SHORT TIME TOLERANCE IN MAN TO SINUSOIDAL VIBRATIONS

The rocket boosters to be used in future manned aerospace flight produce significant omnidirectional vibrations during various stages of lift-off and initial flight. Ballistic reentry of spacecraft is also expected to produce such vibrations. In both cases, the predicted frequency spectrum of translational and angular motions contains sizable components in the range under 20 cps. It is in this range that such vibrations have their maximum effect on man's ability to function and/or survive as a crewman. The sustained linear accelerations associated with boost and reentry have less effect on man if they are directed mainly through the X axis of the body. The effects of these long duration accelerations, as well as the abrupt impulsive decelerations produced by ground landing impact are assumed to be minimized by supports and restraints which closely couple the man to the spacecraft. Existing and future spacecraft are designed so that the long duration linear accelerations, directed through the body as $+G_x$ loads will tend to further couple the crewman to the support system.

Previous studies of the effects of low frequency vibration on man (1) have been focused on the problems associated with flight of conventional aircraft, where the crewman is exposed to vibrations which act mainly through the Z axis of the body. Under these conditions vibration transmission is mainly through the seat where inefficient coupling to the vibration generator is often seen. Furthermore, the effects of vibration on some of the critical body structures, such as the head, tend to be reduced by virtue of the rather efficient attenuation afforded by the body.

The present study was designed to explore the effects on man of high magnitude sinusoidal vibrations directed through the X, Y and Z axes of the body. The subjects were restrained in a whole body support couch in the semisupine position on the vibration table in such a way that gravity produced primarily a $+G_x$ force.

In this communication, the terminology proposed by Clark (2) will be used to describe the orientation of the inertial force resulting from vibration as well as the orientation of the effect of gravity. Subjects positioned as described above, for example, when exposed to vibration in the Z axis are exposed to a force environment which will be described $+G_x/nG_z$. In describing these orientations, the upward inclination of the torso and the head has been neglected.

METHODS

The support system used was a contoured rigid fiberglass couch similar to the one used in the Mercury spacecraft. The dimensions of this couch were such that comparatively uniform support over the dorsal surface of the body was provided for each member of the subject panel. The degree of lateral and vertical coupling of the subject's body to the couch was, to some extent, variable from one subject to the next. The couch provided a 12 degree elevation of the torso and head above the horizontal, duplicating the position which has been found to be optimal for sustained acceleration (3,4). Subjects were restrained in the couch with 2 inch type III Dacron straps shown in figures 1-3. They wore light weight cotton surgical suits and athletic supporters.

A Western Gear mechanical vibration table, capable of producing either vertical or horizontal motions was used. The frequencies studied were 3,5,6,7,8,10,15 and 20 cps. The procedure was to increase the amplitude of vibration at a rate of 0.75 mm D.A. per second at a preset frequency until the subject indicated he had reached his limit of voluntary tolerance by stopping the machine.

In this study, voluntary tolerance is defined by the following instructions, which were given to each subject, prior to each vibration exposure. Based on previous experience (1), each subject was indoctrinated as to the importance of maintaining regular respiration during vibration and was prompted to do so during the exposure when it was deemed necessary. In order to facilitate tolerance criteria uniformity, the subjects were told to maintain their position in the couch, with the head in the headrest as best they could by their choice of various bracing and straining procedures. If symptoms from head buffeting became very severe before the onset of other symptoms, they were told to lift their head from the headrest and to continue with the exposure until such symptoms were so intense that they felt further exposure was either unbearable or that further exposure might result in bodily harm.

During studies of the G_z and G_y displacements, two or three measurements of subjective tolerance were made on the same subject at different frequencies, with approximately 5 - 10 minutes of rest between exposures. This was deemed an acceptable expedient since the symptoms causing termination of the experiment varied with the frequency of vibration. For example, chest pain might limit the exposure at 6 cps, but testicular discomfort or pain might cause termination of the test at 15 cps. Vibrations directed through the X axis, on the other hand, produced the same general symptomatology regardless of frequency so that usually only one (occasionally two) exposures of the same subject were made in one day.

The subject panel consisted of 30 healthy male military volunteers who received incentive pay. They ranged in age from 23-35 years, in height from 165 - 184 cm., and in weight from 66 to 100 kgm. Each subject defecated within 12 hours of vibration exposure; all subjects voided immediately prior to exposure. A light breakfast or lunch was eaten the day of the experiment.

A low mass electrode system was used to obtain the electrocardiogram

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before, during, and after vibration. The standard limb leads were employed using the area over the deltoid muscle for attachment of the upper limb leads, since this location led to the least disturbance in the record.

RESULTS

Tables 1-3 show the individual subjective tolerance limits. Figure 4 displays the mean tolerance in "G" units as a function of frequency of vibration. The curve contours from G_z and G_y vibrations are remarkably similar; the absolute values are within one standard deviation at comparable frequencies. The G_x curve however, demonstrates that above 8 cps, the magnitude of acceleration tolerated by the subjects increases at a much lower rate with increasing frequency than in the other two directions. Below 8 cps the accelerations tolerated during G_x exposure is greater than for either G_z or G_y vibration.

