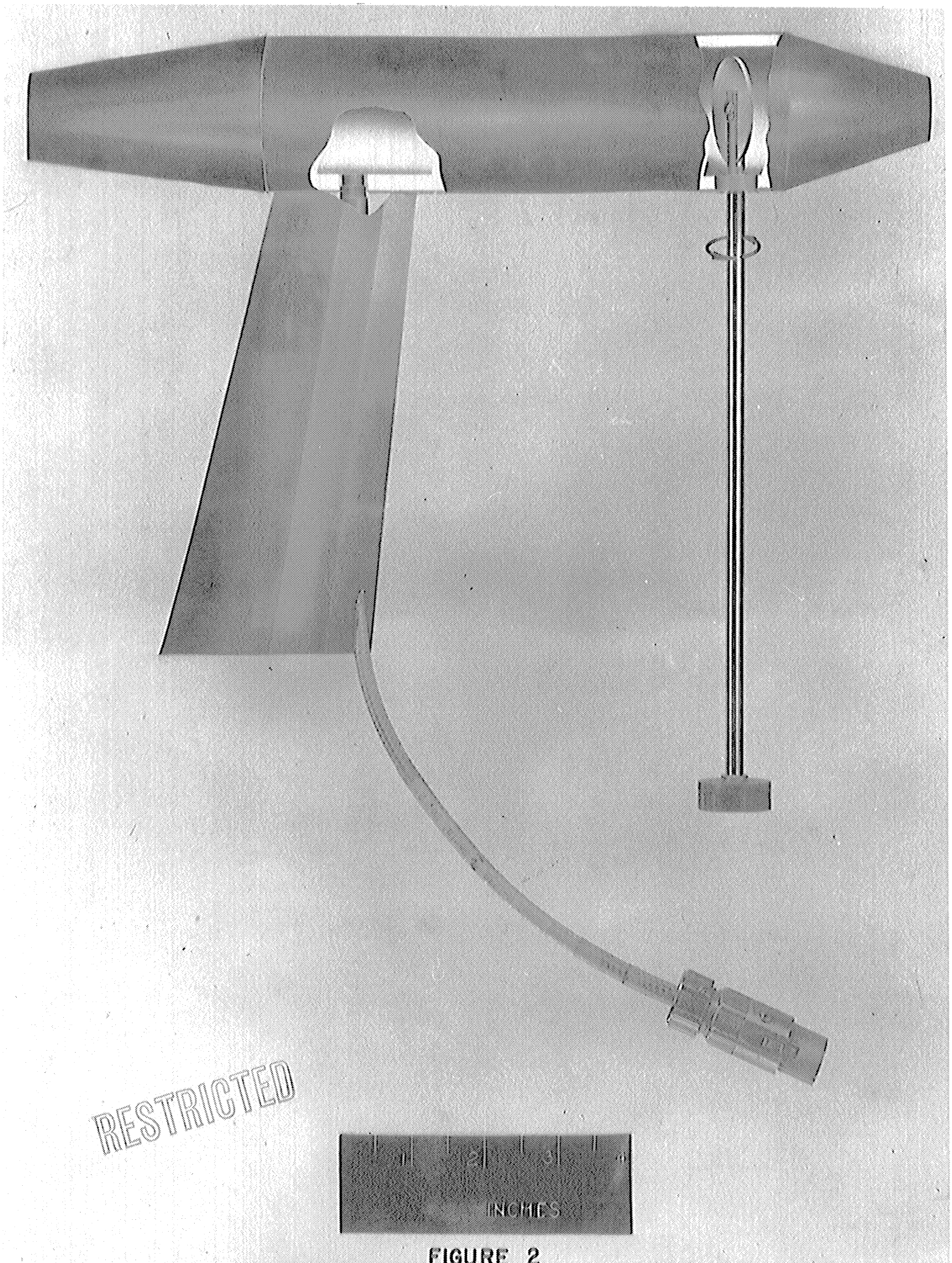


FIGURE 1

EXPLODED VIEW OF RAM-JET BUTTERFLY MODEL
WITH MASSA PRESSURE MICROPHONE AND BUTTERFLIES



RESTRICTED

FIGURE 2
CUT-AWAY VIEW OF MASSA PRESSURE MICROPHONE AND BUTTERFLY MOUNTED WITHIN MODEL.

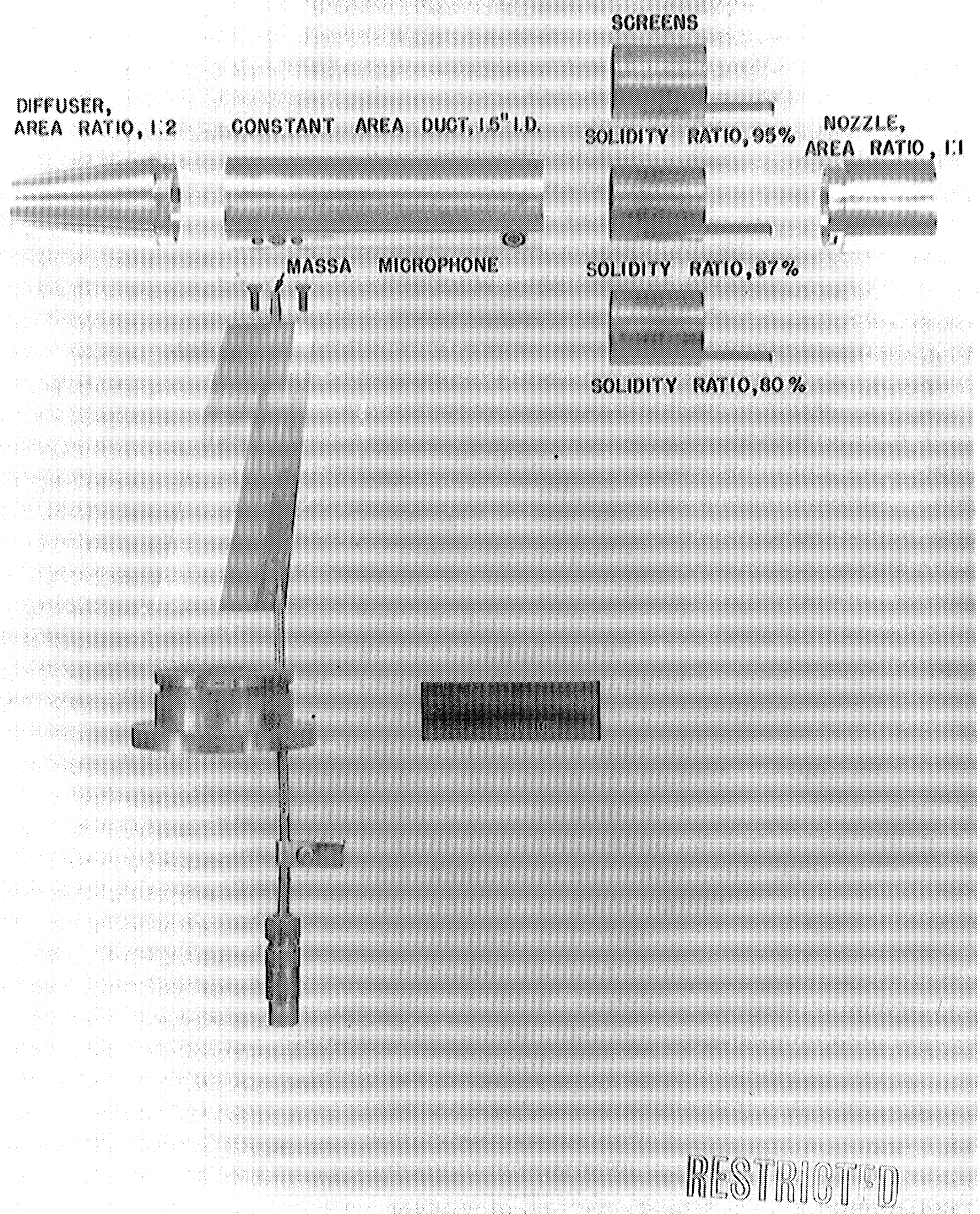


FIGURE 3

EXPLODED VIEW OF RAM-JET BUTTERFLY MODEL
WITH MASSA PRESSURE MICROPHONE AND FLOW CHOKING SCREENS

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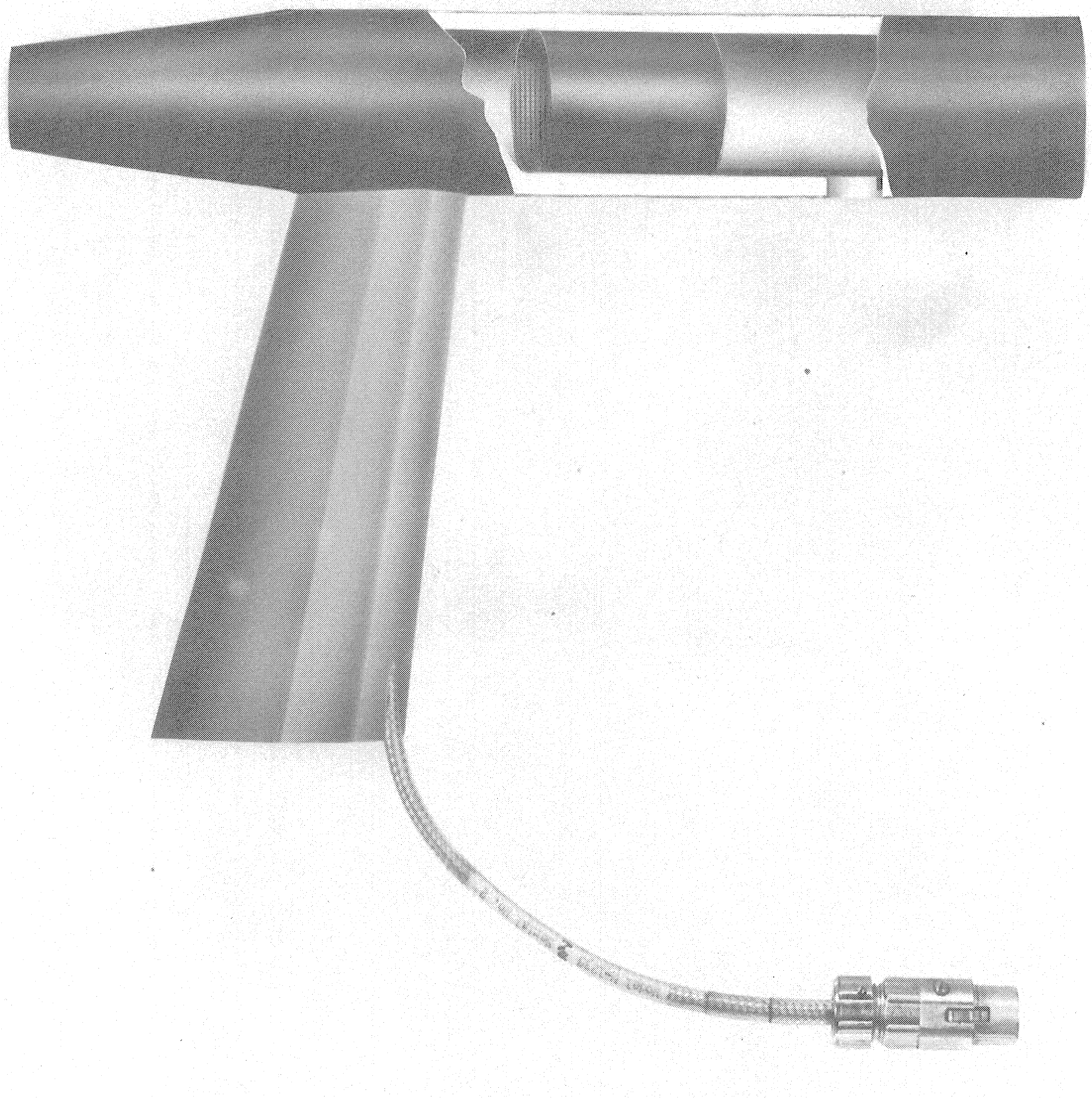

