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UNIVERSITY OF MICHIGAN
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SEMI-ANNUAL PROGRESS REPORT

SHOCK ON ELECTRICAL COMPONENTS IN TRACK LAYING AND WHEELED VEHICLES

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FOREWORD

The work described in this report was done in the Department of Electrical Engineering, University of Michigan, under the supervision of Professor H. S. Bull.

Much of it represents the labor of Mr. Harris Olson, who devoted his entire time to the project. In addition the project has benefited from the expert counsel of Professor Jesse Ormondroyd of the Department of Engineering Mechanics and Professor David Ragone of the Department of Chemical and Metallurgical Engineering, as well as others who are specifically mentioned in the report.

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A. HISTORICAL BACKGROUND

1. Growth of Electrical Power Requirements on Vehicles

For over ten years the Army Ordnance Corps and the lamp manufacturers have been disturbed by the short life of the many types and sizes of lamps used on military vehicles. During this period the amount of electrical equipment needed on these vehicles increased progressively, necessitating large increases in battery and generator capacity. The practical limits of successful operation at 6 volts were soon exceeded, and it became necessary to redesign the electrical components for 12-volt operation. More recently the voltage has been raised to 28 volts. The redesign of the lamp-filament structure for these higher voltages had to conform to certain restrictions on bulb size and lamp wattage that led to the use of smaller wire diameter. It thus became increasingly difficult to make the filament structure capable of withstanding the vibration and road shock accompanying the operation of the vehicle.

2. SAE Committee Formation and Lines of Action

In recognition of the serious nature of this situation, the Society of Automotive Engineers (SAE), in collaboration with Army Ordnance and the lamp manufacturers, established a committee to study the problem and to initiate research covering its various phases. The principal lines of attack will be discussed.

a. Study of Shock Mounting. Experimentation with shock mounts to cushion lamp housings from the effects of damaging vibrations has been carried on in several laboratories. Chrysler recommended an isolation pad on their ordnance-truck tail lamps in 1944 to protect them against failure.[1] Later they introduced another mounting that could be adapted to all ordnance vehicles.[2] The isolation theory of protecting lamp filaments has been studied by the Ordnance Corps, the Guide Lamp Division, and the Cleveland Tank Plant of Cadillac Motors. Each reports some instances where life was increased.

b. Studies of Critical Frequencies. In an effort to meet the problem of the short life of military lamps, a number of tests were conducted for the purpose of establishing the vibratory frequency present at various lamp locations on Ordnance vehicles.

The General Motors Truck and Coach Division reported the results of an investigation conducted to determine the frequencies of vibration present at the lamp housings on a Reo Army Truck, M-48.[3] Three types of vibratory excitation were used on the vehicle: engine excitation with the vehicle stopped, the vehicle coasting on smooth road with the engine stopped, and the vehicle coasting on Belgian Block road with engine stopped. Statham accelerometers were mounted on the left front marker light, blackout drive lamp, service drive lamp, tail lamp, and instrument panel.

The principal frequencies observed and peak acceleration (in terms of g) are tabulated below.

	Engine		Smooth Road		Belgian Block	
	cps	g	cps	g	cps	g
Left Front Marker Light	50	0.89	48	1.0	48	4.0
	48	3.59				
	55-60	1.69				
	240	0.69				
Blackout Drive Lamp	28-34	1.0	32	0.8	30	3.4
	55-60	1.6				
	360	0.4				
Service Drive Lamp	47	1.4	47	0.2	47	0.8
	55-60	0.8				
Tail Light	160	0.4	10	0.6	10	1.6
	110	1.2	300	0.4	100	2.2
	80	0.6	600	0.5		
Instrument Panel	40	0.2	47	0.2	50	2.2
	50	0.2				
	360	0.2				

General Motors conducted a similar test on a GMC Army Truck, M-135. This work was motivated by observed early failures of 28 volt lamp filaments. The methods of excitation of vibration were essentially the same as in the previous test except vehicle acceleration on a smooth road and slamming the hood were added to the tests. The predominant frequencies (in cps) observed at the various lamp assemblies were as follows:[4]

Service drive light	55 to 57 cps
Instrument panel light	40 to 54 cps
Left front marker light	46 cps
Blackout drive light	110 to 550 cps
Tail light	18 cps

All vibrations of one-g acceleration or more observed at any of the lamp assemblies were in a frequency range from 8-120 cps. One exception to this was a blackout drive light where a 550-cps vibration was present at an acceleration amplitude of 2.0 g. The largest acceleration was at the tail light, where 5.6 g was recorded.

General Motors continued their tests of deriving the vibrations present in the service drive lamp on a GMC Army Truck, M-135. These tests represented a more intensive study of the service drive-lamp vibrations and the cause of filament failure. The report concluded:[5]

1. The probable cause of filament failure is the coincidence or near-coincidence of the filament resonant frequencies with the frequencies of vibration of the lamp assemblies.
2. The range in which this coincidence of frequencies occurs is from 240 to 320 cps.
3. The frequencies of vibration of the lamp in this range are due primarily to a resonant mode of the mounting panel and resonant modes within the lamp assembly itself.
4. There is some evidence from these tests that the coincidence of resonant frequencies occurs more often on the right lamp than on the left under operating conditions.

The method of excitation of vibration in this test was made by the engine running and by coasting on the Belgian Block road with the engine idling.

The Cleveland Tank Plant of the Cadillac Motor Car Division issued a report on tests conducted to isolate the tail lamp from destructive vibrations.[6] They found that the No. 1251 bulb filaments would resonate at various frequencies between 250 and 400 cps. By designing a new bracket which isolated the bulb from these critical frequencies, near-normal lamp life was experienced.

The Development and Proof Services at the Aberdeen Proving Grounds were authorized to determine the amplitudes and frequencies of vibrations encountered in wheeled and track-laying vehicles during different modes of operation. The First and Second Memorandum Reports of the project gave the maximum accelerations and corresponding frequencies found at selected stations on the vehicles. Tabulated below are representative values found in a 3/4-ton, 4 x 4, M-37 truck.[7]

Course	Engine rpm	Road Speed, mph	Accelerometer Location	rms Acceleration g's	Frequency, cps
Static	2600	-	Headlight-vertical	0.26	130
Static	2900	-	Headlight-vertical	0.25	130
Static	2600	-	Headlight-horizontal	1.11	130
Static	2900	-	Headlight-horizontal	0.52	130
Gravel	1850 (2)	10	Headlight-vertical	*0.1	-
Gravel	1950 (3)	20	Headlight-vertical	*0.1	-
Gravel	1800 (4)	30	Headlight-vertical	0.14	12
Gravel	2350 (4)	40	Headlight-vertical	0.13	28
Gravel	1850 (2)	10	Headlight-horizontal	0.13	88
Gravel	1950 (3)	20	Headlight-horizontal	*0.1	-
Gravel	1800 (4)	30	Headlight-horizontal	*0.1	-

(2) Second Gear, (3) Third Gear, (4) Fourth Gear. *Less than

When the results from all the tests are studied two facts emerge:

1. Peak accelerations were never very great on any of the vehicles studies.

2. The vibratory frequencies ranged from about 40 to 150 cps, including excitation by the engine alone, and by road shock. For some reason, tail lamps occasionally experienced higher frequencies.

c. Vibration Studies Using a Shaker Table. Magnetic vibrators have been used frequently in the study of filament behavior. Hubbard determined the resonant frequency of a composite lamp by the use of such an instrument.[8] Mahon used a similar procedure in determining the frequencies that produced failures in the Cadillac tank tail lamp.[9] They vibrated both the bulb and the entire tail-lamp assembly, and through this procedure they were able to design corrective mountings.

J. P. Terry, of Tung-Sol Electric, ran a series of tests to determine the critical frequencies of Ordnance lamps.[10] His means of excitation was a M-B vibrator which is an electromagnetic vibrator. Later he ran similar tests on lamps with certain filament changes for improvement of lamp life.

Lewis R. Hetzler of GMC Truck and Coach Division used a shaker table in his work on lamp failures.[11] His table was a 25-watt speaker adapted to excite lamps at their natural frequency. He used this for vibratory life tests and for calibration of special indicator lamps.

The magnetic vibrator is an ideal instrument for the study of critical frequencies in incandescent lamps. The vibrator can be tuned to the frequency desired for an individual lamp. The use of the shaker permits either determination of a natural frequency or the testing of a lamp at a certain frequency.

d. Studies of Lamp Performance under Service Conditions. The Ordnance Corps has undertaken some ambitious programs for the determination of the life expectancy of lamps and how failures occur in service. These tests have been instigated for varying purposes, such as comparison of experimental sealed-beam units, determination of lamp failures in vehicles undergoing durability operations, endurance tests of all-glass units and winter tests on shock-mounted tail lamps. Collectively, seventy-three vehicles participated in these tests. The tests included most of the common wheeled and track-laying vehicles.

The data presented in the Ordnance Corps reports are quite general and do not give a clear story of all the lamp failures.[12] From the given data the following observations can be made:

1. Failure frequency does not seem to have much correlation from test to test.

2. The all-glass sealed-beam service drive lamp appears to have a longer life expectancy than a composite unit.

3. Climatic conditions probably have no effect on the life of lamps.

4. Lamps used in wheeled vehicles have a longer life than similar lamps in track-laying vehicles.

5. The failure in service drive lamps occurs in both major and minor filaments almost equally.

On April 9, 1953, a conference was held at the Aberdeen Proving Ground for the purpose of discussing the short life expectancy of 28-volt Ordnance lamps. Lewis Hetzler examined a collection of approximately ninety failed 28-volt lamps. His observations of the failures indicated the following:[13]

1. Type 1683, 32 CP stop lamp: construction is actually two 12-volt filaments in series.

    a. Tung-Sol TS 1683: all failures appeared to have occurred with power applied. Filaments apparently broke off at one support and subsequently vibrated against it causing arcing which melted the support down to half normal length. Ten units were observed.

    b. GE type 1683: all but one failure appeared to be when cold. Breakage appeared to be a clear case of fatigue due to vibration. Failure occurred at or near the weld. Eight units were observed.

2. Failure of type 1251, 3 CP bulb appeared to be identical in all makes. In general, filaments are tangled and broken indicating severe vibration of the whole structure.

3. The headlamp units with Tung-Sol (1), GE (12), and Westinghouse (3) inner bulbs all had identical failures. Failure occurred near the support arm apparently due to fatigue of the filament caused by vibration.

All the reports established the fact that early failures do occur in Ordnance lamps. There is a lack of information in each report which reduces its usefulness. One report might establish life expectancy of lamps in vehicle miles and hours, another might establish failure characteristics, and another, failures of one specific lamp. The conditions of the tests varied widely which made correlation of data impractical. Future service tests could perhaps be planned to give more detailed data on field failures.

e. Lamp Durability Determined by Impact Machines. The impact method of setting up vibration has been used for many years in determining the durability of vehicular lamps. As long ago as 1940 the SAE approved a design for a vibration machine[14] which was essentially a form of impact machine adapted to test vehicular lamps.

On May 1, 1943, the Ordnance Corps requested the Chrysler Engineering Division to build a machine to be used in determining the durability of vehicular lamps by the impact method.[15] This machine, now known as the Ordnance Incandescent Lamp Impact Tester, performed very satisfactorily and has been used more or less continuously ever since, both for routine acceptance testing and for special research problems.

In acceptance testing, a specified number of lamps were drawn from each shipment and mounted on the impact tester. Careful records were kept of the number of surviving lamps at the end of each hour of contiuous operation of the machine. If after, say, 10 hours, the number of lamps surviving was considerably below an arbitrary norm, the shipment was rejected.