Tables 4-6 summarize the subjective symptoms according to body area and severity. At 3 cps the subjective tolerance during G_x vibrations was in excess of the capability of the machine. During G_y at this frequency, the accelerations tolerated were much lower due to the marked lateral displacement of the lifted head as the higher amplitudes were approached. Both muscle fatigue as well as spasm of the neck muscles severly limited the amount of acceleration tolerated by the subjects. At 5 cps, during Z and Y displacements, fatigue again played a role in affecting the subjective tolerance. Between 5 and 8 cps, the thoracoabdominal system was most frequently involved in all three axes. Unlike the response noted in the G_y and G_z displacements, thoracoapigastric complaints appeared to be independent of frequency on G_x exposure. The chest and abdominal symptoms of pain and pressure were associated with dyspnea in 36% of the cases in the Z axis, 55% of the cases in the Y axis and in 56% of the cases in the X axis. Although the combined symptoms were noted in the Z axis as often as they were noted independently, dyspnea was never seen in the X axis except in conjunction with thoracic or epigastric pain and was noted by itself on only one occasion during G_y displacement. These findings did not appear to be related.to frequency. Suprapubic pressure was noted at 10, 15, and 20 cps in all three orientations and was described as either an urge to void, an urge to defecate or a feeling of testicular fullness although the testicles themselves did not necessarily disturb the subject. Testicular symptoms per se were noted in the G_y and G_z experiments only. On G_y exposure the subjects felt as though the testicles had been repeatedly tapped. On G_z exposure they complained of a squeezing sensation in the testicles. In some subjects both testicles were involved, in others only one, no consistency being noted.

Headache was most frequently observed during G_z vibrations between 6 and 10 cps. It was less frequently observed during G_x vibrations and, in this orientation, occured at the higher frequencies. The symptoms of headache, fatigue sore neck and possibly abdominal discomfort were probably accentuated by the effort required to hold the head out of the headrest.

At higher frequencies, burning of the hips, thighs, calves and areas underlying restraint straps played a dominant role in limiting tolerance to G_z and G_y vibration. This was not such an important factor in G_x vibrations since the subject did not experience the same degree of relative velocity with respect to the couch. These burning sensations were verified by post-vibration observation of marked erythema of the back, thighs, calves and areas under the straps. Actual blistering of epidermal areas, comparable to first and second degree burns, was noted in several subjects.

Table 7 shows the heart rate response to vibration as recorded by the ECG. Since the values recorded appeared to be similar regardless of frequency or direction of vibration, they are presented together. On setting the frequency dial of the vibration machine, the motor will be driven at that frequency with its accompanying noise response. During this time, there will be minimal displacement, sinusoidal vibration only occurring after engaging the amplitude switch. At this point a mild increase is seen in the heart rate, with a marked increase being observed at subjective tolerance levels, a return to previbration levels occurring within 30 to 60 seconds after terminating the vibration. Although the tracings were usually unintelligible at subjective tolerance levels, the rate could be ascertained from the record within ≠ 5 seconds of this level. With the exception of heart rate, the only other ECG change noted was an occasional flattening of the T wave, which bacame evident before actual vibration was initiated. The T waves returned to normal on cessation of the vibration.

DISCUSSION

The subjective tolerance curves as well as the absolute accelerations tolerated during G_z and G_y exposures are remarkably similar. With the exception of the increased frequency of headaches during G_z vibrations, the subjective sensations limiting tolerance were also of a similar nature. This was not the case during G_x vibration. Below 8 cps, the accelerations tolerated during G_x exposure were greater than those experienced during G_z and G_y vibrations, while above 8 cps, they were significantly lower. The difference in the tolerance curve contours may be due to the fact that during G_x exposure, theracoabdominal complaints were uniformally noted throughout the frequency range explored as opposed to the change in symptomatology seen above 8 cps during G_z and G_y vibrations. The initial rise in heart rate noted on setting the frequency as well as the flattening of the T waves seen in several individuals in certainly indicative of an anxiety response. The role of muscular effort is probably not as great as presupposed, since enzyme studies (5-6) and urinary sediment studies (6) have been negative in previous studies of comparable accelerations.