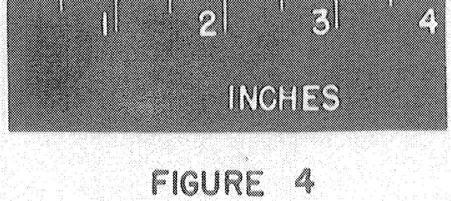

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FIGURE 4
CUT-AWAY VIEW OF FLOW CHOKING SCREEN MOUNTED WITHIN MODEL

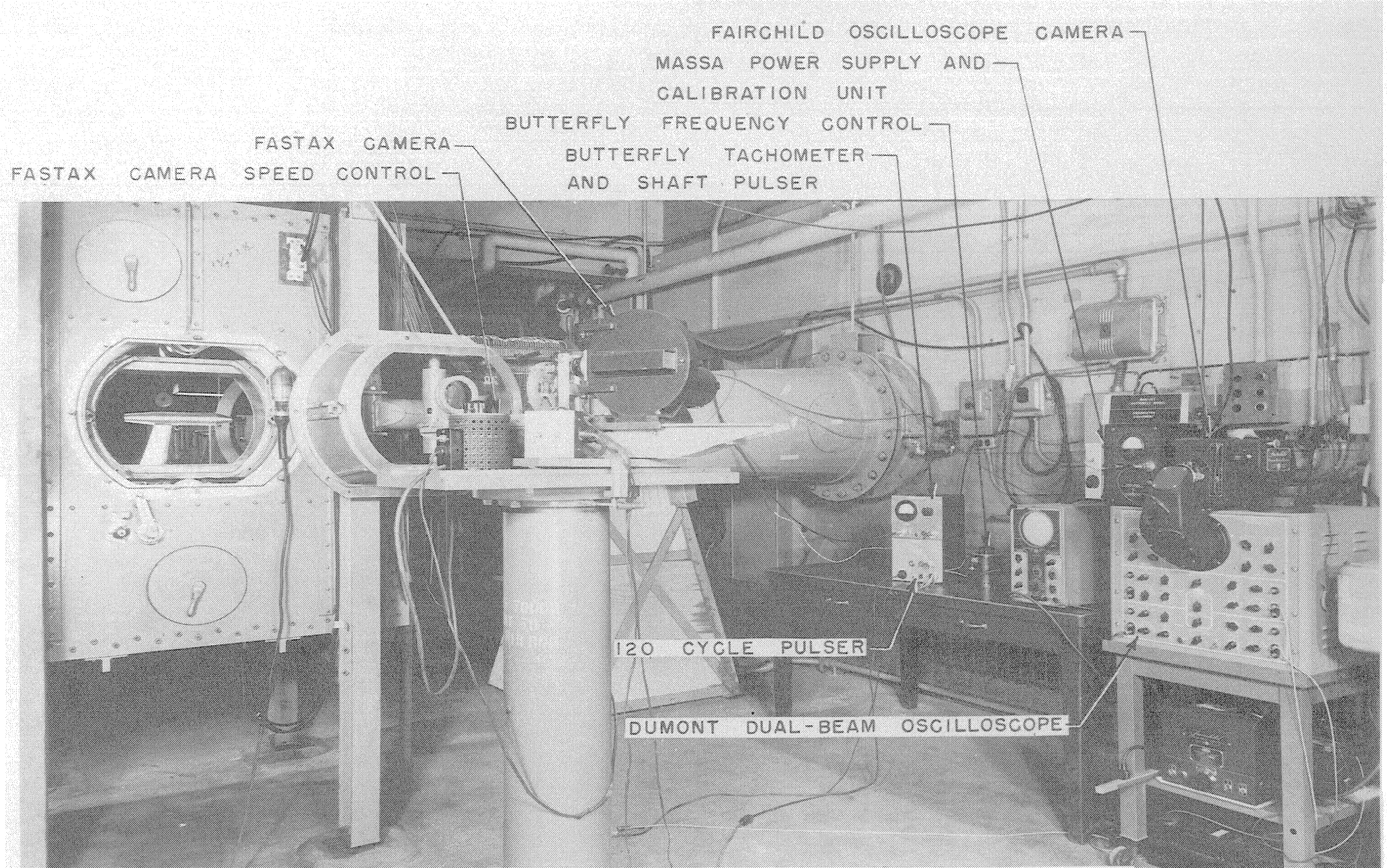


FIGURE 5

RAM - JET BUTTERFLY MODEL ASSOCIATED EQUIPMENT

IV. TEST CONDITIONS

A total of 26 runs was made on August 12, October 12, 13, and 14, 1949. The program was interrupted in August because of mechanical difficulties encountered in operating the butterfly shaft.

As has already been pointed out all runs were made at a test section Mach Number of 1.9. The dew point ranged from -8 to -23°F. The reservoir temperature always fell between 53 and 60°F except the runs in August which were at 79°F. The reservoir or barometric pressure was consistently between 29.33" Hg and 29.56" Hg. The tank vacuum immediately preceding a run never fell below 24" Hg nor above 27" Hg. The length of test runs was generally about 7 seconds, although one was as long as 13 seconds and one was of 6 seconds length. The model was orientated at zero angle of attack and yaw.

The Fastax Schlieren yielded data regarding the relation between bow shock pulsation frequency, other flow phenomenon and the butterfly exciting frequency. The Massa microphone, by way of the oscilloscope film, indicated magnitudes and frequencies of internal static pressure variations in comparison with butterfly exciting frequencies. These were the important variables outside of butterfly size and nozzle area ratio.

The accuracy of all frequency measurements, except where noted, is not worse than ± 1.5%. With the Massa calibration unit used, the pressure differentials are subject to as much as ± 20% error. Improvement of the calibration unit, shortly to be undertaken, will allow considerable reduction in this pressure differential error.

Since the Massa microphone was being used for the first time in this organization it was to be expected that certain difficulties would be encountered. As a result there was an insufficient number of pressure differential points to provide a firm foundation for plotting curves. Figure 7A is an exception but even this is not quantitative.

On the oscilloscope film, time correlation between the timing trace and pressure wave trace is subject to error since it was not possible to maintain at the same level the neutral position of both beam images on the oscilloscope screen. It is estimated that this level variation might be as high as ±0.04 inches on the screen. This level variation represents a possible time correlation error of ± 1/400 seconds between the two traces on the oscilloscope film at film speeds of 50 to 60 in./sec.

V. COMMENTARY ON TEST RESULTS

Butterfly Tests:

Inspection of Figure 6 shows that bow shock pulsation frequency varies directly with butterfly exciting frequencies from 0 to 940 cps - except for two points at butterfly frequency of approximately 50 cps. Whenever the amplitude of the shock pulsation got small, as in the case with 0.75 in. butterfly, the frequency was impossible to measure. Therefore it is possible that the shock pulsation amplitude for these two points was too small to detect. The Figures 8 and 12 show typical Fastax from which these data were obtained. Also refer to Table 1.

Figure 7 of pressure wave frequency variation with butterfly exciting frequency duplicates the results obtained from the Fastax. In this case, the 50 cps points were obtained from oscilloscope film, whereupon there was considerable noise. Again it is possible that the oscillation defied detection. However, these 50 cps points were accompanied by another phenomenon to be pointed out later. Examples of oscilloscope film yielding these data can be seen on Figures 9, 10, 11, and 12 (especially Figure 10, Run Nos. 49-10-14-14 and 49-10-14-12).

Very interesting information was acquired from Run No. 49-10-14-10. In this instance the butterfly accelerated from rest to 900 cps. Even though this did not represent steady state conditions there seemed to be sufficient evidence that the natural frequency of the model is approximately 270 cps. This is about 85% of the theoretical closed tube natural frequency. The third harmonic of the model appears to be about 700 cps, which does not agree too well with theory. These facts are to be noted on Figure 7A, which was obtained from film reproduced as Figure 11. It is to be seen that the maximum pressure differential occurs at butterfly exciting frequency of 700 cps. However, Figure 7B shows that the acceleration was appreciably lower at the 700 cps peak than the 270 cps peak. This can easily account for the distorted picture.

Reducing the size of butterfly used from 1.25 inches to 0.75 inches caused a drop in pressure differential by approximately 90% at similar butterfly frequencies.

In every run but one, using an open tail pipe for a nozzle, the model was choked irrespective of butterfly speed. This is evidence that nozzles with smaller area ratios should have been used.

Flow Choking Screen Tests:

On the basis of cold model internal flow blocking tests by use of plugs (Reference 1) it was thought that bow shock pulsation could be induced by using high density screens. Screens of 80%, 87%, and 95% solidity ratio were used and no shock pulsation was noticeable. In each case the model was choked. Increasing the solidity ratio resulted in movement of the bow shock upstream. Figure 13 has reproduced oscilloscope films from runs with the different screens.

During several runs there appeared on the oscilloscope film unsteady intervals which displayed a pressure wave frequency between 700 and 750 cps. This occurrence accompanied each of the flow choking screen runs. It also showed up during the runs where the butterfly frequency was 50 cps and one where the butterfly was known to be stationary. The model was choked in each case and the Fastax gave no evidence of bow shock pulsation. Table 1 and Figure 14 indicate the evidence.

VI. DATA REDUCTION

This section is divided into three main parts. The first, Table 1, consists of a complete summary of all important data recorded during the tests.