Hetzler studied the operation of this machine and concluded[17] that the severity of the test was much greater than a vibratory test on the shaker table.

f. Studies of Possible Changes in Filaments. The possibility of improving lamp life by altering the filament structure has been given considerable attention. Chrysler, in 1944, tested a number of lamps having various filament diameters and efficiencies and various arrangments of lead wires.[18] Hetzler, of GMC Truck and Coach, made several recommendations of filament changes which were tried by the lamp manufacturers. Very little improvement in lamp life has resulted from these efforts to date.

g. Use of an "Indicator Lamp". Visual observations of filament motion are not always possible. The vibratory motion of a cold filament can usually be observed by illuminating it with the flashing light of a stroboscope tuned to the proper frequency. The image of a hot filament, enlarged by suitable lenses, can sometimes be projected on a screen and its displacement due to vibration can then be measured. Both methods, of course, work best under controled conditions in the laboratory.

In the course of Hetzler's study of filament failures, a unique method of observing the vibratory motion of a hot filament was employed.[19] This was accomplished by modifying the structure of a type 2416 lamp to permit to so-called "Edison effect" to be utilized. Figure 1 shows the lamp as modified. The minor filament has been omitted and its supporting rod now can function as an anode to collect electrons emitted by the heated major filament.

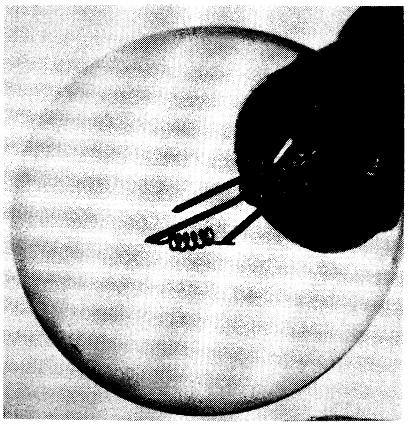


Fig. 1.

Figure 2 shows the operating circuit. The number of electrons reaching the anode per second will, of course, be a function of the voltage gradient between the anode and the hot filament. This in turn is a function of the separating distance. As the filament vibrates, the variations in current collected by the anode are converted into output-voltage variations which can be observed on an oscilloscope. Figure 3 shows the performance of a typical lamp.

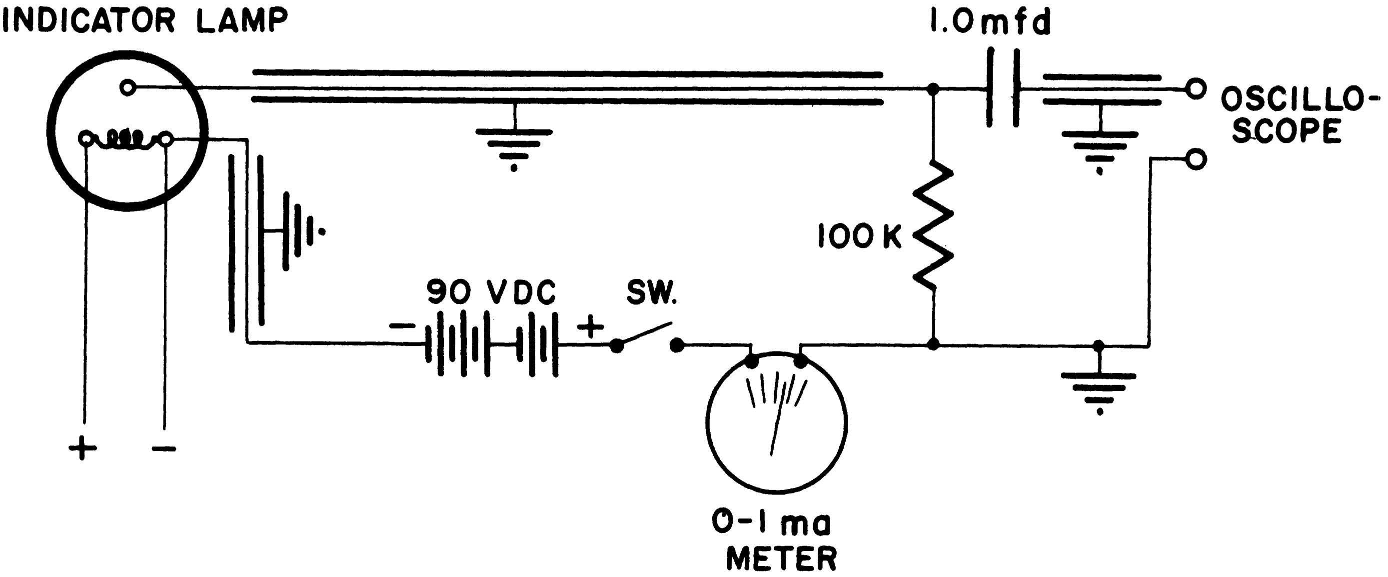


Fig. 2. Schematic Diagram of the Indicator Lamp Circuit.

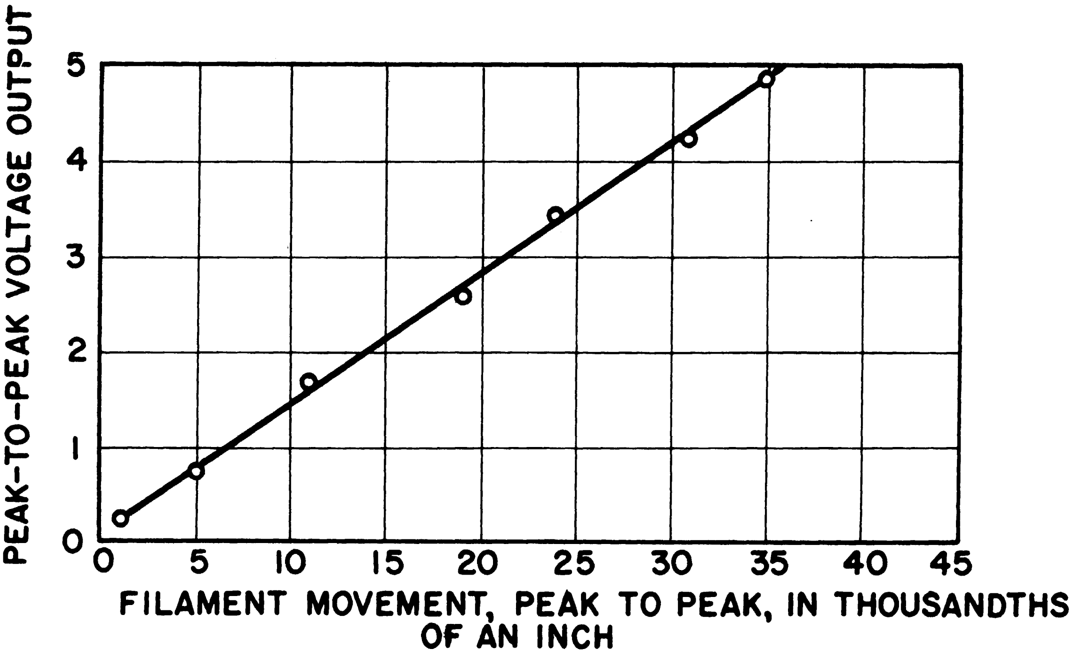


Fig. 3. Calibration Curve for No. 66 Special 2416 Indicator Lamp.

Calibration is accomplished in the following manner:

1. The indicator lamp is mounted on a shaker table and an optical system set up to project the image of the hot filament on a ruled screen.

2. The shaker table is adjusted to vibrate the lamp filament at its critical frequency.

3. Simultaneous measurements of the peak-to-peak motion of the filament image and the peak-to-peak amplitude of the voltage wave are made and plotted.

4. Several different amplitudes of filament vibration are secured by varying the power input to the shaker table, and the measurements described in step 3 are repeated. Care must be taken to avoid amplitudes that might permanently distort the filament.

B. THE ORDNANCE RESEARCH PROJECT AT THE UNIVERSITY OF MICHIGAN.

In April, 1953, a research program sponsored by the Detroit Arsenal, acting for Army Ordnance, was started at the University. At first it was directed primarily at the problem of the effects of vibration and mechanical shock on the electrical components of wheeled and track-laying vehicles. In September, 1953, the program was broadened in scope, and by November research work got under way on the broadened program.

A listing of the principal items in this program follows:

1. Significant physical and operational properties of tungsten filaments.

2. Possible new methods of constructing and mounting filaments to improve lamp life.

3. Methods of testing large numbers of lamps and correlating such tests with actual lamp performance.

4. Possible modifications of the Ordnance lamp impact tester that might improve its performance.

5. Rewrite lamp specifications for military vehicles.

6. Coordinate the studies and testing programs of the makers and users of lamps for military vehicles.

The research activities at the University dealing with this new program will now be described and the accomplishments during the period from November, 1953 to May, 1954 will be discussed.

1. Further Work with the Indicator Lamp

Using Hetzler's techniques the Michigan project has made frequent use of indicator lamps. They have been mounted on a magnetic shaker table and vibrated at their resonant frequency with varying amplitudes in order to observe the peak-to-peak displacement required to produce destruction or permanent distortion of the filament. They have also been used on the Ordnance impact tester in conjunction with an accelerometer to determine the acceleration values associated with severe filament distortion. They have been helpful in evaluating the performance of a new and simplified form of impact tester in its early stage of development.

The project has been supplied with a considerable quantity of indicator lamps by the three major lamp manufacturers. Although all these lamps have employed the 2416 major filament and have been nearly identical in physical dimensions and in appearance their performance characteristics have differed greatly. Only about 10 percent of all lamps received have developed a-c output waves of usable shape and amplitude. Quite a few have shown no output whatever. Others have been discarded because of square-wave outputs, oscillation at about 25 kilocycles or sudden changes in either the a-c wave shape or the d-c current or both. It is obvious that the anode-to-cathode spacing is very critical, but the theory underlying the operation of these lamps is still not clearly understood as regards the critical parameters. Before indicator lamps can be used reliably in either laboratory or field tests further study of their properties is required.

2. The Magnetic Shaker Table

Soon after the Michigan project got under way it became evident that a magnetic shaker table would be very useful, and steps were taken to secure the components needed for its assembly. These are listed below.

Jackson audio-frequency oscillator, Moden 652,
Grommes amplifier (Precision Electronics Inc.),
General Electric 12" speaker type 1200 D,
Lamp adapters.

When it was desired to subject a lamp bulb to vibration of a particular frequency, the bulb was mounted in a suitable adapter and clamped to the speaker cone. The oscillator was then tuned to give a signal of the desired frequency and this signal was fed to the amplifier. The output from the amplifier drove the speaker at the selected frequency.

A Jones and Lamson optical comparator happened to be available in the laboratory. Hence, when measurements of hot-filament deflection under a vibratory stimulus were desired, the shaker table, with bulb attached, was placed on the comparator and the motion of the filament image on the comparator screen could then be observed and measured.

To facilitate life-testing of a bulb on the shaker table, a photoelectric-cell and magnetic-relay combination was so arranged that the failure of the filament darkened the photocell and tripped the relay, thus shutting down the oscillator and amplifier.

The more obvious advantages of a magnetic shaker table for use in vibratory studies are as follows:

1. It is compact, portable and inexpensive.

2. May be operated over a wide range of frequencies.

3. May be oriented in almost any position.

4. Permits quick determination of the critical or resonant frequencies of either hot or cold filaments.

5. Has a fairly smooth sinusoidal output.

Some of the disadvantages are:

1. Can only be used to test one lamp at a time.

2. Cannot develop a large acceleration.

3. The audible tone accompanying its operation is often disturbing.

Figure 4 shows the speaker and its associated amplifier and oscillator or arranged for use.