This study revealed several shortcomings in the support and restraint systems as we used them. A part of the experimental design in this study was the exploration of the desirability of raising one's head when marked discomfort occurred secondary to head buffeting. The results obtained from employing this procedure suggest that the benefits accrued by so doing are counterbalanced by the fatigue engendered and by the accentuation or precipitation of symptoms arising in the head, neck, and thoracoabdominal areas. In subsequent limited studies the subjects were asked to keep their heads in the headrest until they were forced to terminate the exposure due to symptoms arising from head buffeting, if they should occur before other symptoms. In those limited studies, significantly higher levels of head buffeting vibrations were tolerated than had been reached in the subjective tolerance study, i. e., the subjects kept their heads in the headrest for longer periods of time, while the amplitude of the vibration table wax continuously increasing. Under operational conditions it will be difficult for the crewman to lift his head during the intense vibrations since the perturbations causing the vibrations occur during the boost and reentry periods when the linear accelerations imposed on him may seriously limit this ability. Unless the head is well coupled to the system severe buffeting may occur with deleterious consequences. If the head and helmet were well coupled to the structure, the head symptoms precipitated at the very low frequencies (3-5 cps) should be minimized. However, the problem may be accentuated at the higher frequencies (10, 15 and 20 cps) where head resonance may impose serious limitations. Another drawback to the present system was the frictional head generated by the subjects at 10, 15, and 20 cps during G_z and G_y vibrations. If the lateral displacement of the torso could be restricted to a greater degree by mose efficient coupling of the body to the support structure, than this problem might be minimized. A structure which provides such lateral support, adjustable for each subject, has recently Seen developed at this Laboratory. Its efficacy in reducing the aforementioned problems will be studied in the near future.

CONCLUSIONS

The voluntary subjective tolerance limits of man to sinusoidal vibrations were determined for the three orthogonal orientations of the inertial force vector at preset frequencies of 3-20 cps. Tolerance was defined as the maximum acceleration bearable ty the subject as the magnitudes of vibration were gradually increased. The volunteers were oriented on the vibration table such that gravity produced a 1 G_x force. While the absolute magnitude of acceleration attained at each frequency and, to some extent, the specific symptomatology leading to these limits is influenced by the experimental design and the support and restraint used, these studies define the general shape of curves depicting tolerable levels of vibration acceleration as a function of frequency.

Direct application of these data for use in designing operational vehicles undergoing high linear accelerations and vibrations is limited due to the unknown effect of these forces when applied simultaneously. The data serve as a rough guide in evaluating the severeness of the effects of vibrations in the various directions. Furthermore they again point out the fact that for manned vehicles, the frequency range below 20 cps should be avoided in system design if at all possible.

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TABLE 1

Subjective Tolerance To Sinusoidal Vibration

$$1\,G_x \angle\, n\,G_x$$

	Frequencies (cps)							
	3	5	6	7	8	10	15	20
	4.0*	2.2	2.6	3.0	2.9	2.9	4.3	9.0
	4.0*	3.0	2.9	2.7	3.7	2.9	3.4	7.2
	4.2*	3.5	2.5	2.4	3.1	2.1	4.7	7.2
	4.2*	3.0	3.0	4.4	3.0	3.9	5.7	7.2
		3.5	3.2	3.7	3.5	3.0	3.4	6.0
		3.8	3.4	3.2	311	3.2	5.1	6.6
Average Input G	4.1	3.2	2.9	3.2	3.2	3.0	4.4	7.2
S.D.	0.1	0.6	0.4	0.9	0.3	0.7	0.9	1.0

* Close to subjective tolerance. Exposure was limited by maximum capability of the machine

TABLE 2

Subjective Tolerance To Sinusoidal Vibration

$1\ G_x \neq n\ G_y$

	Frequencies (cps)							
	3	5	6	7	8	10	15	20
	2.2	1.8	2.8	1.7	2.6	3.9	8.0	9.0
		2.2	2.2	2.4	3.5		9.8	12.6
	2.9	2.1	2.2	2.3	4.1	6.9		12.2
			2.7	3.0	3.6	3.6	7.0	18.3
	1.0	1.8	2.4	2.6	2.6	4.1	12.5	16.3
	2.4	1.8	2.3	2.2	3.0	5.6	8.0	12.2
	1.7	2.4				6.1	10.3	13.0
	1.3	2.0			3.3	5.4	8.0	19.2
	2.3				4.4	5.0	10.8	
	2.5							
~~Input~~ Average G	2.0	2.0	2.4	2.4	3.4	5.1	9.3	14.1
S. D.	0.7	0.3	0.3	0.4	0.7	1.2	1.8	3.5

TABLE 3

Subjective Tolerance To Sinusoidal Vibration

$1\ G_x \angle\ n\ G_z$

	Frequencies (cps)						
	5	6	7	8	10	15	20
	2.6	2.2	2.5	2.0	5.6	7.4	14.5
	3.0	1.7	2.4	2.0	4.3	7.9	14.4
	2.0	1.7	2.8	3.6	4.0	7.7	12.0
	2.2	1.7	3.4	2.1	4.0	9.0	9.9
	2.0	2.2	3.0	2.8	4.8	6.3	13.6
	2.8	2.6	3.1	4.0	3.4	8.4	8.8
	2.5	2.5	2.9	3.5	3.8	7.9	13.8
	2.2			3.7		8.4	12.0
Average G_{Input}	2.4	2.1	2.9	3.0	4.3	7.9	12.4
S. D.	0.4	0.4	0.3	0.8	0.7	1.1	2.1