The second part contains all information, in detail, obtained from the Fastax Schlieren motion pictures. The method by which the butterfly and bow shock pulsation frequencies were calculated is as follows. From the 120 cps timing pips on the sound track (Figure 8) the film speed in frames per second for a certain length of film was determined. During this length, the number of frames passing per cycle ($\frac{1}{2}$ revolution from one butterfly pip to the next) of butterfly operation was read. Dividing the film speed by the frames per butterfly cycle yielded the butterfly exciting frequency. The computation of the shock pulsation frequency was similarly carried out. Since the butterfly motion is rotary the speed in rpm for each frequency is given.

The last part presents all data reduced from the oscilloscope motion pictures. The determination of pressure wave and butterfly frequencies was identical with the method used in analyzing the Fastax film. In most cases, the frequencies were checked by noting the number of cycles occurring during one 1/120 second cycle (Figures 9 and 11) and then multiplying by 120. This eliminated the intermediate step of computing the film speed. Where the film is accelerating, this latter method was preferred. Obviously the pressure differential magnitudes were acquired merely by comparing the wave in question with the associated calibration curve.

The chronological order of presenting the Fastax and oscilloscope data follows that used in Table 1.

Fastax Schlieren Data

Fastax No. 9 (Run No. 49-8-12-1):

Film Speed frames/sec.	Butterfly Exciting Freq. frames/cyc.	cps	rpm	Bow Shock Pulsation Freq. frames/cyc.	cps
4560	8.0	570	17,100	8.0	570
4560	7.9	577	17,310	8.0	570
4560	7.85	581	17,430	7.85	581
4320	7.2	600	18,000	7.2	600
3960	6.5	610	18,300	6.5	610
3600	5.8	620	18,600	5.8	620
3120	5.0	624	18,720	5.0	624
2760	4.4	627	18,810	4.4	627
2520	4.0	630	18,900	4.0	630

Intermittently some of the butterfly pips seem to be missing. One of the shaft contacts must be faulty since the same pip is missing repeatedly.

It was the intention to accelerate the butterfly during film exposure. Data shows the opposite happened. The film was over-exposed so that the flow field could not be seen except for one bow shock reflection above and downstream of model. The oscillation of this reflection was used to determine shock frequency.

An expansive exhaust from the nozzle was noted to oscillate at same frequency as butterfly.

Fastax No. 10(Run No. 49-8-12-2):

Butterfly was stationary. Model was not choked at any time during film exposure and no shock pulsations were detected. Film was over-exposed.

Fastax No. 11 (Run No. 49-8-12-3)

During exposure of the film the model was choked during three intervals. The period between first and second interval was about 0.46 seconds and between second and third interval about 0.28 seconds. Except for these intervals the model was not choked.

It seems certain that the butterfly was not rotating steadily. It was probably turning erratically or wobbling back and forth. A study of the sound track showed that the butterfly was in its most closed position during the three instances where the model was choked. This is evidence that the model can be choked with the combination of 1.25 in. butterfly and 1.5 in. nozzle.

At the time of the test run considerable confusion was experienced regarding this run since the butterfly tachometer indicated the butterfly to be turning at approximately 2500 rpm. It was later discovered that the tachometer would indicate 2500 rpm if the 120 cps pulser unit was on while the butterfly was stationary.

The film was not sufficiently good in quality to print for this report.

Fastax No. 18 (Run No. 49-10-14-1):

The butterfly was not turning but was orientated in its most open position. No shock pulsation was detectable. The model was choked throughout run. See Figure 8 for a selected strip of this film.

Fastax No. 16 (Run No. 49-10-13-6):

Film Speed frames/sec.	Butterfly Exciting Freq. frames/cyc.	cps	rpm	Bow Shock Pulsation Freq. frames/cyc.	cps
3000	13.7	219	6570	13.0	231
3340	15.3	218	6540	16.0	209
3660	16.7	219	6570	17.0	215
3840	17.5	219	6570	17.5	219
4030	18.3	220	6600	18.0	224
4220	19.0	222	6660	19.5	217
4500	20.2	223	6690	20.5	220
4710	21.2	222	6660	21.0	224
4840	21.8	222	6660	22.0	220
4990	22.5	222	6660	22.5	222

The bow shock pulsed quite violently while the model was in a choked condition. It appeared that the bow shock was in its most downstream position when the butterfly was approximately closed. Actually, the shock started moving upstream approximately 0.001 seconds before the butterfly fully closed. See Figures 8 and 12.

Fastax No. 17 (Run No. 49-10-13-7):

Film Speed frames/sec.	Butterfly Exciting Freq. frames/cyc.	cps	rpm	Bow Shock Pulsation Freq. frames/cyc	cps
2980	7.4	403	12,090	7.0	426
3360	8.5	395	11,850	8.5	395
3720	9.5	392	11,760	9.5	392
3920	10.0	392	11,760	10.0	392
4120	10.5	393	11,790	10.5	393
4300	11.0	391	11,730	11.0	391
4500	11.5	391	11,730	11.5	391
4720	12.2	387	11,610	12.0	393
4920	13.0	379	11,370	13.0	379

Fastax No. 17 (Run No. 49-13-7): Cont'd

Bow shock definitely pulsed but not so violently as in Run No. 49-10-13-6. The shock hesitates somewhat while it is in its downstream position. It appears that the shock is upstream when the butterfly is closed. This condition is opposite from that for Run No. 49-10-13-6. See Figure 8.

Fastax No. 14 (Run No. 49-10-13-4):

Film Speed frames/sec	Butterfly Exciting Freq. frames/cyc.	cps	rpm	Bow Shock Pulsation Freq. frames/cyc	cps
3000	4.7	638	19,140	4.7	638
3320	5.2	639	19,170	5.25	632
3700	5.8	638	19,140	5.8	638
4020	6.3	638	19,140	6.3	638
4220	6.67	633	18,990	6.6	639
4500	7.1	634	19,020	7.1	634
4680	7.25	645	19,350	7.25	645
4890	7.6	644	19,320	7.67	638
4980	7.8	638	19,140	7.8	638

The bow shock is again definitely pulsing. The amplitude of the shock pulsation is decreasing as the butterfly exciting frequency decreases.

The shock is in its most downstream position about 0.0005 seconds before butterfly closes. See Figure 8.

Fastax No. 25 (Run No. 49-10-14-9):

Film Speed frames/sec	Butterfly Exciting Freq. frames/cyc.	cps	rpm	Bow Shock Pulsation Freq. frames/cyc	cps
3000	3.2	938	28,140	3.2	938
3300	3.2	943	28,290	3.5	943
3580	3.8	942	28,260	3.8	942
3910	4.15	943	28,290	4.15	943
4200	4.33	970	29,100	4.33	970
4380	4.67	938	28,140	4.7	933
4500	4.8	938	28,140	4.8	938
4680	5.0	937	28,110	5.0	937
4800	5.1	942	28,260	5.1	942
4920	5.2	947	28,410	5.3	930

The amplitude of the bow shock pulsation is quite small but still large enough to make frequency measurements. The bow shock is downstream just before the butterfly closes. The butterfly shaft was seen to whip badly but its frequency was not measurable. See Figure 8.

Fastax No. 13 (Run No. 49-10-13-2):

Film Speed frames/sec.	Butterfly Exciting Freq. frames/cyc	cps	rpm	Bow Shock Pulsation Freq. frames/cyc	cps
3000	11.3	266	7980	11.0	273
3290	12.5	263	7890	13.0	253
3600	13.5	266	7980	13.5	266
3960	14.8	265	7950	15.0	262
4200	15.7	268	8040	16.0	262
4440	16.5	269	8070	16.5	269
4680	17.3	270	8100	17.5	268
4860	18.0	270	8100	18.0	270

Fastax No. 13 (Run No. 49-10-13-2) Cont'd

The bow shock frequency was difficult to determine since the compression areas were light on the film negative. Shock reflections near tail of model proved to be fairly successful in computing pulsation frequency. No accurate time correlation between shock and butterfly position because of the light compression areas.

Fastax No. 12 (Run No. 49-10-13-1):

Film Speed frames/sec.	Butterfly Exciting Freq. frames/cyc	cps	rpm
3120	5.1	612	18,360
3240	5.25	617	18,510
3360	5.33	630	18,900
3600	5.6	643	19,290
3700	6.0	617	18,510
3850	6.3	612	18,360
4060	6.6	615	18,450
4280	6.7	639	19,170
4440	6.9	643	19,290
4560	7.25	629	18,870
4680	7.6	616	18,480
4800	7.5	640	19,200

The bow shock definitely pulsed. However, no accurate determination of shock frequency could be made for two reasons. First, the amplitude of shock pulsation was extremely small. Second, the compression areas on the negative were light. Nevertheless, comparison with Fastax #14, wherein butterfly frequency was 638 cps showed that shock frequencies for this run were about the same order of magnitude as the butterfly frequencies.

Fastax No. 12 (Run No. 49-10-13-1) Cont's

The butterfly frequency is seen to be unsteady. The butterfly shaft was known to be near a resonant condition. Review of film shows shaft is whipping. The average butterfly exciting frequency was taken to be 626 cps.

Fastax No. 30 (Run No. 49-10-14-14):

Film Speed frames/sec	Butterfly Exciting Freq. frames/cyc	cps	rpm
2580	47.5	54	1620
3120	62	50	1500
4010	89	45	1350
4500	106	42	1260
4920	120	41	1230
4960	120	41	1230

The model was choked throughout run but the flow was steady with no apparent bow shock pulsation. There appeared to be some expansive exhaust issuing from the model outlet. This exhaust oscillated at same frequency as the butterfly.

Fastax No. 28 (Run No. 49-10-14-12)

Film Speed frames/sec.	Butterfly Exciting Freq. frames/cyc	cps	rpm
4890	91	54	1620
4950	113	44	1320
4800	142	34	1020
4650	201	23	690
4320	-	0	0

The model was choked throughout run but the flow was steady with

Fastax No. 28 (Run No. 49-10-14-12) Cont'd

no apparent bow shock pulsation. There appeared to be some expansive exhaust issuing from the model outlet. This exhaust oscillated at same frequency as butterfly.

Fastax No. 27 (Run No. 49-10-14-11)

Film Speed frames/sec	Butterfly Exciting Freq. frames/cyc	cps	rpm
5040	47.0	107	3210
5040	47.0	107	3210
4900	45.5	108	3240
4680	44.5	105	3150
4380	41.7	105	3150
4080	38.2	107	3210
3840	36.1	106	3180
3240	30.8	105	3150
2640	25.1	105	3150

The model was choked and the bow shock pulsed. However, the amplitude was too small to make any frequency calculations. However, it is estimated that shock frequency was the same order of magnitude as butterfly frequency.