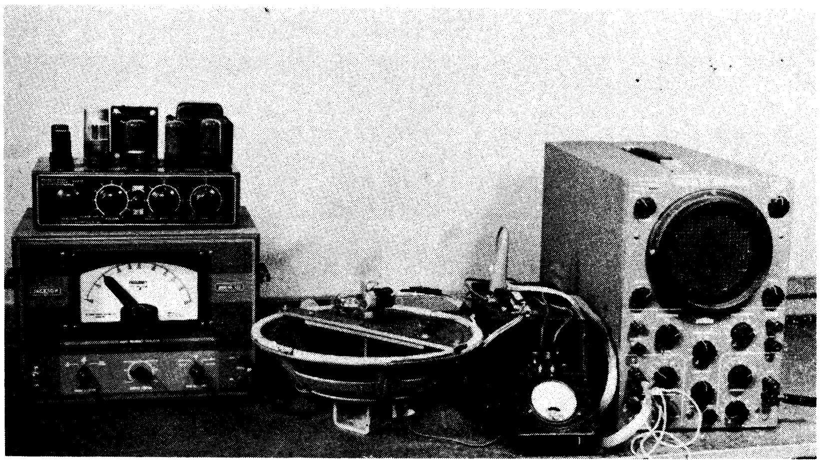


Fig. 4.

3. Studies of the Arsenal Impact Tester

Early use of the impact tester, designed for Army Ordnance (Detroit Arsenal) by Chrysler Engineering, indicated its probable value as a means of acceptance testing of lamps purchased for military vehicles. Copies of the drawings and specifications were therefore sent to the major lamp companies, to several truck manfuacturers, and to the Bureau of Standards, and each of these concerns proceeded the build impact testers for their own use. It soon became apparent however, in comparing data taken on different, but presumably identical, machines, that considerable differences existed in the performance of these machines. Consequently, a careful study of the design and operation of the Arsenal impact tester was made an important item in the agenda of the Michigan research program.

The tester arrived on November 5, 1953. Careful comparison of the machine with the drawings disclosed the following discrepancies:

1. The lamp holder plates had collets of an entirely different design.

2. No wiring was provided for the neon glow lamps used as indicators.

3. No provision was made for Amphenol connectors and connecting wires on the back plate.

4. The movable arm was not coated with a sound absorbent.

5. The cam was inaccurately ground.

6. The pulley sizes differed slightly from specifications.

The a-c motor which came with the tester was replaced by a 220-volts d-c adjustable-speed motor which permitted rotation of the cam shaft at almost any desired speed between 100 and 1000 rpm.

a. High Speed Film Studies. In order to reveal any peculiarities in the motion of the cam follower and the upper anvil, a series of high-speed motion pictures was taken of the tester in operation. A Fastax 16-mm high-speed camera and a skilled operator were secured from the University's Rocket Propulsion Laboratory. The camera, with a 4-inch lens, was mounted 16 feet from the front of the tester. Supplementary lighting was provided by two No. 2 photoflood lamps. Two parallel reference lines, one inch apart, were placed in the front surface of the upper and lower anvils in direct view of the camera. The camera was loaded with Eastman Super XX negative-type film.

Seven runs were taken, one for each of the following cam speeds: 980, 800, 700, 600, 482, 400, and 300 rpm. The camera speed in each case was 2000 frames per second. These films were studied carefully, frame by frame, in an Eastman film reader. They were also projected at standard speed, thus giving a slow-motion view of the tester in operation. The prints shown in Figure 5 and 6 illustrate typical behavior at the highest speed (film 1) and the lowest speed (film 7), respectively.

Studies of these films revealed the following behavior pattern:

1. At the higher cam speeds, the two anvils never seemed to come in contact. All contacts occurred between the cam and cam follower.

2. At the higher speeds, some oscillation of the arm about an axis through the cam follower was observed.

3. Noticeable bouncing of the cam follower on the cam occurred.

4. At 600 rpm and below, the cam follower began to respond more faithfully to the cam, less oscillation was produced and the pattern of anvil motion became more repetitive.

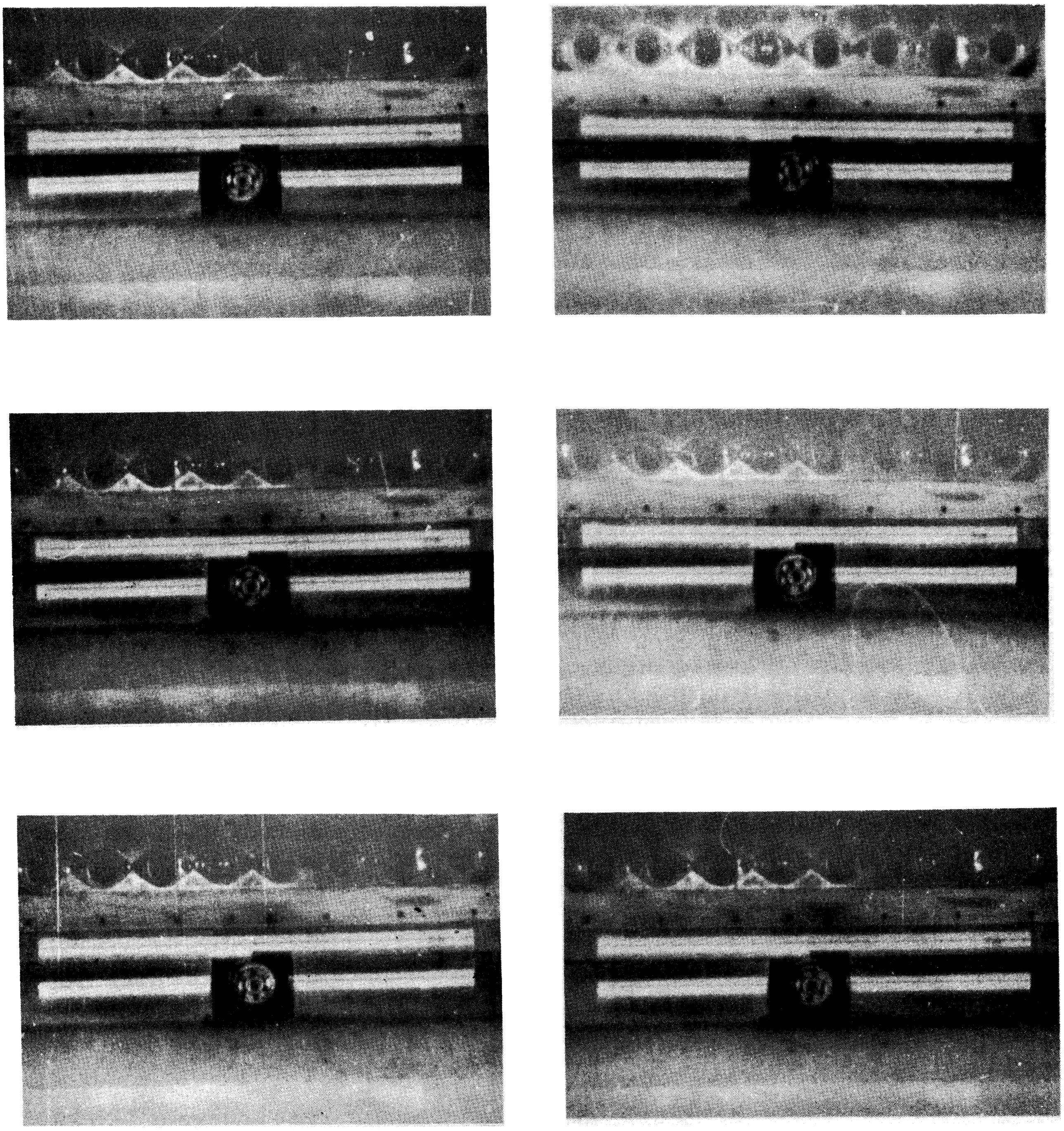


Fig. 5

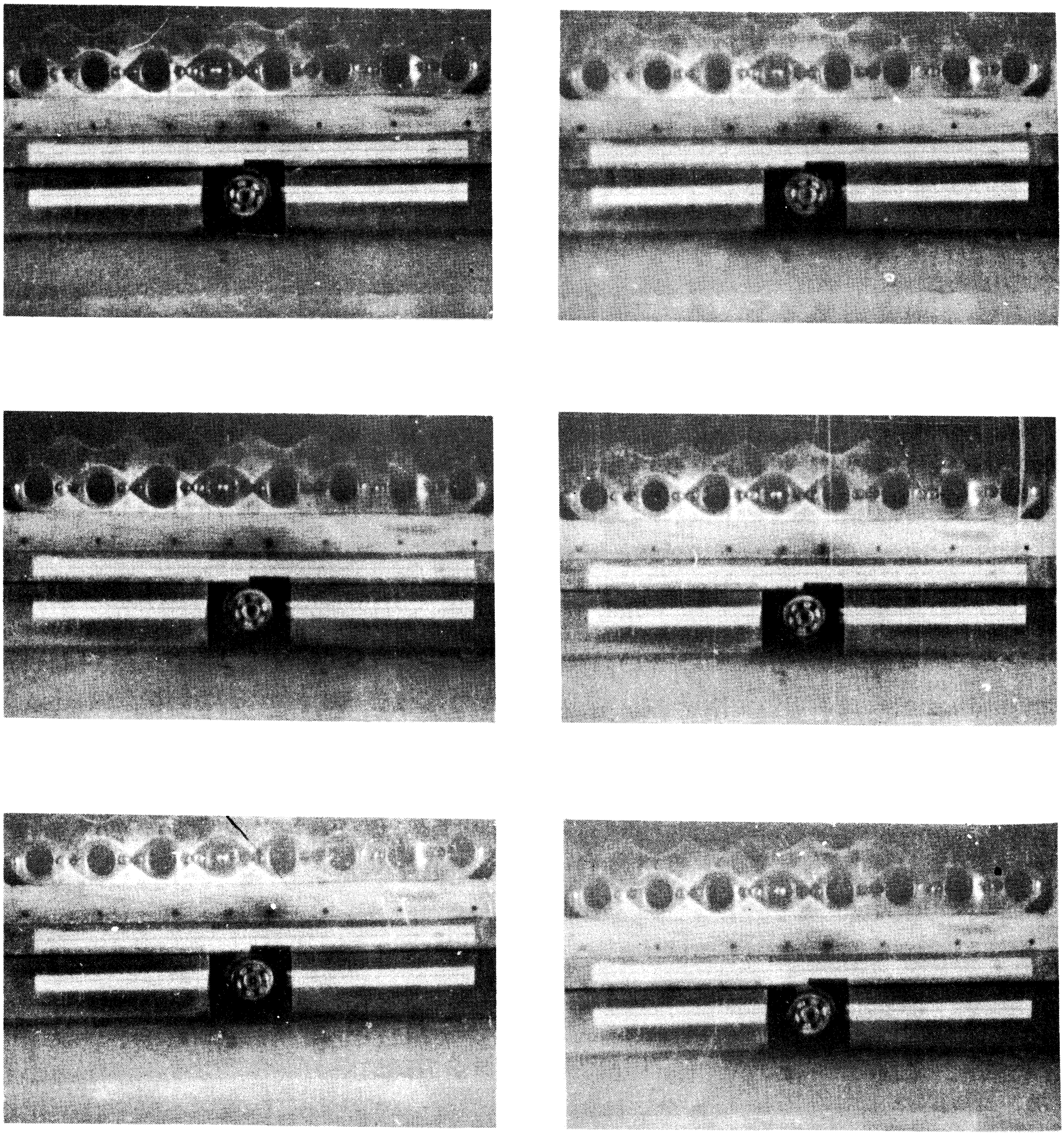


Fig. 6

The following conclusions were tentatively established by these high speed films:

1. The original specification of 900 rpm for the cam speed was much too high.

2. Theoretical studies of the mechanics of the arm and hinge combination were needed.

3. More quantitative data on the performance of the tester were needed, utilizing accelerometers, displacement measurement devices, and indicator lamps in various combinations.

b. Determination of Mechanical Constants. The natural frequency of oscillation of the movable arm of the tester when attached to the back plate by means of the original bolted mounting was 4.69 cps. This measurement was taken with a 7.5-pound lamp-holder plate attached to the arm.