TABLE 4

SYMPTOMS LIMITING SUBJECTIVE TOLERANCE DURING 1 $G_x \pm n\ G_x$ VIBRATION

	Frequencies (cps) 3	5	6	7	8	10	15	20
I. GENERAL								
A. Disorientation				2	1	22	1	
B. Fatigue	2222	2						
C. "Had Enough"					1			
II. HEAD								
A. Headache								
1. Frontal		1				11	11	21
2. Occipital								2
3. Parietotemporal							2	
III. CHEST								
A. Precordial Pain or Pressure			1		11			
B. Substernal Pain or Pressure		11112	11111	1111	11	1111	111	112
C. Subcostal Pain or Pressure				1		11	2	1
D. Subcapular Pain or Pressure				1				1
E. Subclavical Pain or Pressure								1
F. Thoracoabdominal complaints plus dyspnea		11	1111	11111	11	111	111	1
IV. RESPIRATION								
A. Inspiratory Dyspnea		11	111	2111	1	111	111	1
B. Expiratory Dyspnea					1			
V. ABDOMEN								
A. Epigastric Pressure						11	1	
B. Suprapubic Pressure						2	1	11
C. Right Lower Quadrant					1			

Note: 1 - Tolerance factor
2 - Symptoms noted, but not necessarily limiting tolerance

TABLE X-

SYMPTOMS LIMITING SUBJECTIVE TOLERANCE DURING 1 $G_x \neq n\ G_y$ VIBRATION

	Frequencies (cps)							
	3	5	6	7	8	10	15	20
I. GENERAL								
A. Disorientation								
B. Fatigue	212112		11221					
C. Confusion	2	1	1	1				21
D. Tingling or Banging, Burning in Hips of Thighs					2121	1111	121	1111
E. "Just Wanted to Stop"		1						
II. HEAD								
A. Sore Neck	11111	2						
B. Headache								
1. Frontal								
2. Occipital				1				
3. Parietotemporal	1							
III. CHEST								
A. Subcostal Pressure		11	11121	11	1111	1	1	1
B. Substernal Pressure		2		22				
C. Thoracoabdominal complaints plus dyspnea	1	1111	1111	1111	11	1	1	1
IV. RESPIRATION								
A. Inspiratory Dyspnea		1122	211	211	1			2
B. Expiratory Dyspnea		2		2			1	
V. ABDOMEN								
A. Epigastric Pressure	1	12	1	111	111			1
B. Periumbilical Pressure					1		1	
C. Suprapubic Pressure						111	111	1
D. Testicular Pressure					2		122	2

TABLE 6

SYMPTOMS LIMITING SUBJECTIVE TOLERANCE DURING $1\ G_x + n\ G_z$ VIBRATION

	Frequencies (cps)						
	5	6	7	8	10	15	20
I. GENERAL							
A. Disorientation							
B. Fatigue	1222122				1		
C. Confusion	11	12				1211	21
D. Burning in Thighs						121	1
E. "Just Wanted to Stop"			111	1	1	11	1
II. HEAD							
A. Sore Neck	121	1		2	1		
B. Headache							
1. Frontal		111			111	1	
2. Occipital			1	1	1		
3. Parietotemporal					1		
III. CHEST							
A. Subcostal Pressure		1		111	1		
B. Substernal Pressure	11	11		11		1	
C. Thoraboabdominal complaints plus dyspnea	11	11		111	1		1
IV. RESPIRATION							
A. Inspiratory Dyspnea	111	112	1				111
V. ABDOMEN							
A. Epigastric Pain or Pressure		111	1	11	2	1	1
B. Testicular Discomfort			12	11	22	1	121121
C. Urge to Defecate						11	

Note: 1.- Tolerance factor
2.p-Symptoms noted, but not necessarily limiting tolerance

TABLE 7

HEART RATE RESPONSE TO SINUSOIDAL VIBRATIONS DURING G_x, G_y, and G_z EXPOSURES

Control	Frequency Set	At Subjective Tolerance	30-60 Seconds Following Vibration
82 13(67)*	92 14(170)	121 15(121)	93 17(96)

* Number of observations.