Fastax No. 29 (Run No. 49-10-14-13)

Film Speed frames/sec.	Butterfly Exciting Freq. frames/cyc	cps	rpm
5040	22.7	222	6660
4920	22.0	224	6720
4800	21.5	223	6690
4560	20.3	224	6720
4320	19.25	224	6720

Fastax No. 29 (Run No. 49-10-14-13) Cont'd

Film Speed frames/sec.	Butterfly Exciting Freq. frames/cyc	cps	rpm
3950	17.5	226	6780
3600	15.7	229	6870
3240	14.1	230	6900
2880	12.3	235	7050

The model was choked and bow shock pulsed. However, the amplitude was too small to make any frequency calculations. It is estimated that shock frequency was the same order of magnitude as butterfly frequency. Also, it appeared that bow shock pulsation amplitude was greater than that for Fastax No. 27. See Figure 12.

Fastax No. 19 (Run No. 49-10-14-2):

Film Speed frames/sec	Butterfly Exciting Freq. frames/cyc	cps	rpm
5040	15.0	336	10,080
5040	15.1	334	10,020
4920	14.7	335	10,050
4800	14.4	333	9,990
4500	13.4	336	10,080
4260	12.6	338	10,140
3820	11.4	335	10,050
3360	10.0	336	10,080
3000	9.0	333	9,990

The model was choked and bow shock pulsed. However, the amplitude was too small to make any frequency computations. It is estimated that shock frequency was the same order of magnitude as butterfly frequency.

Fastax No. 26 (Run No. 49-10-14-10)

Film Speed frames/sec	Butterfly frames/cyc	Exciting Freq. cps	Exciting Freq. rpm
4920	4.9	1003	30,090
4920	4.9	1003	30,090
4740	4.8	987	29,610
4500	4.6	979	29,370
4320	4.45	971	29,130
3960	4.25	932	27,960
3720	4.1	908	27,240
3370	3.9	864	25,920
3000	3.65	822	24,660
2520	3.4	741	22,230
1800	3.1	580	17,400
1560	3.0	520	15,600

The model was choked and bow shock pulsed. The amplitude of pulsation was very minute. Therefore, no shock frequencies were calculated. It was estimated that shock frequencies were of same order of magnitude as butterfly frequencies.

Fastax Nos. 15 and 24 (Run Nos. 49-10-13-5 and 49-10-14-7):

In these runs the butterfly was stationary. The model was choked but no shock pulsation was evident.

Fastax Nos. 20, 21, 22, 23 (Run Nos. 49-10-14-3, -4, -5, -6):

In each instance the presence of the internal screens caused the model to be choked. However, there was no noticeable shock pulsation. It appeared that the bow shock was displaced upstream with increased solidity ratio of screens used.

Data from Massa Microphone:

Oscilloscope Film No. 49-10-14-1:

Calibration curve (crest to trough): 0.1 psi = 0.13 in. The pressure trace shows no periodicity - only noise. The pressure differential is 0.1 psi. The butterfly was stationary in its most open position. See Figure 9.

Oscilloscope Film No. 49-10-13-6:

Calibration curve: 1.0 psi = 0.27 in. The butterfly exciting frequency was 237 cps. The pressure wave frequency was 237 cps. The pressure wave differential was 2.7 psi. The high pressure side of the wave went slightly off the record. However, this was taken into account in measuring the differential. The maximum film speed was 59.40 in/sec. See Figures 9 and 12.

Oscilloscope Film No. 49-10-13-3:

Calibration curve: 1.0 psi = 0.17 in. The intensity of the 120 cps timing pips and butterfly frequency pips was too weak to provide a basis for any frequency measurements. Knowing the nominal film speed as 60 in./sec. the pressure wave frequency was estimated as 358 cps. It is certain that the butterfly was rotating. The pressure wave differential was 0.37 psi. See Figure 9.

Oscilloscope Film No. 49-10-13-7:

The exact calibration is doubtful. It was not recorded at the time of the run. Later questioning of the oscilloscope operator produced evidence that the calibration was 1.0 psi = 0.27 in. On this basis the pressure wave differential was 1.85 psi. The 120 cps timing pips and butterfly were illegible. From the nominal film speed of 60 in./sec. a pressure wave frequency of 375 cps was estimated. It is certain that the butterfly was rotating. See Figure 9.

Oscilloscope Film No. 49-10-14-9:

Calibration curve: 0.1 psi =.09 in. The butterfly exciting frequency was 923 cps. The pressure wave is somewhat obscure but quite regular. The calibration should have been in 1.0 psi range observing the maxima and minima of the trace. Nevertheless, it can be said that the pressure wave differential exceeds 0.85 psi. Even though the pressure trace is obscure it is certain by inspection that the pressure wave frequency is also 923 cps. See Figure 9.

Near the end of the record the butterfly decelerated from 923 cps to 570 cps. It is quite interesting to watch the pressure wave change shape as the butterfly slows. The pressure wave differential decreases as the butterfly frequency decreases. At butterfly frequency of 630 cps the pressure wave differential is approximately 0.5 psi. This value agrees quite well with pressure wave differential of 0.57 psi at butterfly exciting frequency of 628 cps obtained during Run No. 49-10-13-1. The butterfly diameter was 1.25 inches in either case. During this region of butterfly deceleration it proved impossible to measure pressure wave frequency since the wave pattern changed so rapidly.

Oscilloscope Film No. 49-10-13-2:

Record was void because of operating difficulties.

Oscilloscope Film No. 49-10-13-1:

Calibration curve: 1.0 psi = 0.175 in. There were no 120 cps timing pips or butterfly frequency pips. Knowing that the nominal film speed was 60 in./sec. the pressure wave frequency was estimated as 628 cps. It is certain that the butterfly was rotating. The pressure wave differential was 0.57 psi.

Oscilloscope Film No. 49-10-14-14:

Calibration curve: 0.1 psi = 0.195 in. The butterfly exciting frequency was 50 cps. The pressure trace is mostly noise. There are intervals, however, which display wave periodicity of approximately 750 cps. During these intervals the maximum pressure wave differential is about 0.062 psi. It seems there is no correlation between butterfly position and the appearance of these 750 cps intervals. See Figures 10 and 14.

Oscilloscope Film No. 49-10-14-12:

Calibration curve: 0.1 psi = 0.13 in. The butterfly exciting frequency is 56 cps. The pressure trace is mostly noise. There are intervals, however, which display wave periodicity of approximately 750 cps. During these intervals the maximum pressure wave differential is about 0.075 psi. There seems to be no correlation between butterfly position and the appearance of these 750 cps. intervals. See Figure 10.

Oscilloscope Film No. 49-10-14-11:

Record was void because of operating difficulties.

Oscilloscope Film No. 49-10-14-13:

Calibration curve: 0.1 psi = 0.09 in. The butterfly exciting frequency was 218 cps. The pressure wave frequency was 218 cps. The pressure wave differential was 0.245 psi. See Figures 10 and 12.

Oscilloscope Film No. 49-10-14-2:

Calibration curve: 0.1 psi = 0.08 in. The butterfly exciting frequency was 336 cps. The pressure wave frequency was 336 cps. The pressure wave differential was 0.200 psi. See Figure 10.

Oscilloscope Film No. 49-10-14-10:

There was no calibration curve. During this run the butterfly was made to accelerate from 0 to 1050 cps (31,500 rpm) in approximately 2.35 seconds. The velocity and acceleration characteristics of the butterfly as taken from the film are tabulated as follows:

Velocity - time		Acceleration - time			
Time	Butterfly Exciting Freq.	Time	Butterfly Exciting Freq.	Butterfly Acceleration	a/a_{100}
sec. x120	cps	sec. x120	cps	cps / 1/120 sec.	%
0	0	1.0	100	51.9	100
1.0	100	4.3	200	36.7	71
4.3	200	6.8	275	23.6	46
8.0	300	10.3	365	28.6	55
11.7	400	11.7	400	22.8	44
14.0	450	16.3	475	12.4	24
18.0	500	20.7	550	22.6	44
20.7	550	25.3	635	14.3	28
23.0	600	30.3	693	9.1	18
26.6	650	37.8	740	4.2	8
31.0	700	40.3	755	8.1	16
39.7	750	42.8	780	15.2	29
43.9	800	45.3	810	5.4	10
51.7	850	51.7	850	4.8	9
65.7	900	65.7	900	2.4	5

Oscilloscope Film No. 49-10-14-10 : Cont'd

In the above table a_{100} is the acceleration at butterfly frequency of 100 cps. The table carries to 900 cps only, because higher frequencies were accompanied by a complex pressure wave whose frequency was impossible to ascertain accurately. The pressure wave frequency clearly follows in magnitude the butterfly frequency up to 900 cps. See Figures 7B and 11.

Even though no quantitative measurement of the pressure differentials was possible, qualitatively there was considerable information. The pressure wave differential variation with butterfly exciting frequency is tabulated below. This information was not taken directly from the film but from a print of the film magnified 2.5 times.

Butterfly Exciting Freq. cps	Pressure Wave Differential inches	$\frac{\Delta p}{\Delta p_{max}}$ %	Butterfly Exciting Freq. cps	Pressure Wave Differential inches	$\frac{\Delta p}{\Delta p_{max}}$ %
0	.10	5	600	.55	27
100	.12	6	625	.75	37
150	.27	13	650	1.33	66
200	.36	18	675	1.86	92
250	.48	24	700	2.02	100
270	.56	28	710	1.82	90
300	.43	21	720	.61	30
340	.35	17	730	.68	34
380	.44	22	760	1.07	53
400	.40	20	800	1.07	53
450	.35	17	850	1.18	58
500	.35	17	900	.90	45
550	.46	23			

The theoretical closed tube natural frequency of the model is 315 cps. On this basis the peak pressure should have occurred at approximately the same butterfly exciting frequency. There is a peak at 270 cps. Doubtlessly, the magnitude of it has been greatly affected by the high acceleration of the butterfly at that frequency. Previous tests on this same model showed that the measured natural frequency was about 85% of theoretical. In this case 270 cps is also about 85% of 315 cps. The much higher pressure differential peak at 700 cps is probably the third harmonic showing up. At this frequency the butterfly acceleration is much lower.

It is interesting to note that the pressure wave patterns at 220 and 340 cps agree quite well with the steady butterfly frequencies of 218 and 336 cps reported for Oscilloscope Film Nos. 49-10-14-13 and 49-10-14-2. The model configurations were identical in each instance. See Figures 7A, 7B and 11.

Oscilloscope Film No. 49-10-13-5:

This record consisted of noise only. The pressure wave differential was negligible.

Oscilloscope Film No. 49-10-14-7:

Calibration curve: 0.1 psi = 0.11 in. Butterfly is stationary. The pressure trace is mostly noise. However, there are intervals which display periodicity of 700 - 750 cps. During these intervals, the maximum pressure differential was about 0.1 psi. Near the end of the record the butterfly closed with no apparent change in wave pattern.

Oscilloscope Film No. 49-10-14-8:

Calibration curve: 0.1 psi = 0.08 in. The useful part of the record is very short. The rest is a pressure trace during the tunnel stopping process. Before tunnel stopping, the pressure trace looked very much like that for Run No. 49-10-14-7. The pressure wave differential is 0.1 psi.