When this arm-and-plate comination was disconnected from the back plate and suspended as a pendulum from the back edge, its period was 1.24 seconds per cycle. The weight of arm, plate, and suspension accessories was 23.1 pounds.

The center of gravity for the arm-and-plate combination was 3.62 inches from the front edge of the anvil.

With the arm attached to the back plate, the lower anvils were removed in order to permit a determination of the amount of sag. It settled a distance of 0.229 inch immediately and dropped to 0.232 inch after 24 hours.

The amount of force needed to separate the anvils was measured by mounting a spring balance in front of the lamp holder plate as shown in Figure 7. The results are shown in Figure 8a.

In the process of determining these mechanical constants, a serious weakness in the design of the tester was disclosed. A very slight change in the tension of bolts attaching the arm to the back plate made a large difference in the amount of lifting force needed. It seemed obvious that changes in bolt tension might be an important factor affecting the nonrepetitive action of the tester in service. A new type of elastic hinge was designed and used as a means of attaching the arm to the back plate (see Fig. 9).

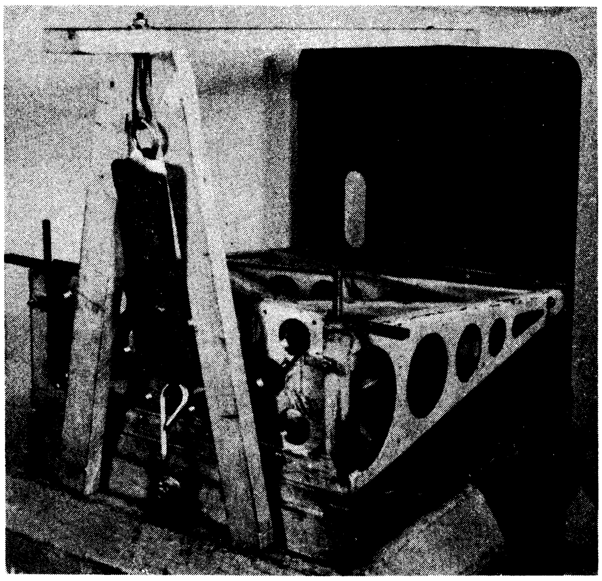


Fig. 7.

The mechanical constants for the arm with this new type of hinge are as follows:

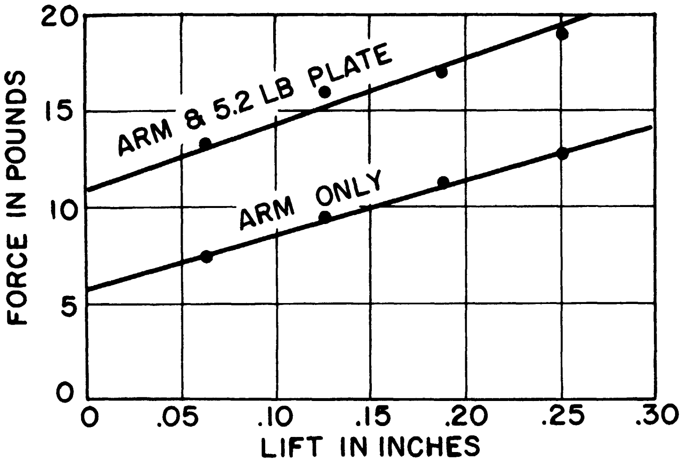
The natural frequency of the arm alone, with the .0815 inch hinge was 9.0 cps. With a lamp holder plate weighing 5.2 pounds attached it was 6.92 cps.

The center of gravity was 7.44 inches from the front edge of the anvil for the arm alone, and 5.0 inches with the plate attached.

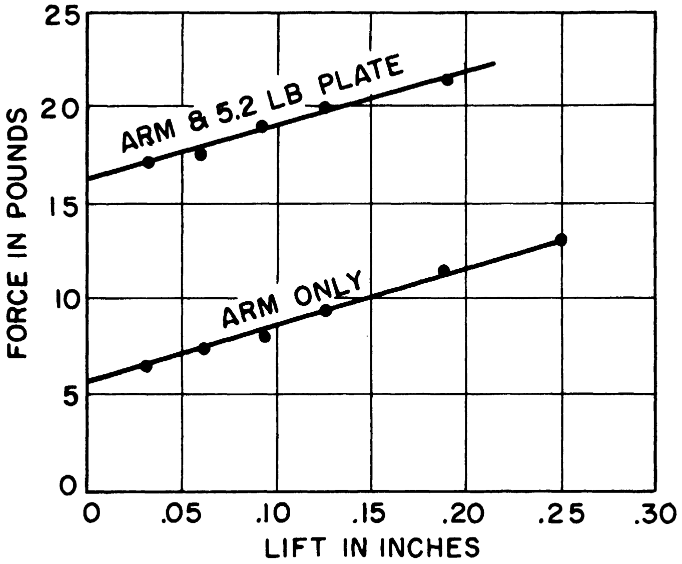
The settling distance was 0.185 inch without the plate.

The pendulum action was observed and the results are indicated below:

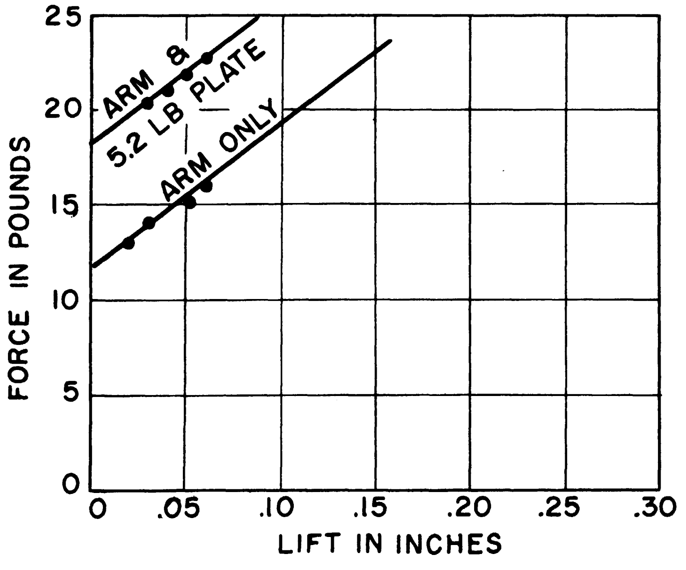
	Period Sec	Weight including Suspension Accessories
Arm only	1.2	22.56
Arm and 3.8-lb plate	1.24	26.36
Arm and 5.2-lb plate	1.255	27.76
Arm and 10.2-lb plate	1.272	32.76



a. Original Elastic Hinge.



b. New Elastic Hinge 0.050 in.



c. New Elastic Hinge 0.081 in.

Fig. 8

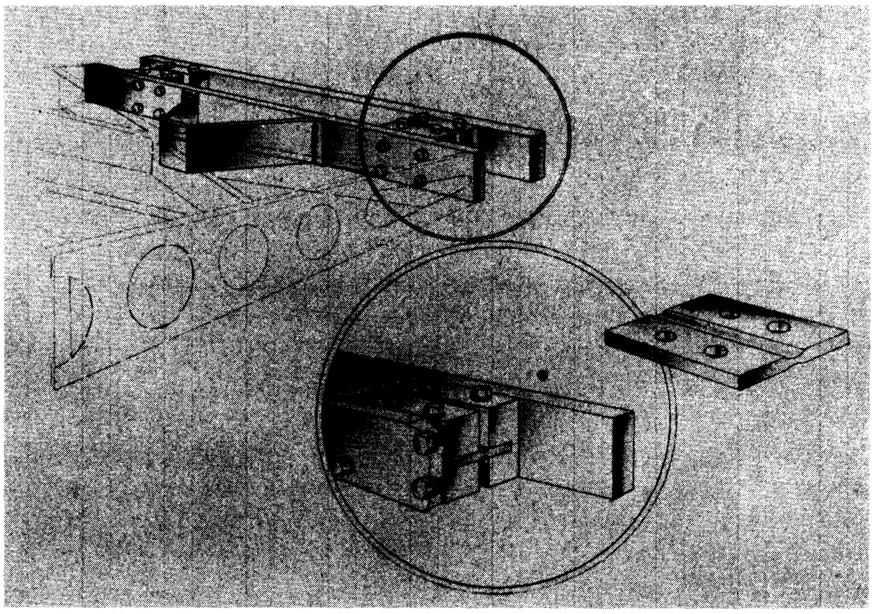


Fig. 9.

The amount of force needed to separate the anvils was determined in the same manner as before, using new elastic hinges of two thicknesses. Figure 8b shows the results obtained for an elastic hinge of 0.050 inch thickness, and Figure 8c for the 0.0815 inch hinge.

c. Theoretical Analysis of Impact Tester.

1. Lamp filaments fail on vehicles under two conditions:

    a. In bending resonance of the two-noded mode of motion excited by motions caused by a high harmonic of the engine torque or force, and

    b. By repeated bending in the two-noded mode at the natural frequency of this mode excited by the motion of the vehicle passing over bumps.

The two laboratory tests which can be used to fail the filaments are:

    a. Steady state vibration on a loud speaker coil at the two-noded-mode resonant frequency, and

    b. Inpact loading which excites the two-noded mode in free vibrations of large enough amplitude to cause ultimate failure.

The actual conditions and the test conditions both excite the two-noded mode of motion; therefore, the effects under both conditions are comparable. Therefore, a lamp which shows superior life under the laboratory conditions should show superior life under road conditions.

2. Study of impact test of lamp filaments. The lamp is mounted in a frame which is attached to the end of a pivoted truss-like arm. The arm is lifted up on a rotating cam and permitted to fall off the end of the cam onto an anvil. The downward motion of the frame is suddenly stopped by the anvil, its motion is reversed by elastic bouncing, and the filament is set in free vibration in its two-noded mode. When this happens often enough the filament fails in fatigue.

The motion of the plate containing the lamp after it leaves the cam is

$$X = A \sin p_1 t + B \cos p_1 t \quad (+ \text{ upward}).$$

when $t = 0$, $x = h + \Delta$ and $\dot{X} = \frac{Nh}{60}$,

where h = height of cam ledge ,

Δ = initial upward set of plate when in contact with the anvil,

N = rpm of cam.

Under these conditions,

$$X = \frac{N}{60p_1} h \sin p_1 t + (h + \Delta) \cos p_1 t \ ,$$

$$\frac{\dot{X}}{p_1} = \frac{N}{60p_1} h \cos p_1 t - (h + \Delta) \sin p_1 t \ .$$

When $X = \Delta$ the plate strikes the anvil. At this time,

$$\dot{X}_1^2 = h^2 p_1^2 \left[1 + \frac{N^2}{3600 p_1^2} + 2 \frac{\Delta}{h} \right],$$

or

$$\overset{\prime}{X}_1 = -hp_1 \left[1 + \frac{N^2}{3600p_1^2} + 2\frac{\Delta}{h}\right]^{1/2} .$$

For the Arsenal impact tester,

$$p_1 = 26.5 ,$$

$$\frac{\Delta}{h} \approx 4 ,$$

$$h = 0.0625 .$$

Therefore, the striking velocity is in the neighborhood of

$$V = \overset{\prime}{X}_1 = -3 \frac{26.5}{16.0} = \frac{79.5}{16.0} = -4.97$$

$$\text{in./sec} \approx -5 \text{ in./sec.}$$

If the frame bounces off the anvil without loss of energy (e=1), the motion of the frame during contact with anvil is

$$X_2 = \frac{V}{p_2} \sin p_2 t ,$$

where

$$p_2^2 = \frac{K}{m} \text{ (+ downward)}$$

and K = spring constant of anvil and frame in contact, V = initial velocity of striking (say the 5 in./sec mentioned above), m = mass of frame.