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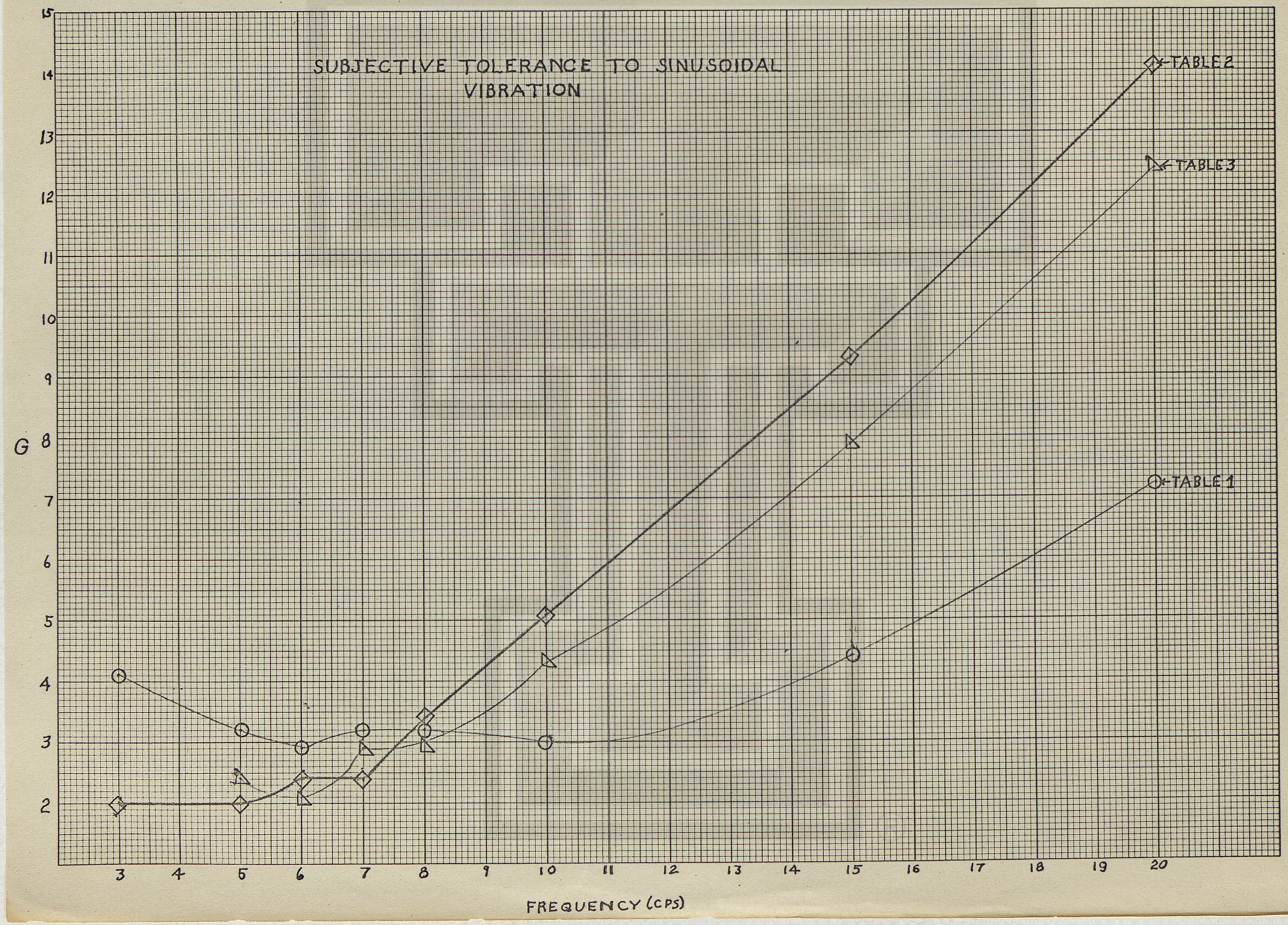