Oscilloscope Film No. 49-10-12-1:

Calibration curve: 1.0 psi = 0.19 in. In this run the Massa microphone was isolated from the airstream by a wax plug. This was done in order to check the noise level of all operating equipment. Butterfly frequency was nominally 270 cps. The pressure trace has no measurable noise. However, there are low amplitude peaks of approximately 0.1 psi. These peaks are all troughs (low pressure) with no crests when compared to the mean line. They show little periodicity.

Oscilloscope Film No. 49-10-12-2:

Calibration curve: 1.0 psi = 0.19 in. The Massa microphone was isolated from the airstream by the same method and for the same purpose as in Run No. 49-10-12-1. The nominal butterfly frequency was 600 cps. Again, the trace showed pressure troughs and no crests. The maximum differential of these troughs was 0.2 psi. There is a slight amount of noise pick-up.

Oscilloscope Film No. 49-10-14-3:

Calibration curve: 0.1 psi = 0.27 in. Butterfly assembly was not installed. The 95% solid flow choking screen was in place. The pressure wave pattern showed considerable noise. During certain intervals there seems to be some pressure wave periodicity but it is unsteady. During these intervals the pressure wave frequency is approximately 750 cps. The maximum pressure wave differential is 0.045 psi. See Figures 13 and 14.

Oscilloscope Film No. 49-10-14-4:

Calibration curve: 0.1 psi = 0.27 in. Butterfly assembly was not installed. The 87% solid flow choking screen was in place. The wave pattern showed high frequency noise. Quite frequently there occurred intervals during which the pressure wave was periodic. These intervals do not appear to be periodic in their occurrence - the whole pattern is unsteady. During the intervals of periodicity the wave frequency is approximately 700 cps. The maximum pressure differential varies between 0.04 and 0.06 psi. See Figure 13.

Oscilloscope Film No. 49-10-14-5:

Calibration curve: 0.1 psi = 0.27 in. Butterfly assembly not installed. The 80% solid flow choking screen was in place. The record was identical with No. 49-10-14-4 except that the maximum pressure wave differential varied from 0.05 to 0.10 psi.

Oscilloscope Film No. 49-10-14-6:

The record was void because of operating difficulties.

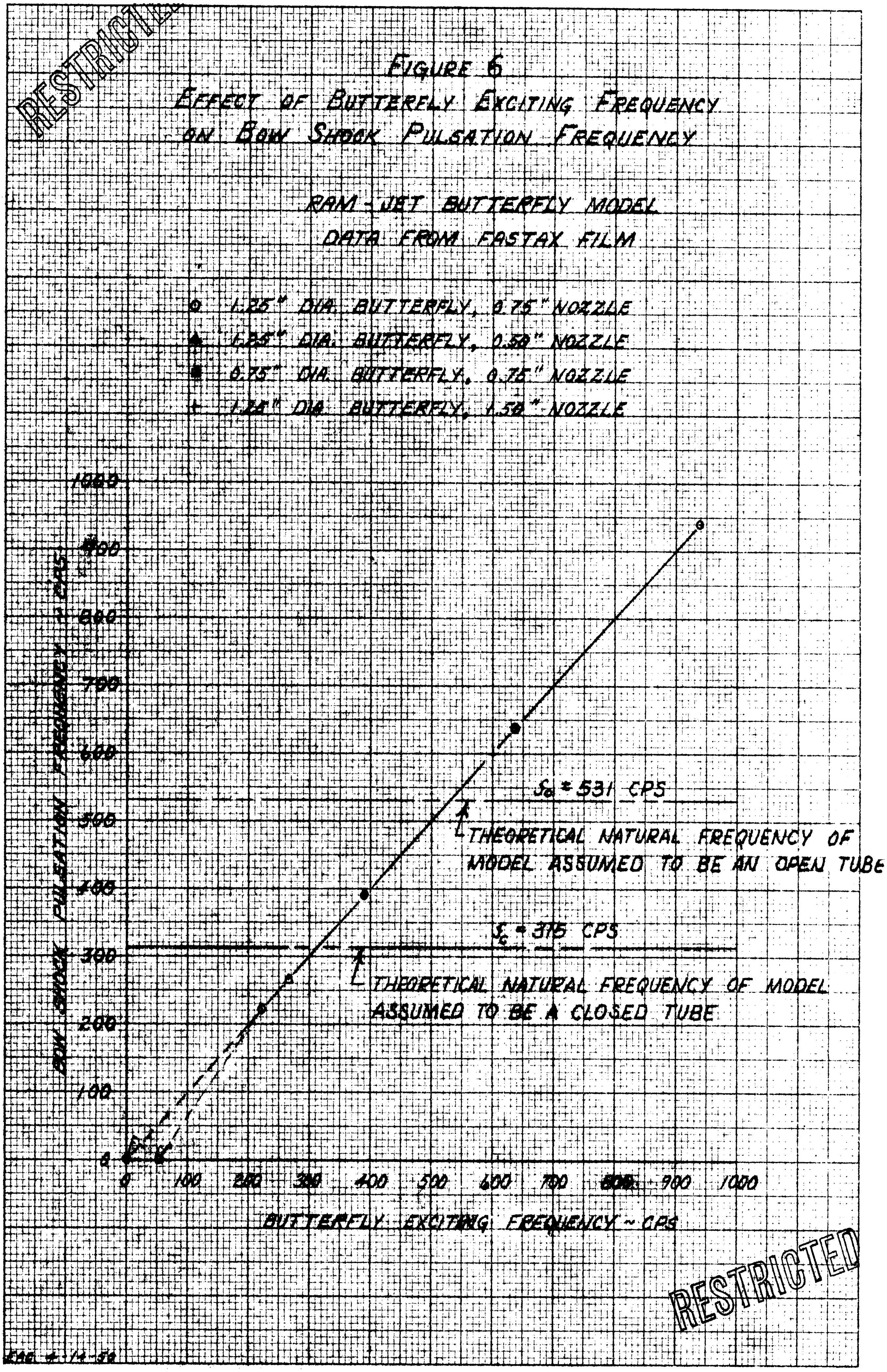
VII. GRAPHS AND PHOTOGRAPHS OF SIGNIFICANT DATA

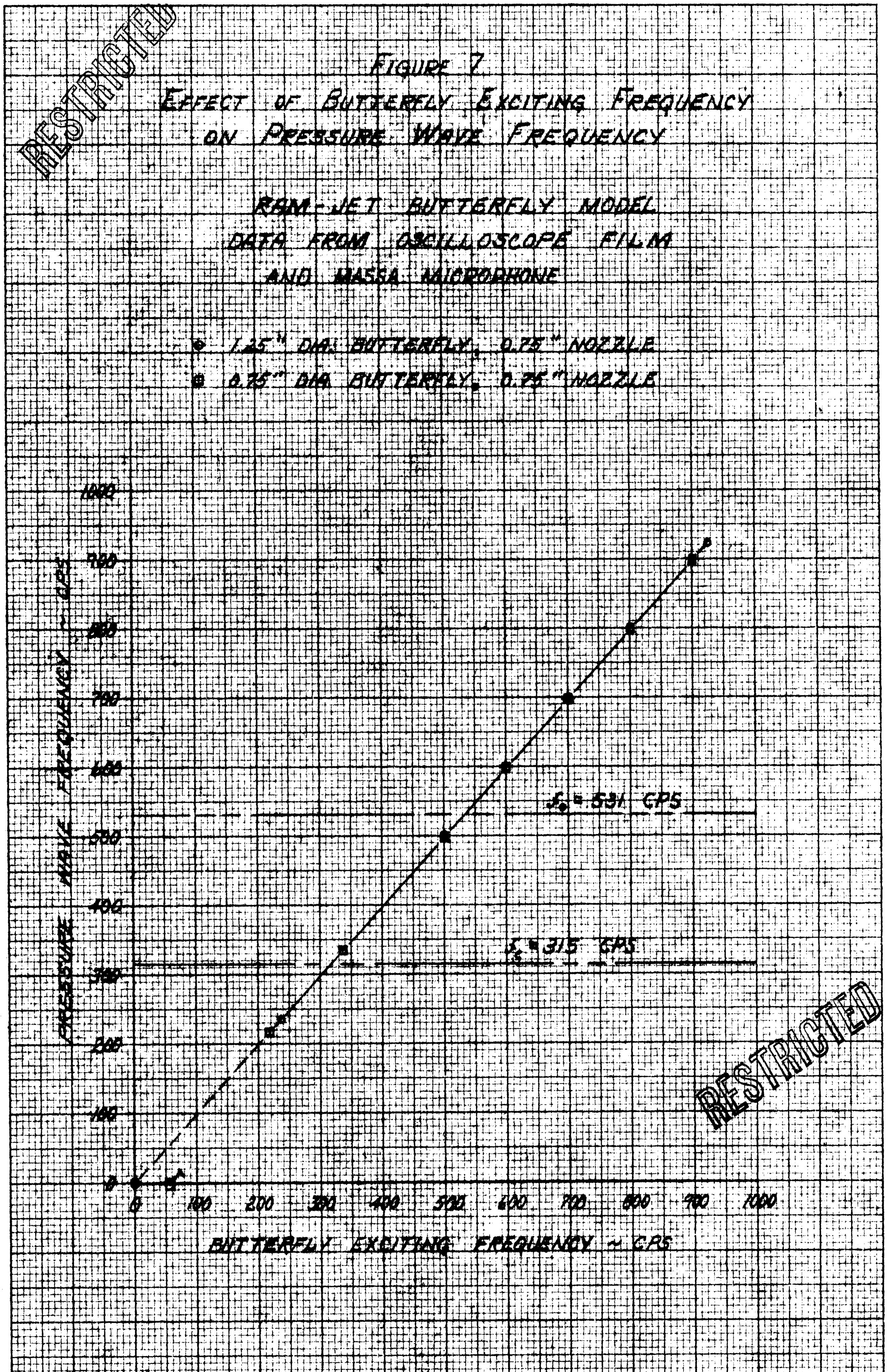
Outside of Figures 6, 7, 7A, and 7B, which are plotted data, the remaining figures in this section are photographic reproductions of portions of important Fastax and oscilloscope film. It is felt that this particular selection includes only those runs which were fruitful.

The several processes involved in making these photographs doubtlessly produced much distortion in them. Thus, no effort should be expended to take accurate data from them.

One will find in checking certain film strips that the frequency data cited in the label do not agree with the record, even allowing for film distortion. The data list average frequency magnitudes. Therefore, the particular film strip chosen for best reproduction purposes is not guaranteed to agree.

Proper manner to read the film is from left to right. The pressure tracks on the oscilloscope film were situated in such a way that the waves approaching peaks correspond to increasing static pressure and the waves approaching troughs correspond to decreasing static pressure.