It may happen that the flexibility of the truss-like arm dominates the rebound acceleration of the system. In this case the accelerations will be much smaller than that estimated below. The spring constant of the anvil plus frame in contact is

$$K = \frac{1}{2}\frac{EA}{d}\frac{1}{1 + 1.38\ \delta/d} \approx \frac{1}{2}\frac{EA}{d}$$

since $\delta \to 0$, where

E = Modulus of elasticity of material in anvil and frame,
A = Cross-sectional area of anvil face,
d = Depth of material in anvil,
δ = Depth of irregularity on anvil surface which keeps anvil contact area less than the cross-sectional area A.

In the Arsenal impact tester,

$$E = 30 \times 10^6 \text{ lbs/in.}^2$$
$$A = 7 \text{ in.}^2 ,$$
$$d = 1/2 \text{ in.} ,$$
$$K = 1/2 \, \frac{30 \times 10^6 \times 7}{1/2} = 210 \times 10^6 \text{ lbs/in.}$$

The plate weighs about 20 lb; therefore,

$$m = \frac{20}{386} = .0518 \, \frac{\text{lb sec}^2}{\text{in.}} ,$$

$$p_2^2 = \frac{210 \times 10^6}{.0518} = 40.6 \times 10^8 ,$$

$$F \approx 10000 \text{ cycles per sec} ,$$

$$p_2 = 6.36 \times 10^4 = \frac{2\pi}{T} ,$$

$$T = \frac{2\pi}{6.36} 10^{-4} = 0.986 \times 10^{-4} \text{ sec.}$$

Time of contact is of the order of 9.86×10^{-5} sec. or 99 microseconds.

The acceleration of the plate during the contact period is

$$\ddot{X}_2 = -p_2 V \sin p_2 t .$$

The maximum acceleration is about 824 g. This estimated value of the acceleration is about 16 times larger than the 50 g which is reported to have been measured at the table. This indicates clearly that the flexibility of the truss-like arm dominates the rebound accelerations. The practical conclusion from this is that the anvil surface does not have to be optically flat.

A detailed investigation of the operation of the impact tester seems to indicate that the upper and lower anvils do not act as short beams in pure compression. There is good evidence to believe that the upper anvil is bent in the vertical plane so that its effective flexibility is due to bending rather than to compression. The Statham accelerometer used in most of the tests on the machine indicates accelerations in the region of 30 to 70 g. If these values are correct the effective spring constant for the anvil impact is of the order of 1×10^6 lb/in. instead of 210×10^6 lb/in. However, a Gulton accelerometer does indicate peak accelerations in the neighborhood of 800 g. The difference in the accelerometer readings in the same type of impact has not yet been explained.

If the bulb is held very tightly in the mounting plate, the acceleration, $\ddot{X}_2 = -Vp_2 \sin p_2 t$, is transmitted to the base of the bulb. The motion of the filament taken as a system of one degree of freedom is obtained from the solution of

$$\ddot{X}_3 + p_3^2 X_3 = Vp_2 \sin p_2 t \quad (+\text{ downward}) \; .$$

when

$$t = 0 \; ,$$

$$X_3 = 0 \; ,$$

$$\dot{X}_3 = V \; ,$$

$$X_3 \doteq 2 \frac{V}{p_3} \left[\sin p_3 t - \frac{1}{2} \frac{p_3}{p_2} \sin p_2 t \right] .$$

since

$$p_2 \approx 63600$$

and

$$p_3 \approx 2000,$$

The forcing term $1/2 \; p_3/p_2 \sin p_2 t$ is negligible; besides, it stops operating as soon as the plate bounces off the anvil. If the truss arm dominates the bounce, this is no longer true. However, this merely reduces the factor 2, in front of the extension, to a number between 1 and 2.

Assuming the forcing term to be negligible,

$$X_3 \approx 2\frac{V}{p_3} \sin p_3 t \approx .005 \sin 2000\, t \quad .$$

This is independent of the acceleration on the anvil. The main purpose of the frame motion is to give the initial velocity, V, to the filament.

If seems that this could be accomplished is some simpler way than the present impact machines--where so much "sound and fury" leads to such a gentle result. The motion of the filament, being damped, actually begins to die away as soon as the bump is over so that the X_3 given above is only the maximum value of the actual motion. The next bump excites the filament in a variety of ways depending on the timing between bumps in relationship to the natural period of the vibrating filament and its damping. The maximum amplitude that the filament will attain depends on the phasing of the filament motion and the bump motion. Probably this phasing is quite different in every impact machine. Therefore, it would not be surprising if the results on different impact machines of the same apparent design differed greatly.

Dropping the bulbs themselves through a distance of 1/32 inch and letting them bounce would apply as much motion and stress to the filament as the present impact machines apply.

4. Comparative Study of Chrysler and Arsenal Testers

a. General Procedures. At this stage of the investigation it appeared that much useful information on tester performance could be obtained if it were possible to have two testers, supposedly of identical design, available in the laboratory for comparison. Chrysler Engineering cooperated splendidly by loaning their impact tester to the Michigan project. It arrived December 21, 1953.

Hetzler and Tucker of GMC Truck and Coach Division brought measuring and recording equipment which they had been using in their studies, and took some acceleration measurements on the two machines under varies operating conditions. The instruments used were:

1. Statham A5A - 100 - 350 Accelerometer ,
2. Consolidated Amplifier,
3. Miller Oscillograph, and
4. Calibrated Indicator Lamp.

The accelerations recorded in these tests are shown in the following table:

	CAM SPEED (rpm)									
	980	840	800	750	700	650	600	550	473	400	350
Arsenal Tester 4.44-lb Plate	47 36.8	36.55*	34.35	28.9	32.3	33.6	32.45	30.63	33.35	35.6	34
Arsenal Tester 9.47-lb Plate	33					22			22.7		23
Chrysler Tester 4.44-lb Plate		37.1		36.1		36.4		36.2	36.65	35.95 36	37
Chrysler Tester 9.47-lb Plate		27				25.5			24		23
Chrysler Tester 8.66-lb Plate (Cable Loose)		36.3				35.6			36.2		35.75
Chrysler Tester 8.66-lb Plate (Cable Attached)		36				34.2			35.2		34.6

* 900 rpm

Examination of these data yields the following conclusions:

1. With operating conditions as nearly identical as possible, the two machines developed quite different peak accelerations.

2. Each machine showed changes in peak acceleration with speed changes. In general, the higher speeds developed the greater acceleration values.

3. The average peak acceleration for the Arsenal machines ranged from 47 g to 28.9 g. On the Chrysler machine the range was from 37.1 g to 35.95 g.

4. Repetitive runs on the same machine with the same operating conditions usually gave different acceleration values.

These tests were taken with the original hinges on the Arsenal machine

Hetzler and Tucker assisted also in conducting the following test on the Chrysler and Arsenal machines. With the cam stationary, feeler gauges of various thicknesses were inserted between the anvils and pulled out suddenly, thus causing an impact. Two runs were taken on the Chrysler machine and one on the Arsenal machine. The results are shown in Figure 10. It will be noted that the acceleration values on the Chrysler machine are consistently higher.

During the course of a visit to Aberdeen Proving Grounds on February 17, 1954, arrangements were made for the loan to the project of a Midwestern multichannel recording oscillograph, an accelerometer, and the necessary auxiliary equipment. This equipment was used extensively in further studies of the behavior of the Chrysler and Arsenal testers.

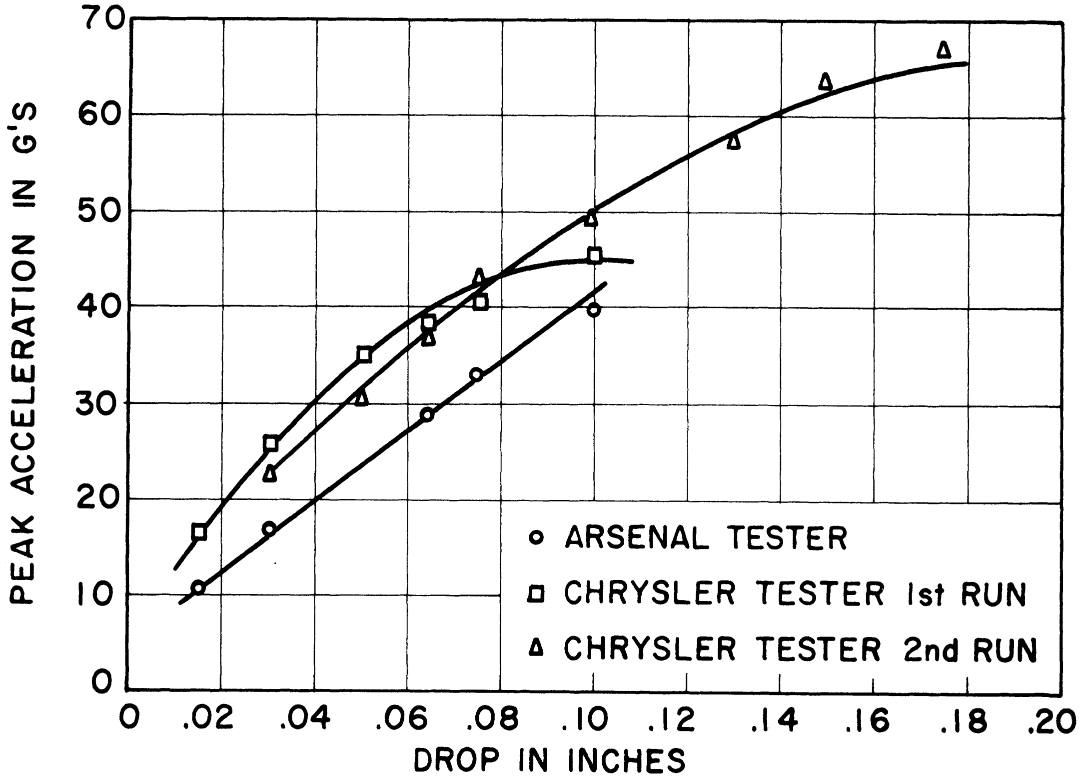


Fig. 10. Comparison of Single Anvil Drops Between the Arsenal Impact Tester and the Chrysler Impact Tester.