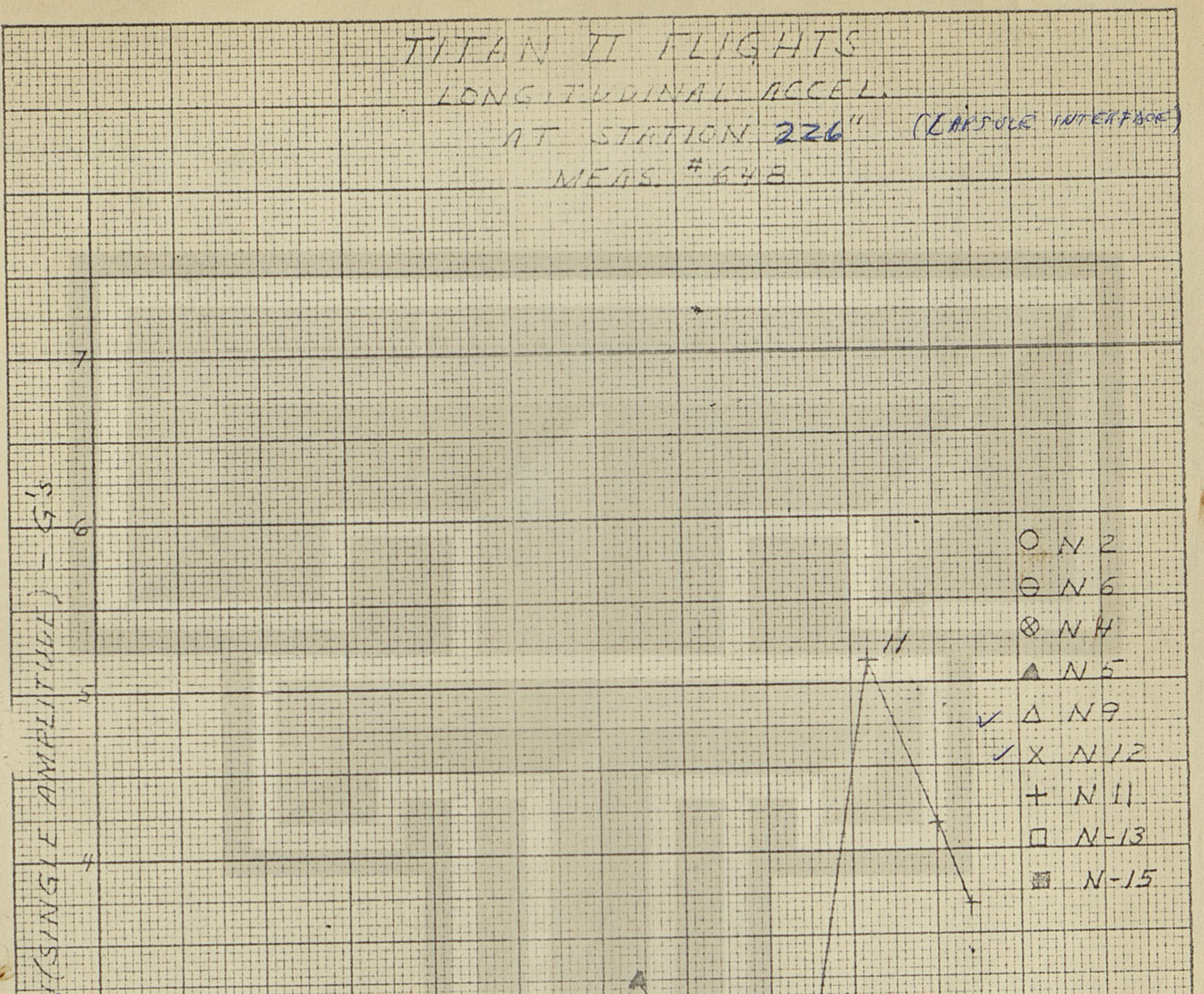
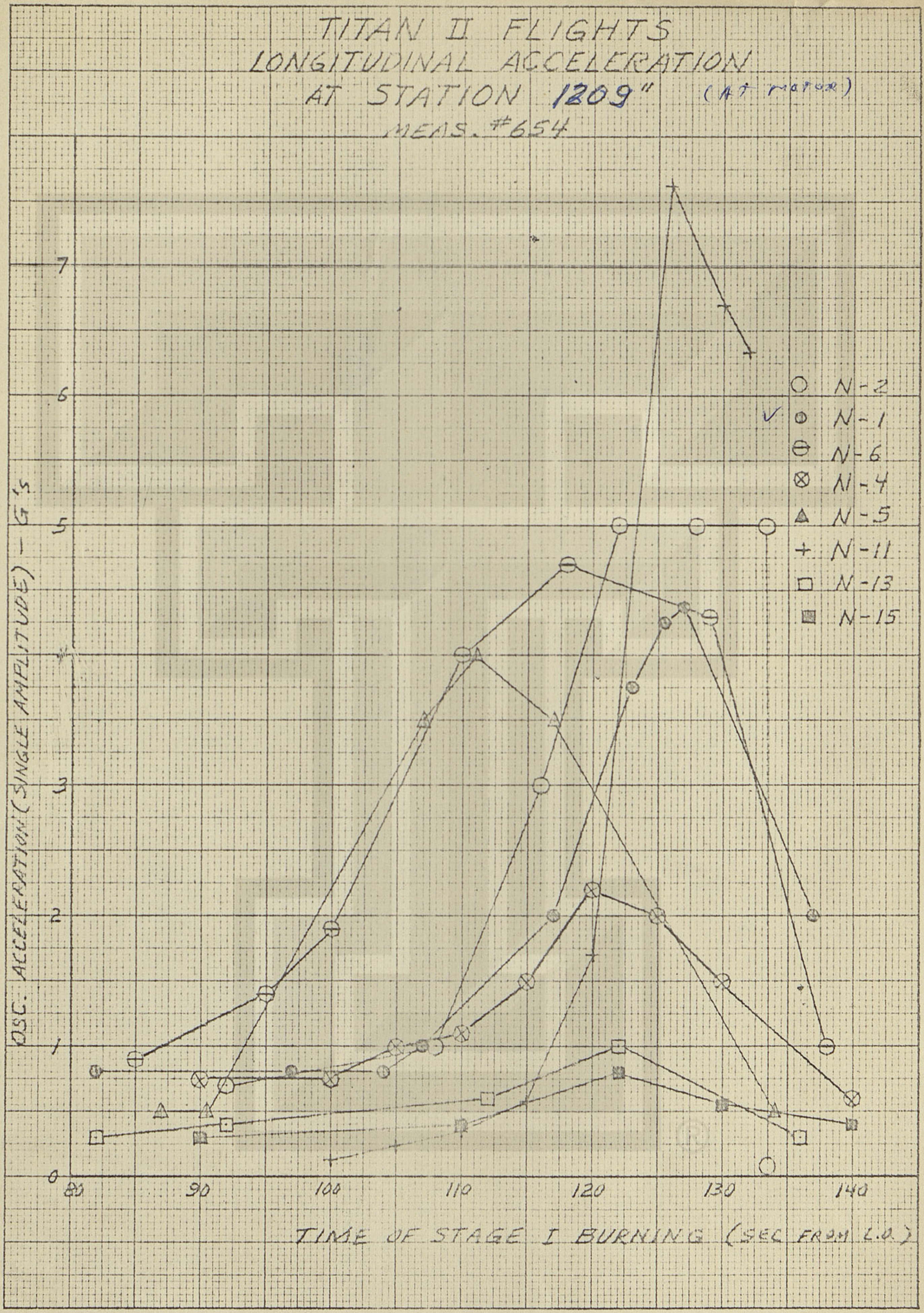