RESTRICTED
FIGURE 6
EFFECT OF BUTTERFLY EXCITING FREQUENCY
ON BOW SHOCK PULSATION FREQUENCY
RAM-JET BUTTERFLY MODEL
DATA FROM FASTAX FILM
1.25" DIA. BUTTERFLY, 0.75" NOZZLE
1.25" DIA. BUTTERFLY, 0.50" NOZZLE
0.75" DIA. BUTTERFLY, 0.75" NOZZLE
1.24" DIA. BUTTERFLY, 1.50" NOZZLE
f_o = 531 CPS
THEORETICAL NATURAL FREQUENCY OF MODEL ASSUMED TO BE AN OPEN TUBE
f_c = 315 CPS
THEORETICAL NATURAL FREQUENCY OF MODEL ASSUMED TO BE A CLOSED TUBE
BOW SHOCK PULSATION FREQUENCY ~ CPS
BUTTERFLY EXCITING FREQUENCY ~ CPS
0
100
200
300
400
500
600
700
800
900
1000
RESTRICTED



RESTRICTED
FIGURE 7
EFFECT OF BUTTERFLY EXCITING FREQUENCY
ON PRESSURE WAVE FREQUENCY
RAM-JET BUTTERFLY MODEL
DATA FROM OSCILLOSCOPE FILM
AND MASSA MICROPHONE
1.25" DIA. BUTTERFLY, 0.75" NOZZLE
0.75" DIA. BUTTERFLY, 0.75" NOZZLE
PRESSURE WAVE FREQUENCY ~ CPS
1000
900
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
BUTTERFLY EXCITING FREQUENCY ~ CPS
f_0 = 531 CPS
f_s = 315 CPS
RESTRICTED

FIGURE 7A

EFFECT OF BUTTERFLY EXCITING FREQUENCY ON PRESSURE WAVE DIFFERENTIAL WITH BUTTERFLY ACCELERATING FROM REST TO 900 CPS

RUN NO. 49-10-14-10
DATA FROM MASSA MICROPHONE AND OSCILLOSCOPE FILM
BUTTERFLY DIAMETER, 0.75 INCHES
NOZZLE OUTLET DIAMETER, 0.75 INCHES

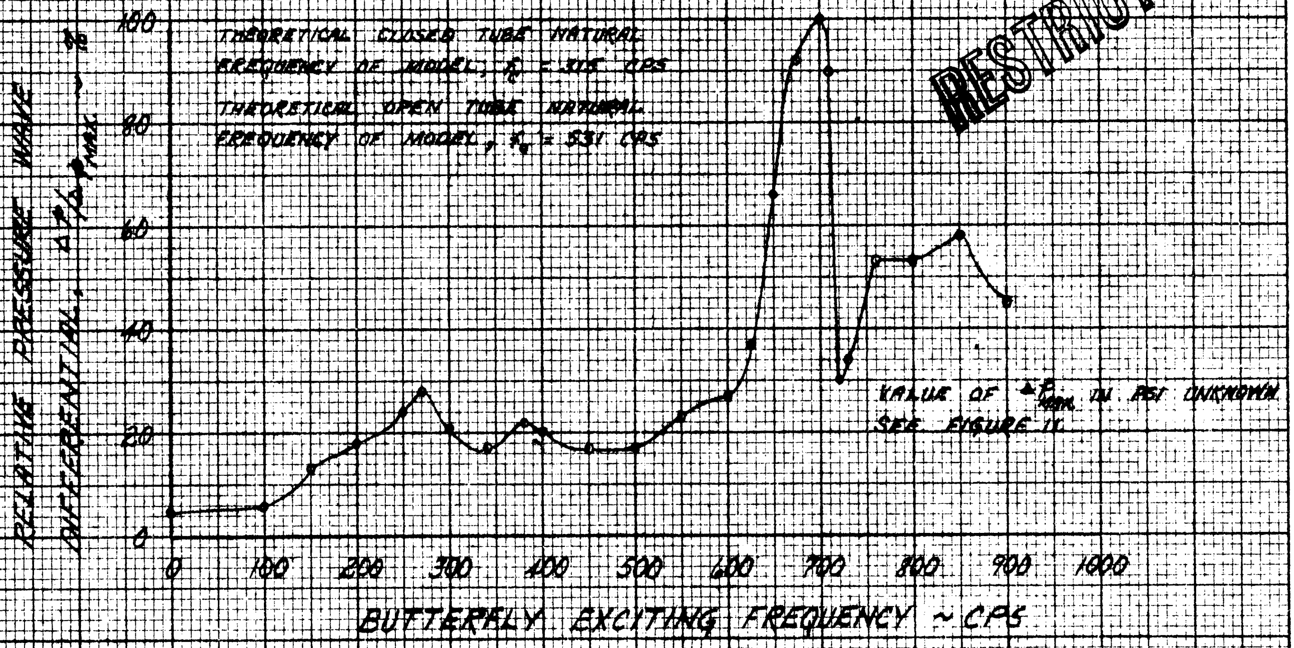
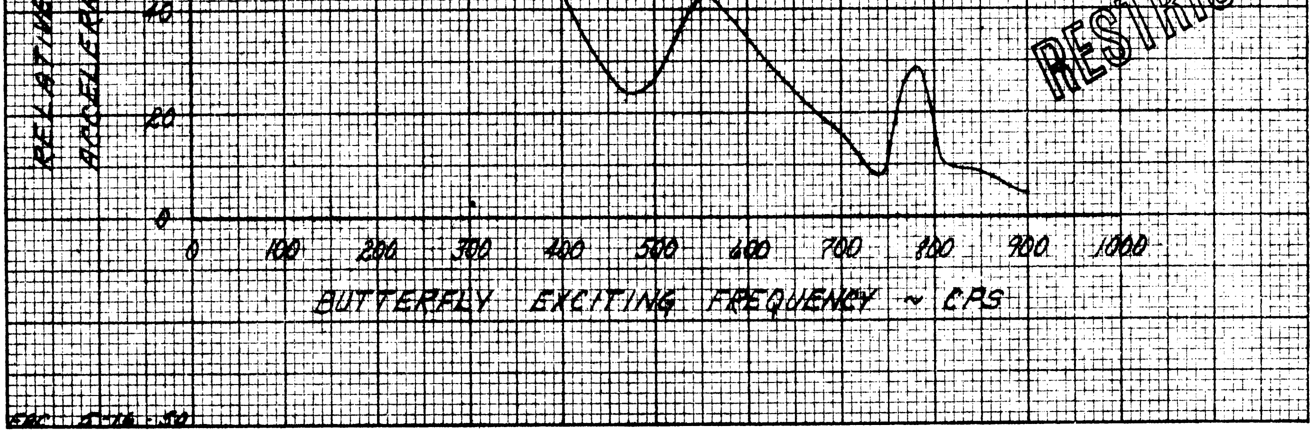


FIGURE 7B

APPROXIMATE BUTTERFLY ACCELERATION CHARACTERISTICS DURING RUN NO. 49-10-14-10

DATA FROM OSCILLOSCOPE FILM



FAC 5-16-50

RUN NO. 49-10-14-1
BUTTERFLY STATIONARY
IN MOST OPEN POSITION
PRESSURE WAVE
DIFFERENTIAL, 0.1 PSI

RUN NO. 49-10-13-6
BUTTERFLY EXCITING
FREQUENCY, 237 CPS
PRESSURE WAVE
FREQUENCY, 237 CPS
PRESSURE WAVE
DIFFERENTIAL, 2.7 PSI

RUN NO. 49-10-13-3
ESTIMATED BUTTERFLY
EXCITING FREQUENCY
AND PRESSURE WAVE
FREQUENCY, 358 CPS
PRESSURE WAVE
DIFFERENTIAL, 0.37 PSI

RUN NO. 49-10-13-7
ESTIMATED BUTTERFLY
EXCITING FREQUENCY
AND PRESSURE WAVE
FREQUENCY, 375 CPS
PRESSURE WAVE
DIFFERENTIAL, 1.85 PSI

RUN NO. 49-10-14-9
BUTTERFLY EXCITING
FREQUENCY, 923 CPS
PRESSURE WAVE
FREQUENCY, 923 CPS
PRESSURE WAVE
DIFFERENTIAL >0.85 PSI

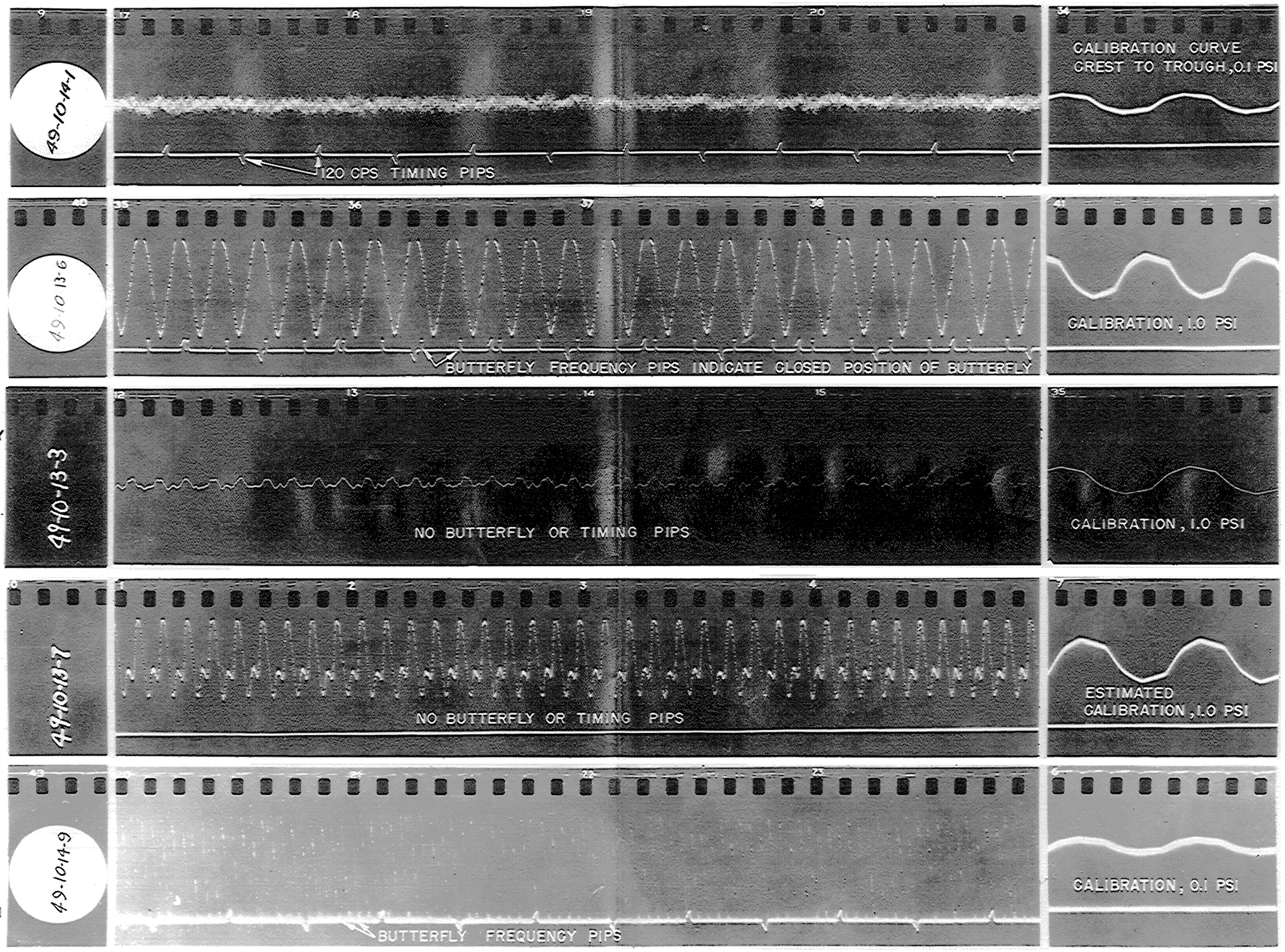


FIGURE 9
SELECTED OSCILLOSCOPE FILM OF PRESSURE WAVE PATTERNS WITH
COMMON MODEL CONFIGURATION AND VARIABLE BUTTERFLY EXCITING FREQUENCY