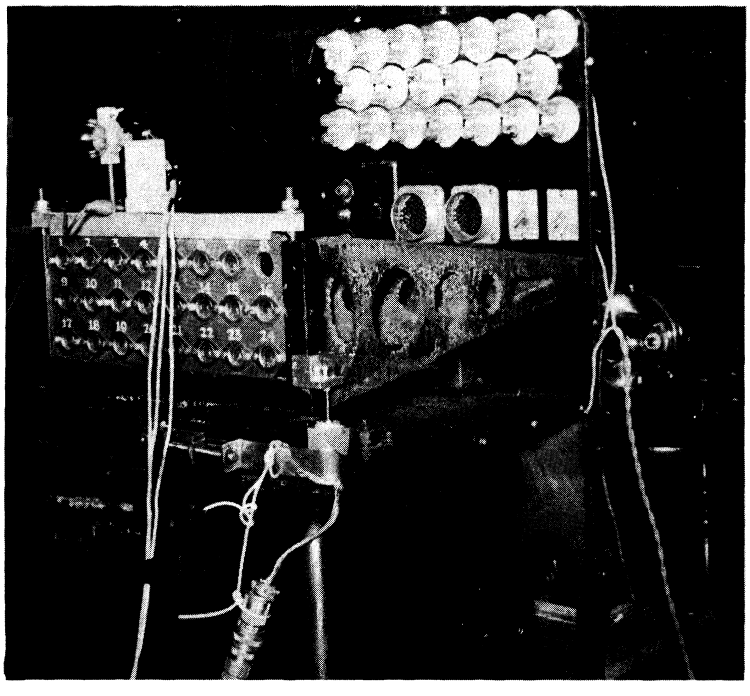
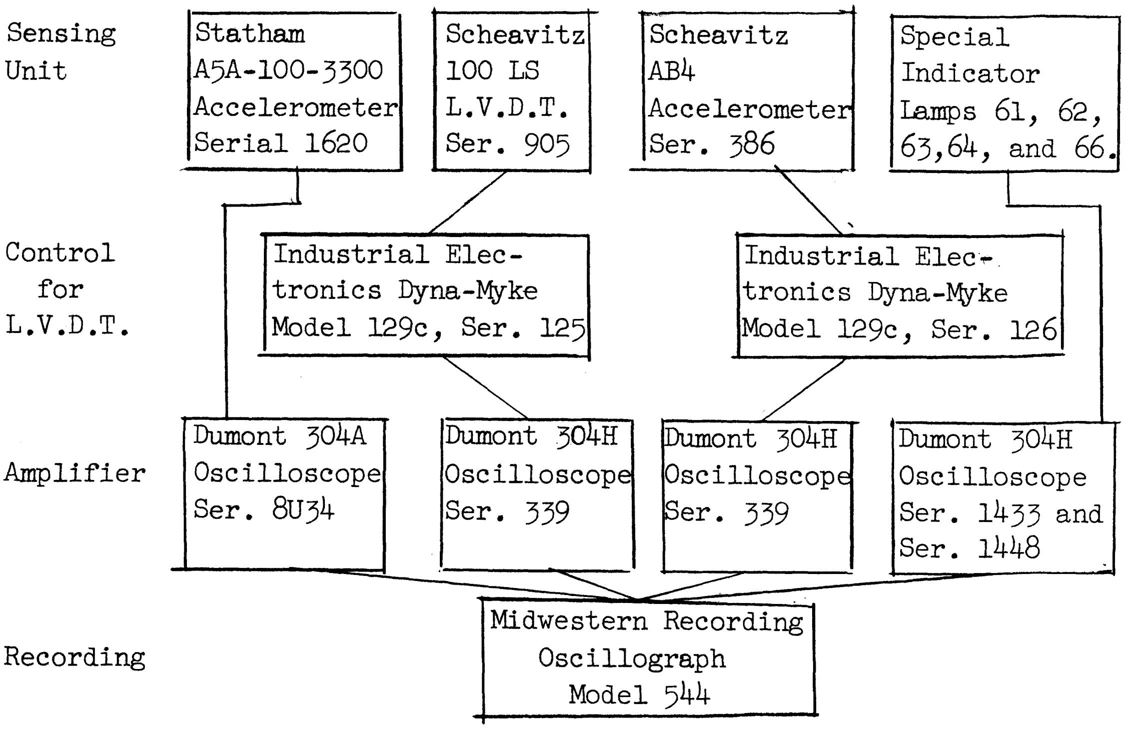


Fig. 11

The following block diagram shows the instrumentation arrangement.



Many of the tests involved simultaneous use of several sensing units. Figure 11 shows a typical arrangement. It will be noted that the Chrysler tester is in this case equipped with a statham accelerometer, a Scheavitz device calibrated to measure arm displacement, and an indicator lamp. The amplifiers in recording unit receiving the data from these devices are shown in assembly in Figure 12.

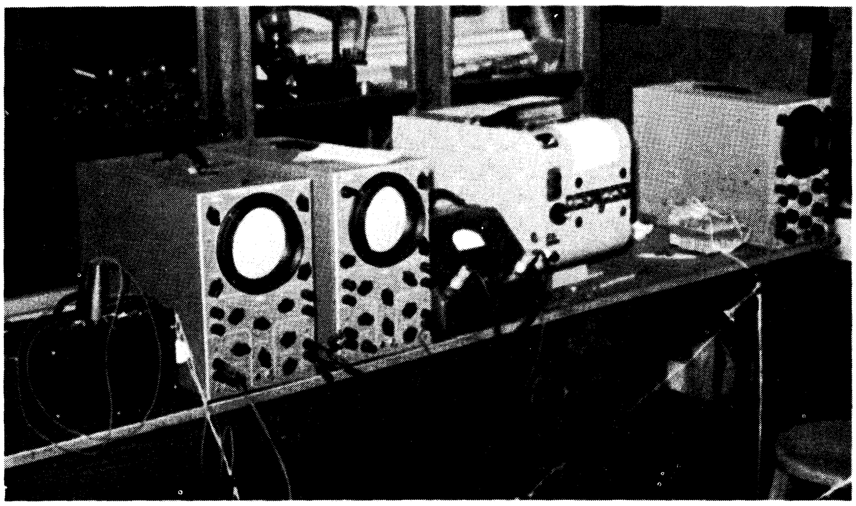


Fig. 12

b. Test Results. Duscussion of the results of these tests will, for convenience, be grouped under seven headings.

1. Effect of Varying the Weight of the Lamp-Holder Plate. The following table shows some typical data.

Run No.	Plate	Accel.	Speed	Comments
437-42	3 lb	32.5-53.5	700	Trace Very Irregular
475-80	3 lb	71	700	Good Trace Pattern
415	5.2 lb	42.5	600	
422	10 lb	34.7	600	

These results show the expected trend. The heavier the plate, the more iertia it has and the lower the value of peak acceleration produced. The Arsenal tester, provided with type S cam (to be discussed later), 0.081-inch elastic hinges, and a waxed arms, was used in these tests.

2. Effect of Operation With And Without the Amphenol Plugs Connected. The data shown below illustrates this effect. They were taken on the Chrysler machine with an 8.7-pound lamp-holder plate.

Connected			Disconnected		
Run	rpm	Accel.	Run	rpm	Accel.
3800	840	36.0	3801	840	36.3
3803	650	34.2	3802	650	35.6
3804	473	35.4	3805	473	36.2
3807	350	34.6	3806	350	35.7

It will be noted that in each pair the test with the plugs disconnected showed a slight increase in acceleration.

3. Effect of Changing the Thickness of the Elastic Hinge. It has already been mentioned that a new type of elastic hinge was designed for the Arsenal tester. Two pairs were made up, one with a thickness of 0.050 inch, and the other, 0.081 inch. The following runs were taken, using a 5.2-pound lamp-holder plate.

0.050-inch Hinge			0.081-inch Hinge		
Run	rpm	Accel.	Run	rpm	Accel.
173	800	27.5-33.5	180-181	800-970	35-36.2
174-175	650-700	27.2-35	182	700	38
176-177	550-600	30	183	600	35
169	Single-drop	27.5	179	Single-drop	35.9

The thicker hinge consistently produced a higher acceleration.

4. Effect of Spring-Loading the Arm to Increase its Velocity. A considerable number of tests were performed on the Arsenal machine to determine its behavior when provided with spring loading. Figure 13 is a sketch showing the method of attaching the springs. Their tension could be increased by drawing up the upper eye-bolts.

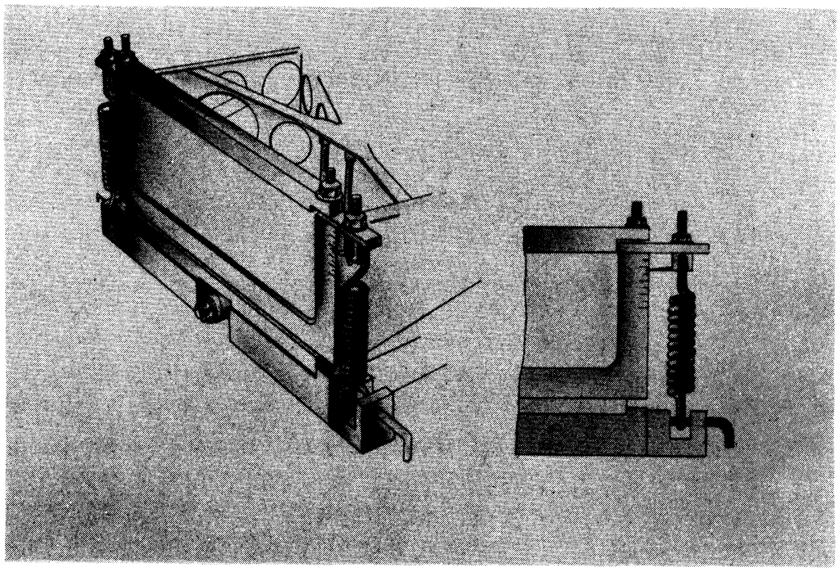


Fig. 13.

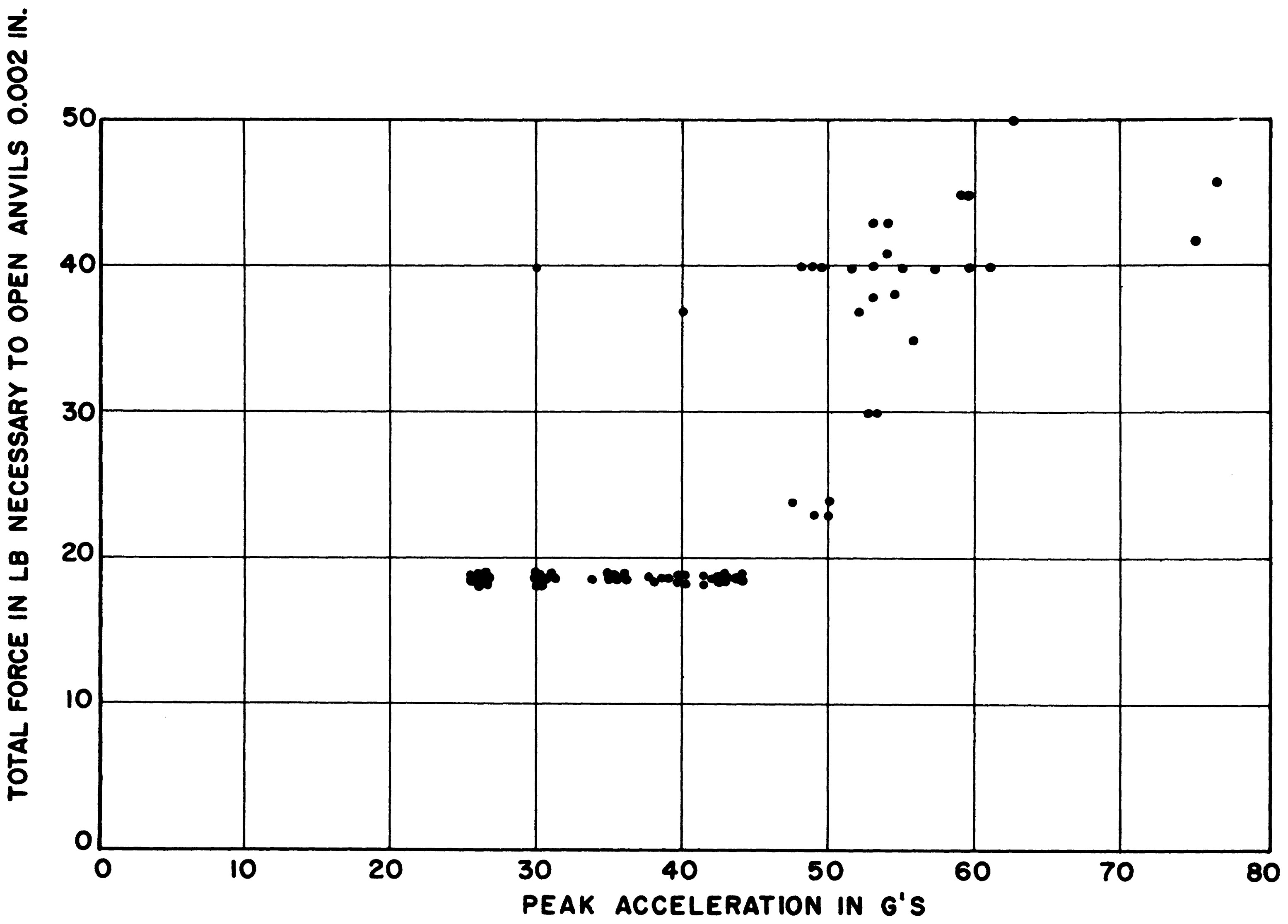


Fig. 14. Peak Acceleration Recorded from the Arsenal Impact Tester with the 5.2-lb Plate and the 0.081-inch Elastic Hinge.