TITAN II FLIGHTS
LONGITUDINAL ACCEL.
AT STATION 226" (CAPSULE INTERFACE)
MEAS. #648
OSC. ACCELERATION (SINGLE AMPLITUDE) - G'S
TIME OF STG I BURNING
N 2
N 6
N 4
N 5
N 9
N 12
N 11
N-13
N-15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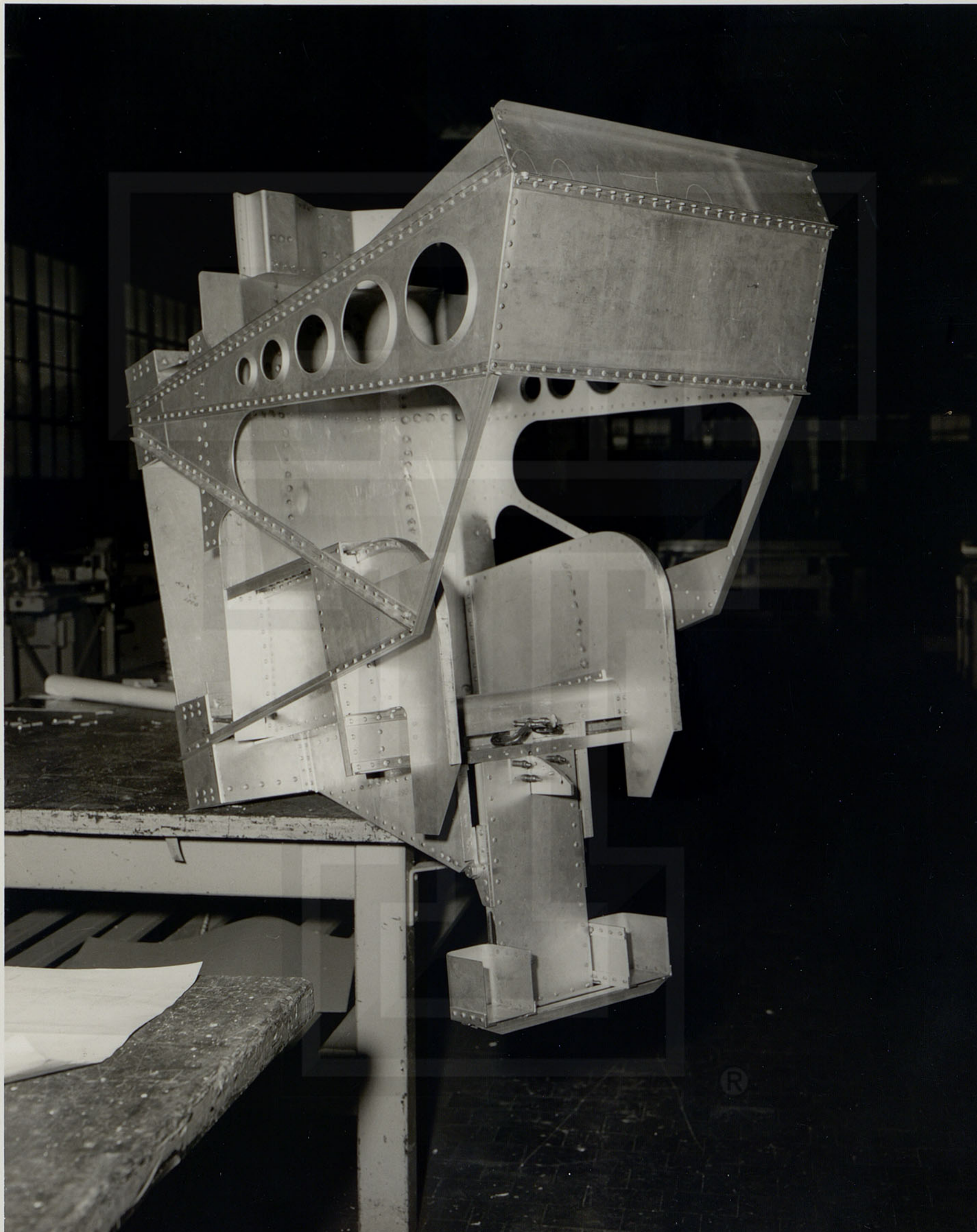
LONGITUDINAL ACCELERATION
AT STATION 1209" (AT MOTOR)
MEAS. #654
OSC. ACCELERATION (SINGLE AMPLITUDE) – G's
0
1
2
3
4
5
6
7
80
90
100
110
120
130
140
TIME OF STAGE I BURNING (SEC FROM L.O.)
N-2
N-1
N-6
N-4
N-5
N-11
N-13
N-15