NOMINAL FILM SPEED, 60 IN./SEC. BUTTERFLY DIAMETER, 1.25 INCHES
FILM MAGNIFICATION, 1.5 NOZZLE OUTLET DIAMETER, 0.75 INCHES

RUN NO. 49-10-14-14
BUTTERFLY EXCITING FREQUENCY, 50 CPS
PRESSURE WAVE FREQUENCY DOUBTFUL
PRESSURE WAVE DIFFERENTIAL, .062 PSI

RUN NO. 49-10-14-12
BUTTERFLY EXCITING FREQUENCY, 56 CPS
PRESSURE WAVE FREQUENCY DOUBTFUL
PRESSURE WAVE DIFFERENTIAL, .075 PSI

RUN NO. 49-10-14-13
BUTTERFLY EXCITING FREQUENCY, 218 CPS
PRESSURE WAVE FREQUENCY 218 CPS
PRESSURE WAVE DIFFERENTIAL, .245 PSI

RUN NO. 49-10-14-2
BUTTERFLY EXCITING FREQUENCY, 336 CPS
PRESSURE WAVE FREQUENCY, 336 CPS
PRESSURE WAVE DIFFERENTIAL, .200 PSI

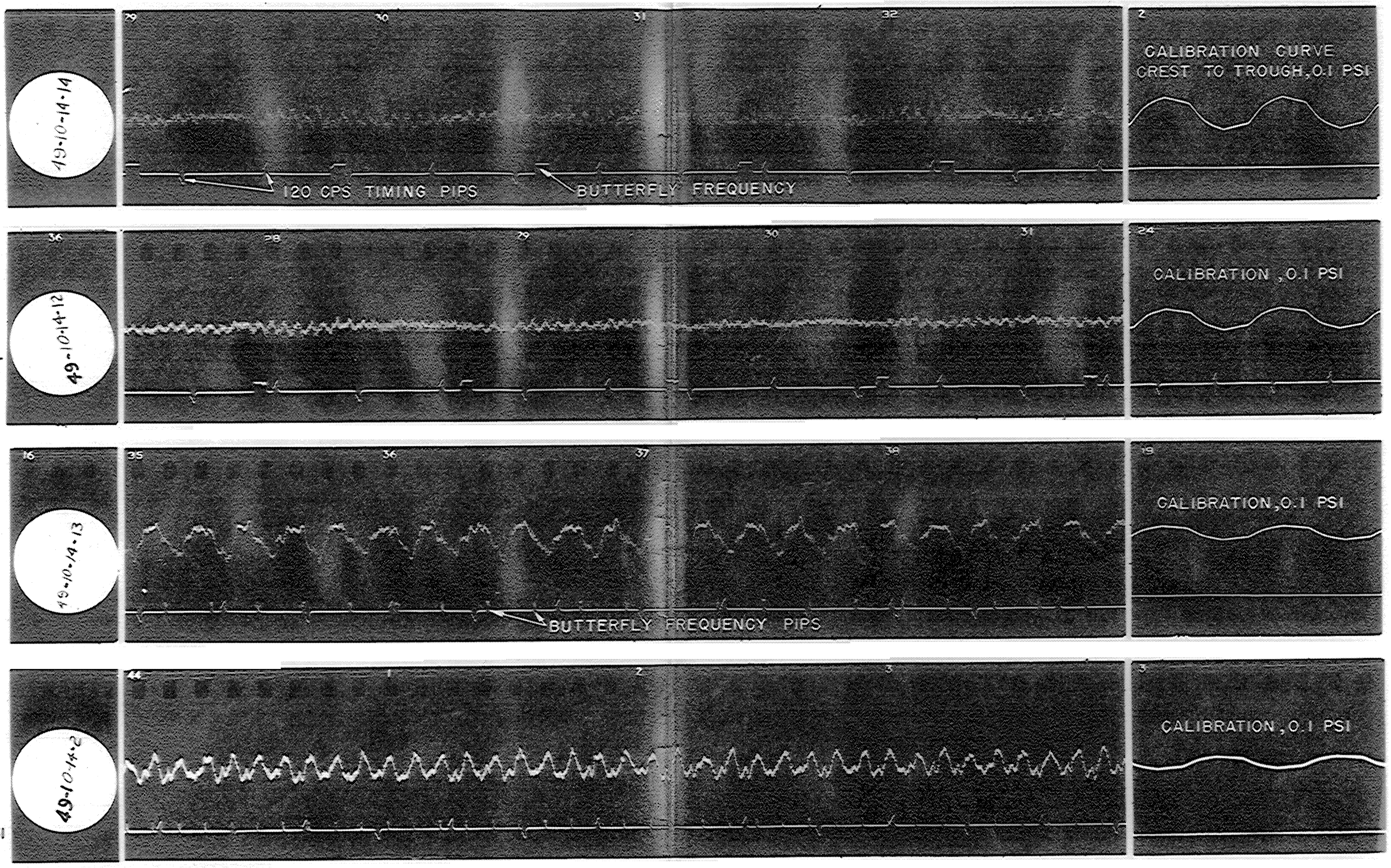


FIGURE 10

SELECTED OSCILLOSCOPE FILM OF PRESSURE WAVE PATTERNS WITH COMMON MODEL CONFIGURATION AND VARIABLE BUTTERFLY EXCITING FREQUENCY

NOMINAL FILM SPEED, 60 IN./SEC. BUTTERFLY DIAMETER, 0.75 INCHES

FILM MAGNIFICATION, 1.5 NOZZLE OUTLET DIAMETER, 0.75 INCHES

RUN NO. 49-10-14-3
SCREEN SOLIDITY
RATIO, 95 %
NOZZLE OUTLET
DIAMETER, 0.75 IN.
PRESSURE WAVE
DIFFERENTIAL, .045 PSI

RUN NO. 49-10-14-4
SCREEN SOLIDITY
RATIO, 87 %
NOZZLE OUTLET
DIAMETER, 1.50 IN.
PRESSURE WAVE
DIFFERENTIAL, .050 PSI

RUN NO. 49-10-14-5
SCREEN SOLIDITY
RATIO, 80 %
NOZZLE OUTLET
DIAMETER, 1.50 IN.
PRESSURE WAVE
DIFFERENTIAL, .075 PSI

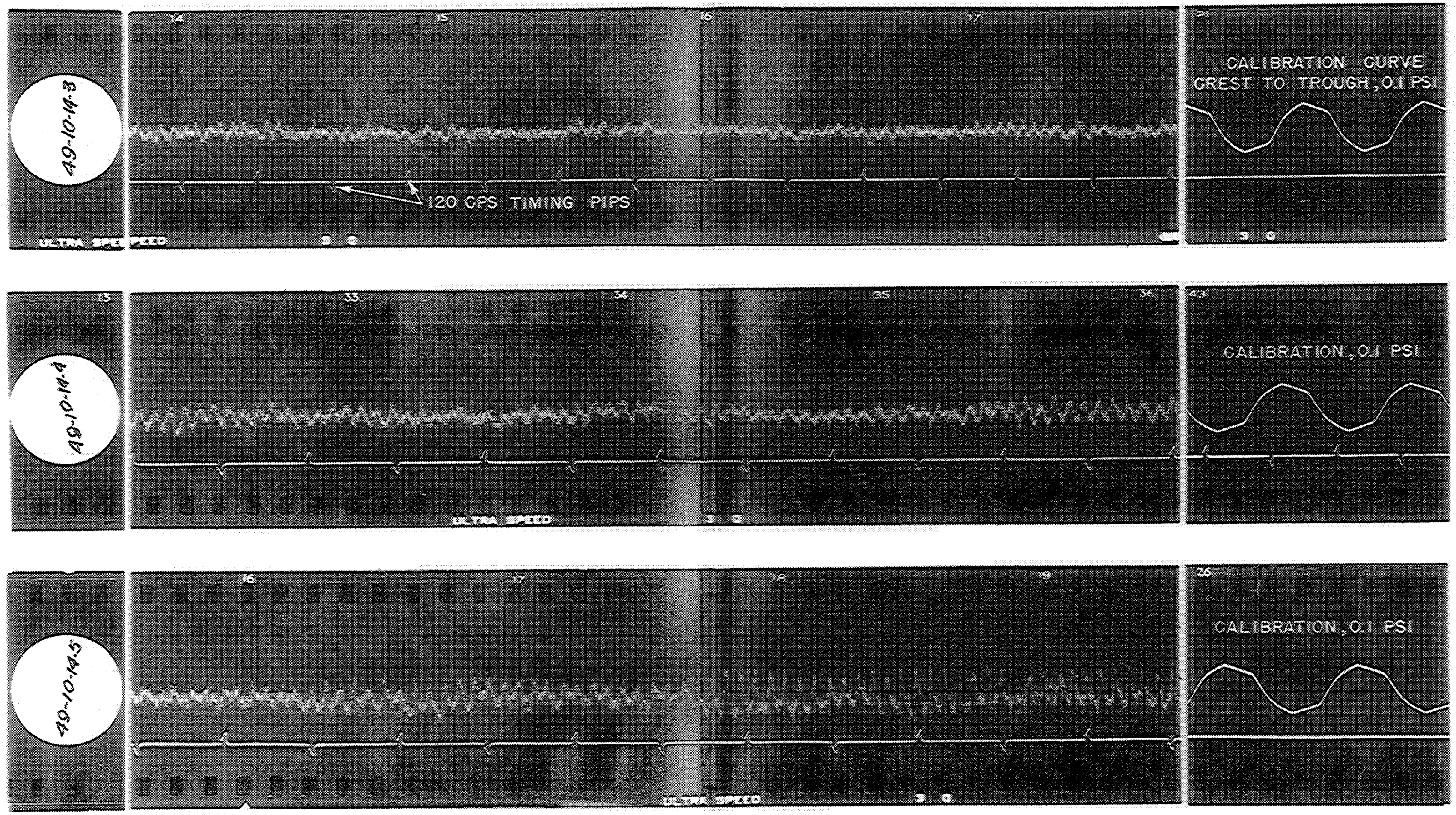


FIGURE 13

SELECTED OSCILLOSCOPE FILM OF PRESSURE WAVE PATTERNS
WITH FLOW CHOKING SCREENS OF VARIOUS SOLIDITY RATIOS

NOMINAL FILM SPEED, 60 IN./SEC.
FILM MAGNIFICATION, 1.5
BUTTERFLY NOT INSTALLED

RUN NO. 49-10-14-14
BUTTERFLY EXCITING
FREQUENCY, 50 CPS
BUTTERFLY DIA., .75 IN.
NOZZLE OUTLET
DIAMETER, .75 IN.