Figure 14 shows total spring force plotted against peak accleration. In all these tests the machine operated with a 5.2-pound lamp-holder plate and the 0.081-inch hinge. The speeds were in the range of 600-700 rpm.

The groups of points lying along the 18.5-pound line were obtained in tests involving the operation of the arm and elastic hinge without any supplementary springs. All others were taken with additional spring loading. For example, the two points lying on the 30-pound line show the peak accelerations in two tests where the additional spring loading was 11.5 pounds.

It will be noted that with additional spring loading there are only seven points outside of the 47-55 g range.

The presence of sound-deadening material in the arm seemed to have no consistent effect on the performance.

5. Changes in Cam Contour. To permit some study of the possible influence of cam shape on performance, two new cams were machined designated by the symbols S and 700S (See Fig. 15).

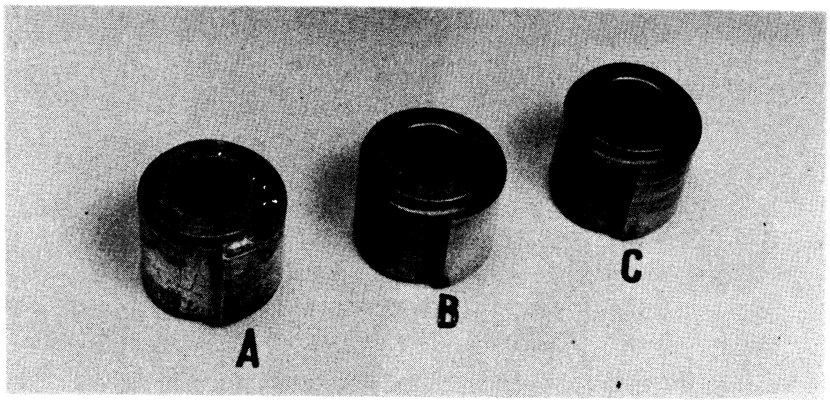
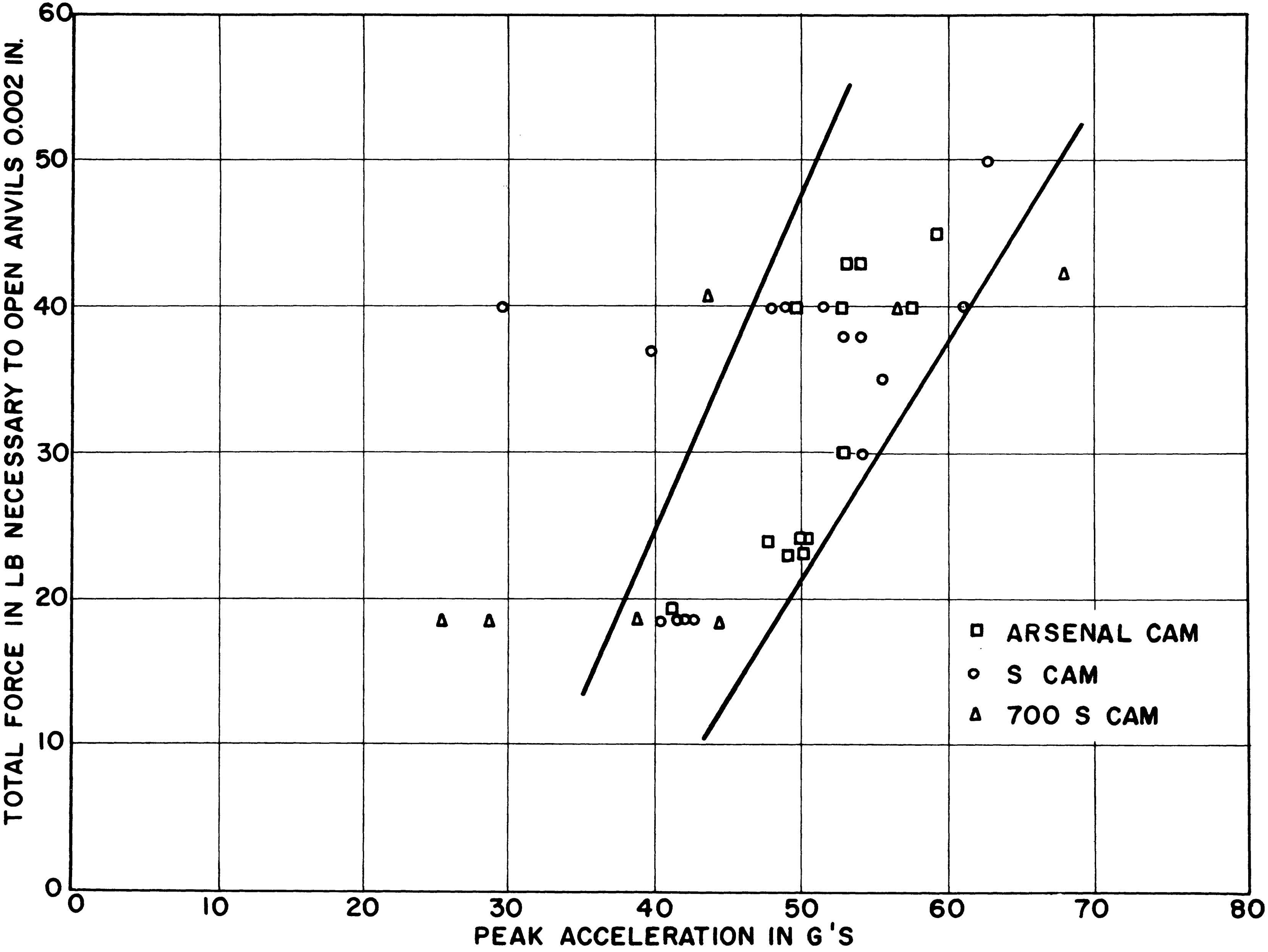


Fig. 15.

Cam S was designed to match the original cam on the Arsenal tester except that the 0.0625)inch lift was obtained by a spiral pattern rather than by a series of short circular arcs of different radii. Cam 700S was designed to start lifting 144° from the point of drop, and to have about 14° of dwell before the drop. This design was supposed to eliminate most of the bouncing if the cam speed was held at 700 rpm.

Figure 16 is similar to Fig. 14 in that it relates peak acceleration to the amount of spring loading. It contains a representative group of runs for each of the three cams. From the scatter of these points, as well as from other observations employing an indicator lamp mounted on the impact-tester arm, it is clear that the behavior of all three cams was very much alike. In fact, it is more likely that the degree of polish and quality of lubrication on the cam surface are much more important factors than the shape of the cam.



60
50
40
30
20
10
0
TOTAL FORCE IN LB NECESSARY TO OPEN ANVILS 0.002 IN.
0
10
20
30
40
50
60
70
80
PEAK ACCELERATION IN G'S
□ ARSENAL CAM
○ S CAM
△ 700 S CAM

Fig. 16

6. Changes in Anvil Contact Area. The following table presents the results of some tests which were made to determine what effect would be produced on the performance of the tester by changing the contact area of the anvils. All these tests were run at 600 rpm with a 5.2-pound lamp-holder plate and 0.081-inch spring hinge.

Max. Contact Area			Min. Contact Area		
Run	Accel.	Comments	Run	Accel.	Comments
403	41.75	Very repetitive	405	42.5-46	
404	41.75	Very repetitive	409	41.5-45.2	Irregular
414	42.75	Very repetitive	410	41.5-44.7	
415	42.75	Very repetitive	412	37.45.2	
419	42.5	Very repetitive	406	76.7	Spring loaded 46 lb
417	47.2	Spring loaded, 40 lb, good pattern	411	75	Spring loaded 42 lb
420	54	Spring loaded, 40 lb, good pattern	413	66-71	Spring loaded 42 lb Very irregular

The larger contact area gave more repetitive acceleration values.

7. Changes in Cam Speed. Numerous runs were taken on the Arsenal tester in which efforts were made to make cam speed the principle variable. Studies of the records taken by means of an indicator lamp and an accelerometer lead to the following conclusions.

1. The average peak acceleration does not vary much over the entire speed range from 400 to 950 rpm.

2. At speeds of 800 rpm and above, the peak acceleration is erratic and nonrepetitive.

3. At speeds of 600 rpm and below, the peak acceleration is quite repetitive but there is time for the filament vibration to be damped out between successive drops of the cam follower. In other words, the filament is not being subjected to fatigue stresses during a considerable portion of each cycle.

4. At about 700 rpm a new vibratory excitation is impressed on the filament just as the previous one begins to decay. There is almost no "idle" time.

5. Recommendations Affecting the Design of the Arsenal Tester

If after a careful review of the results of these tests the SAE committee and Army Ordnance wish to retain the tester in its basic form as a means of acceptance testing the following changes and modifications in design should be incorporated.

a. Standardize on 700 rpm as the cam speed.

b. Use the 0.081 inch elastic hinge for the arm mounting.

c. Change the mounting of the lamp-holder plate to eliminate distortion of the upper anvils. See Figure 17 for a suggested method.

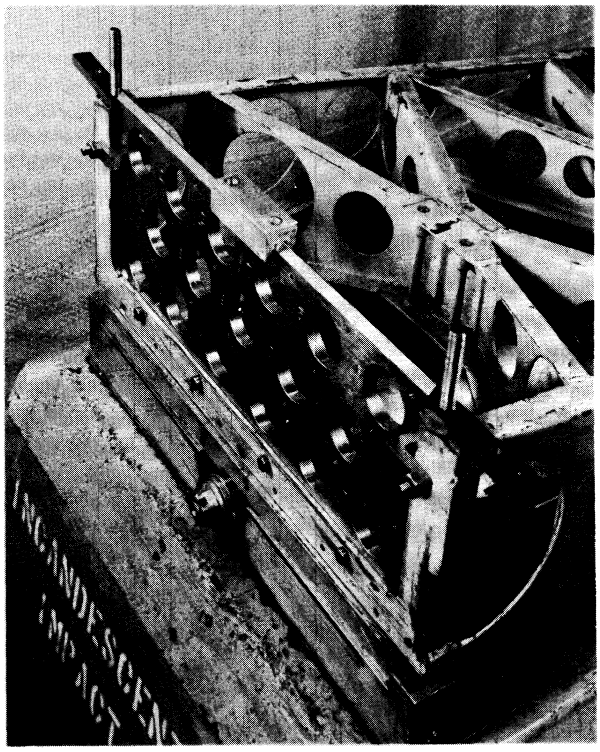


Fig. 17

d. Standardize the weights of the lamp-holder plates and the weight of the entire arm.

e. Consider the possibility of adding spring loading to the arm to increase the peak acceleration up to a ceiling of about 50 g.

Comparative studies of the Chrysler and Arsenal testers having been pretty well completed, the Chrysler machine was returned on April 14, 1954, and the Midwestern recorder was returned to APG on May 5, 1954.

6. A Rotating Drum Impact Tester

In the theoretical analysis of the Arsenal impact tester presented earlier in this report it was pointed out that an arrangement whereby a lamp bulb could be dropped freely a small fraction of an inch would produce as much vibrational stress in the filament as is produced by mounting the lamp on the present impact tester.