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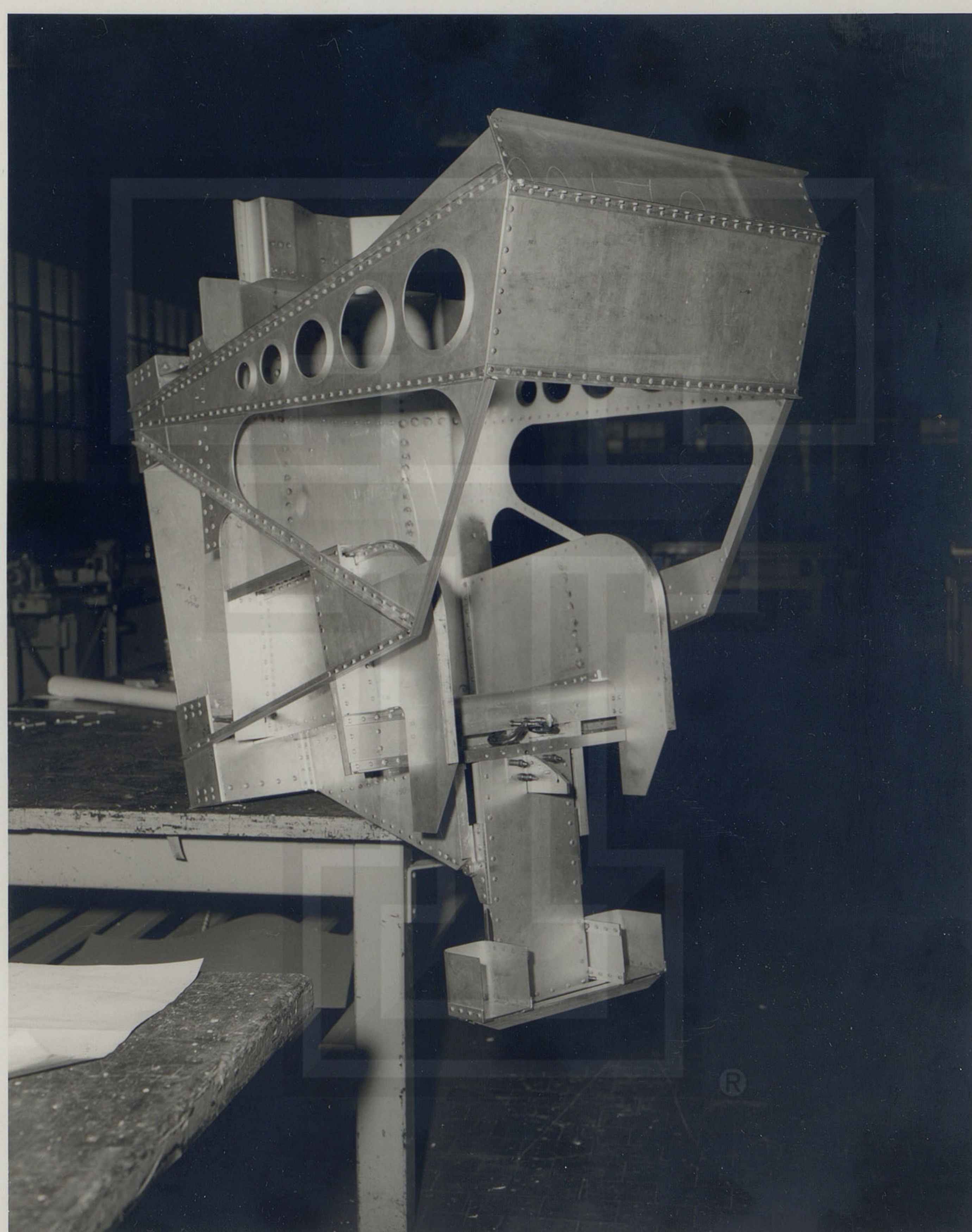

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