RUN NO. 49-10-14-7
BUTTERFLY STATIONARY
IN POSITION UNKNOWN
BUTTERFLY DIA., 1.25 IN
NOZZLE OUTLET
DIAMETER, .75 IN.

RUN NO. 49-10-14-3
NO BUTTERFLY
SCREEN SOLIDITY
RATIO, 95 %
NOZZLE OUTLET
DIAMETER, .75 IN.

RUN NO. 49-10-14-5
NO BUTTERFLY
SCREEN SOLIDITY
RATIO, 80 %
NOZZLE OUTLET
DIAMETER, 1.50 IN.

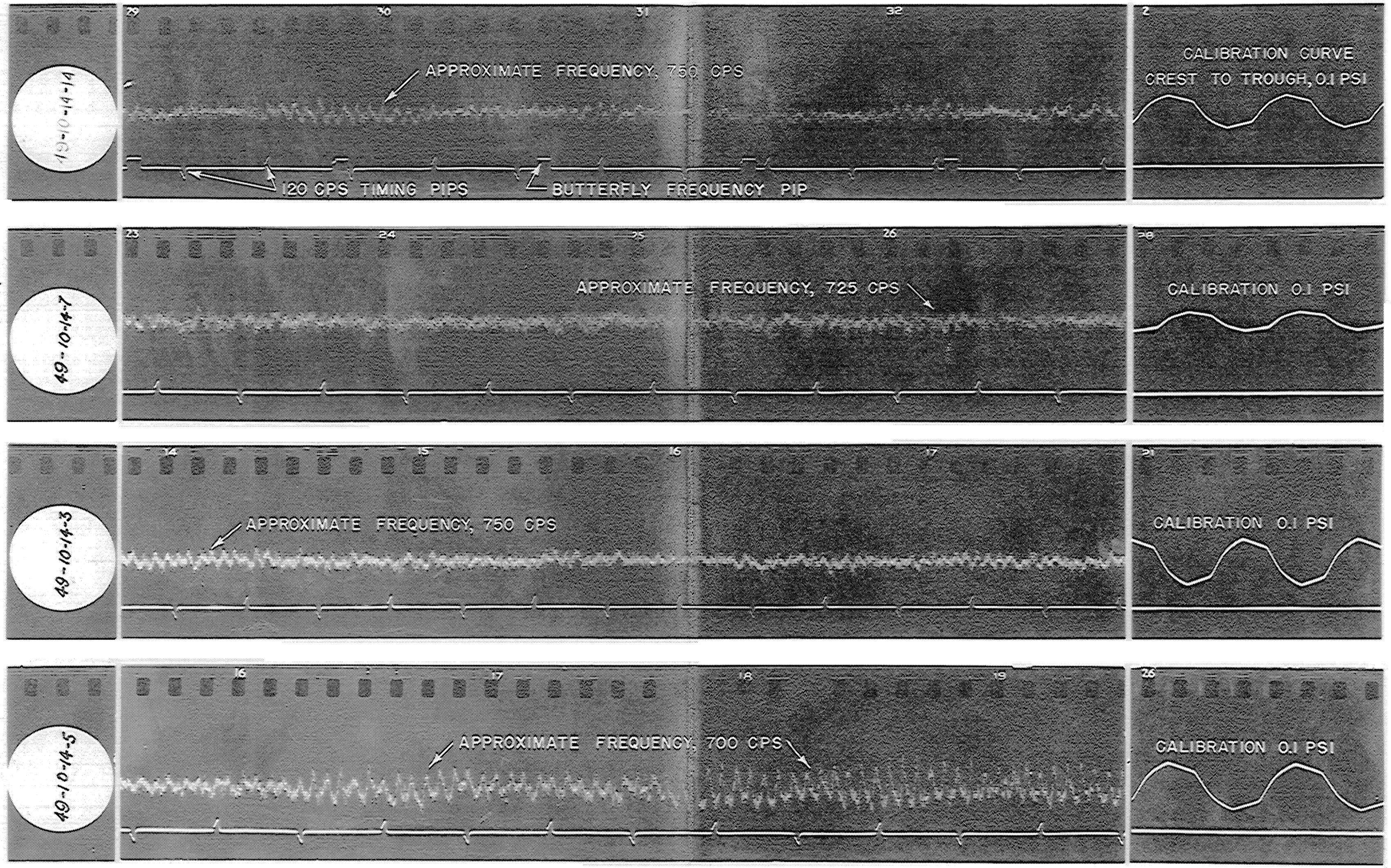


FIGURE 14

SELECTED OSCILLOSCOPE FILM SHOWING INTERVALS WHERE PRESSURE WAVE PATTERN IS PERIODIC BETWEEN 700-750 CPS

NOMINAL FILM SPEED, 60 IN./SEC.

FILM MAGNIFICATION, 1.5

VIII. REFERENCES

1. Parchem, J. A., Ram-Jet Blocking Model Fastax Film Analysis, University of Michigan Aeronautical Research Center WTM-109, Willow Run, 1949.

2. Jacob, D. M., Instruction Book for 120 Cycle Pulser and Tachometer and Shaft Pulser Unit, University of Michigan Aeronautical Research Center EMM-36, Willow Run, 1949.

3. Hausmann and Slack, Physics, D. Van Nostrand Co., New York, 1935.

4. Adler, A. A., Variation with Mach Number of Static and Total Pressures through Various Screens, N.A.C.A. Wartime Report L-23, Washington, 1946.

APPENDIX A

NATURAL FREQUENCY COMPUTATIONS

The natural frequency expression for an air column in a rigid tube is (Reference 3):

$$f = \frac{na}{2L} \text{ cps}$$

where: $n = 1, 2, 3, \ldots$ identifying the harmonic for open tubes
$n = \frac{1}{2}, 3/2, 5/2, \ldots$ identifying the harmonic for closed tubes
a = local speed of sound, ft/sec
L = effective length of tube, ft

Assuming the ram-jet as a closed tube, the physical length of the tube will be equivalent to the distance from model inlet to axis of butterfly rotation. This distance is 10.062 inches. Reference 3 suggests adding 30% of the tube diameter to the physical length in order to obtain effective length. Thus,

$$L_c = (10.062) + (.3)(1.5) = 10.51 \text{ in.}$$

The speed of sound expression is

$$a = \sqrt{kRT} = 49\sqrt{T} \text{ ft/sec} \quad \text{where } T \text{ is static temperature in } {}^{\circ}R$$

Assuming that the Mach Number of model internal flow is 0.3, then

$$\frac{T_o}{T} = 1 + \frac{k-1}{2} M^2 = 1 + \frac{(1.4-1)}{2} (.3)^2 = 1.02$$

where T_o is reservoir temperature

The average T_o for these tests was

$$T_o = 58 + 460 = 518^{\circ}R$$

Therefore,

$$T = \frac{518}{1.02} = 507^{\circ}R$$

Also,

$$a = 49\sqrt{507} = 1103 \text{ ft/sec}$$

The theoretical closed tube natural frequency of the model is, therefore,

$$f_c = \frac{(\frac{1}{2})(1103)(12)}{(2)(10.51)} = \underline{315 \text{ cps}} \qquad \text{where } n = \tfrac{1}{2}$$

If it is wished to calculate the natural frequency of model as an open tube, then the physical length is 12 inches. The effective length turns out to be

$$L_o = (12) + (.3)(1.5) = 12.45 \text{ inches}$$

Assuming all other conditions to remain unchanged except n = 1, the theoretical open tube natural frequency of model is, therefore,

$$f_o = \frac{(1)(1103)(12)}{(2)(12.45)} = \underline{531 \text{ cps}}$$

APPENDIX B

SCREEN CHOKING COMPUTATIONS

The ram-jet blocking model tests reported in reference 1 showed that the model obviously was choked when a solid plug was used (condition of bow shock pulsation). The plug with the smallest orifice (13/16" dia.) which was used did not choke the model nor did it cause the shock pattern to pulsate. The solidity of this 13/16" dia. plus is

$$S = 1 - \frac{A_o}{A_t}$$

where : S = plug solidity, %
A_o= orifice area, in.^{2}
A_t= internal area of model, in.^{2}

$$S = 1 - \frac{(.8125)^2}{(1.5)^2} \cong 71\%$$

In these tests it was estimated that the Mach Number upstream of the plug was between 0.2 and 0.3. As a rough approximation it was assumed that the choking characteristics of plugs with orifices were similar to high density or fine mesh screens. Reference 4 reports results indicating that choking Mach Number in a tube is a function of the screen solidity. On this basis, it was thought that using flow choking screens with solidity ratios greater than the 71% solid plug would choke the model and induce pulsation of the bow shock.

From reference 4 for screens

$$S = (m + n)\, d - mnd^2 = 1 - \frac{M_c}{(.579)\left[1 + (.2)\, M_c^2\right]^3}$$

where: S = Screen solidity ratio, %
m = Mesh of shute, wires/inch
n = Mesh of warp, wires/inch
d = Diameter of wire, inches
M_c= Mach Number before screen for choking at screen.

The screens chosen for this test program were as follows:

a. One-60 x 50 mesh, 0.010" dia. twilled Monel wire

$$S_a = (60 + 50)\ (.01) - (50)(60)(.01)^2 = (1.10) - (.3) \cong 80\%$$

b. One-60 x 55 mesh, 0.011" dia. twilled Monel wire

$$S_b = (60 + 55)\ (.011) - (55)(60)(.011)^2 = (1.265) - (.399) \cong 87\%$$

c. One-30 x 150 mesh, 0.0085" x 0.007" dia. Monel wire

This solidity ratio could not be calculated but was estimated to be 95%.