A crude experiment was devised in an effort to substantiate this statement. Indicator Lamp No. 66 was mounted on the Chrysler tester and given a series of single drops ranging from 0.0185 inch to 0.149 inch. The filament deflection was observed in each case.

Then the same lamp was supported short distances above a sheet of Masonite and was allowed to drop freely by quickly withdrawing the support. The filament deflection was again observed.

Figure 18 shows the results, indicating noticeable increases in deflection for the free drop onto Masonite.

Figure 19 is a sketch of a device designed to test this possibility further. A maple disk provided with four equally-spaced notches on its edge was rotated at about 170 rpm thus producing about 700 drops per minute for the lamp bulb resting on it. Each drop was about 3/32 inch. The actual working model is shown in Figure 20.

The stress was so great in the first run that the lamp failed in just a few seconds. The drops were then changed to 3/64 inch and the stresses were still too severe for practical use. If this scheme is to be used in an acceptance testing program it is probable that deliberate addition of some mass to the lamp base will be necessary in order to reduce the acceleration.

Figure 21 is a sketch of a possible extension of this design to accommodate a considerable number of lamps.

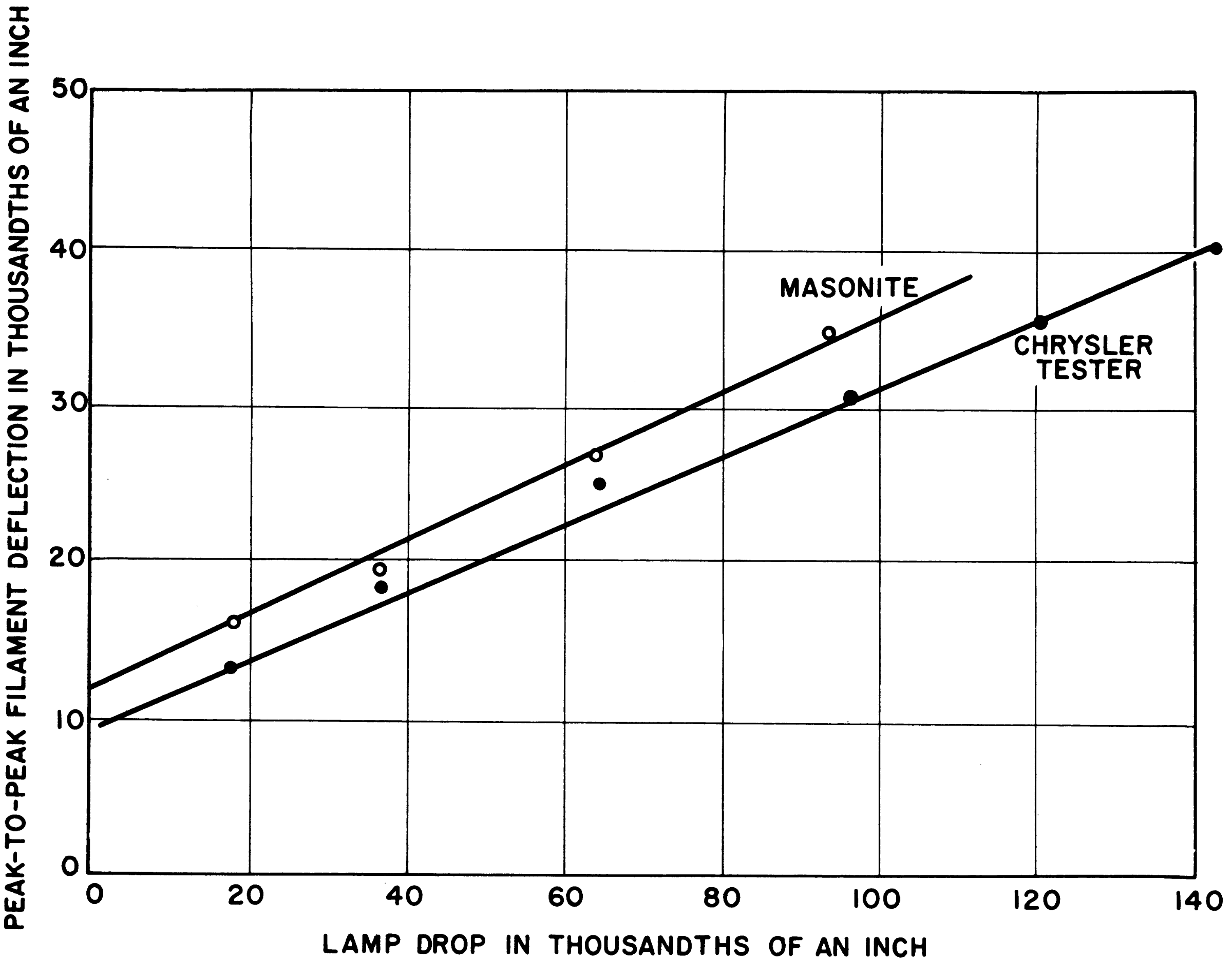


Fig. 18. Comparison of Filament Deflection of Lamp No. 66 Excited by Dropping the Lamp Bulb on Masonite and Excited by Equivalent Drops Mounted on the Chrysler Impact Tester.

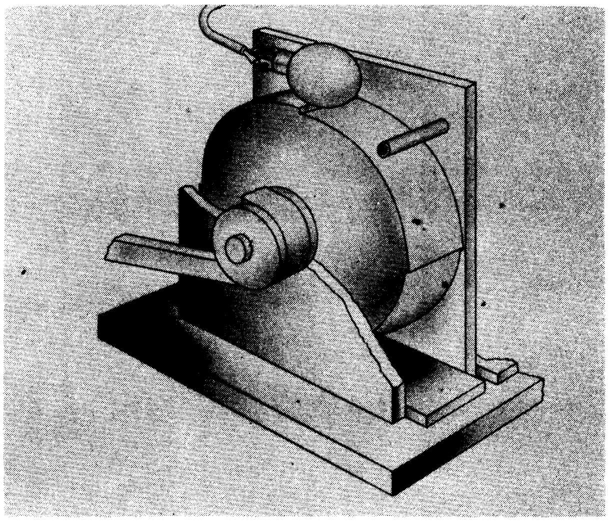


Fig. 19

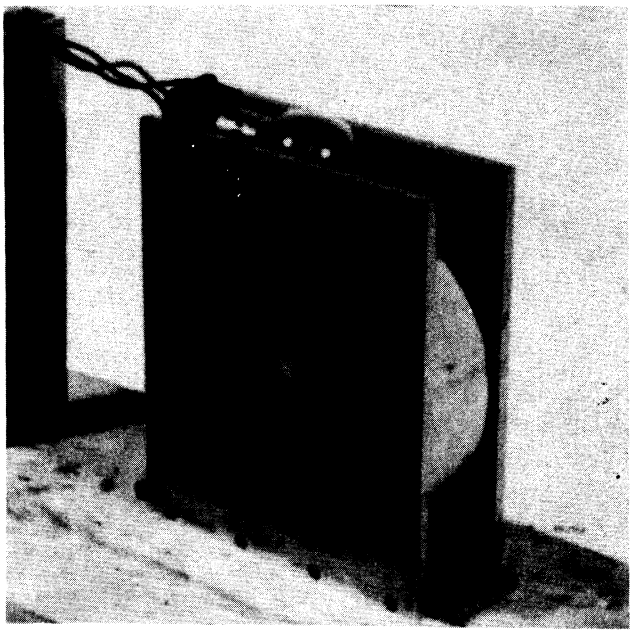


Fig. 20

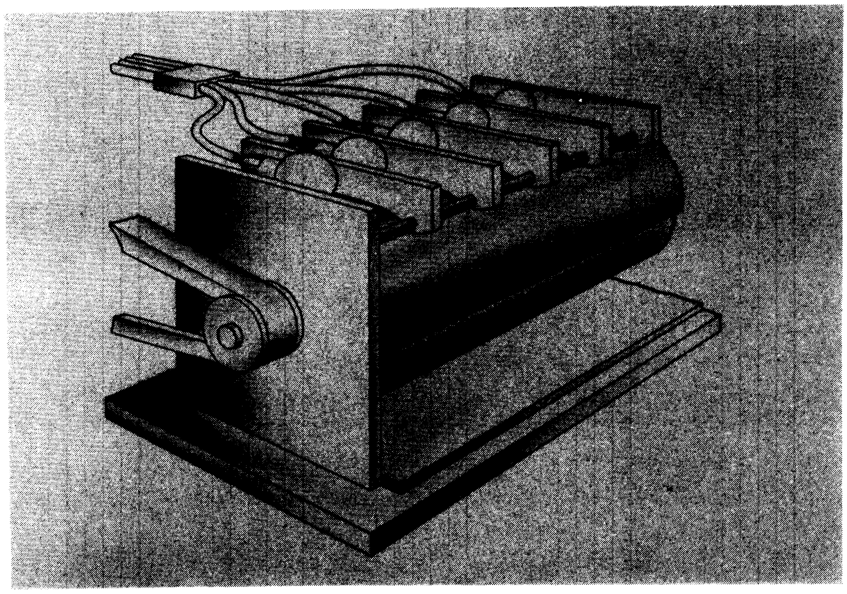


Fig. 21.

7. Significant Properties of Tungsten

The problem of stating the properties of tungsten is complicated by the fact that its properties are not only temperature sensitive but also highly structure sensitive. After cold drawing, the structure is fibrous, and the tungsten exhibits high tensile strength and good ductility. The annealed structure consists of large grains which impart great brittleness to the metal. The tensile strength is also markedly reduced.

Wherever possible, variations of the stated properties with microstructure will be indicated.

a. Physical Properties

Density: 19.3 g/cc

Modulus of Elasticity[24]

$$E_t = E_o \left(\frac{T_s - T}{T}\right) 0.263$$

$$G_t = G_o \left(\frac{T_s - T}{T}\right) 0.263$$

where:

E_t = Modulus of elasticity at a temperature T (°K) ,
E_o = 40,000 ± 1000 Kg/mm^2 , 51.2 x 10^6 ± 1.28 x 10^6 psi
T = Temperature in °K
T_s = Melting temperature in °K (3653 °K) ,
G_t = Shear modulus at a temperature T (°K) ,
G_o = 17,100 ± 300 Kg/mm^2
21.9 x 10^6 ± .384 x 10^6 psi ,

Some values given by Bridgeman[21] for room temperature:

E = 39400 Kg/mm^2 (50.3 x 10^6 psi)
G = 15350 Kg/ mm^2 (19.6 x 10^6 psi)

Poisson's Ratio = 0.284

Isotropy of Tungsten

Elastic Constants:

	Bridgeman[21]	Wright[25]	
C_{11}	51.3	50.1	(x 10^{11} dynes/cm^2
C_{12}	20.6	19.8	(x 10^{11} dynes/cm^2
C_{44}	15.3	15.1	(x 10^{11} dynes/cm^2

Using the condition for isotropy, $1/2\ (C_{11}-C_{12}) = C_{44}$, tungsten is fairly isotropic.

Tensile Strength[22]

Hard Drawn wire 0.1 mm dia.	426,000 psi
Hard Drawn wire 0.05 mm dia.	490,000 psi
Hard Drawn wire 0.015 mm dia.	670,000 psi
Annealed Wire (Recrystalized)	150,000 psi

Ductility[22] (Measured as elongation):

Hard Drawn	1 - 4%
Annealed	0%

For tensile strength and ductility as a function of temperature, see attached figures 22 and 23.

b. Thermal and Electrical Properties [22]

Linear Coefficient of Expansion (per °C):

30°C	4.44×10^{-6}
1030°C	5.19×10^{-6}
2030°C	7.26×10^{-6}

Heat Conductivity:

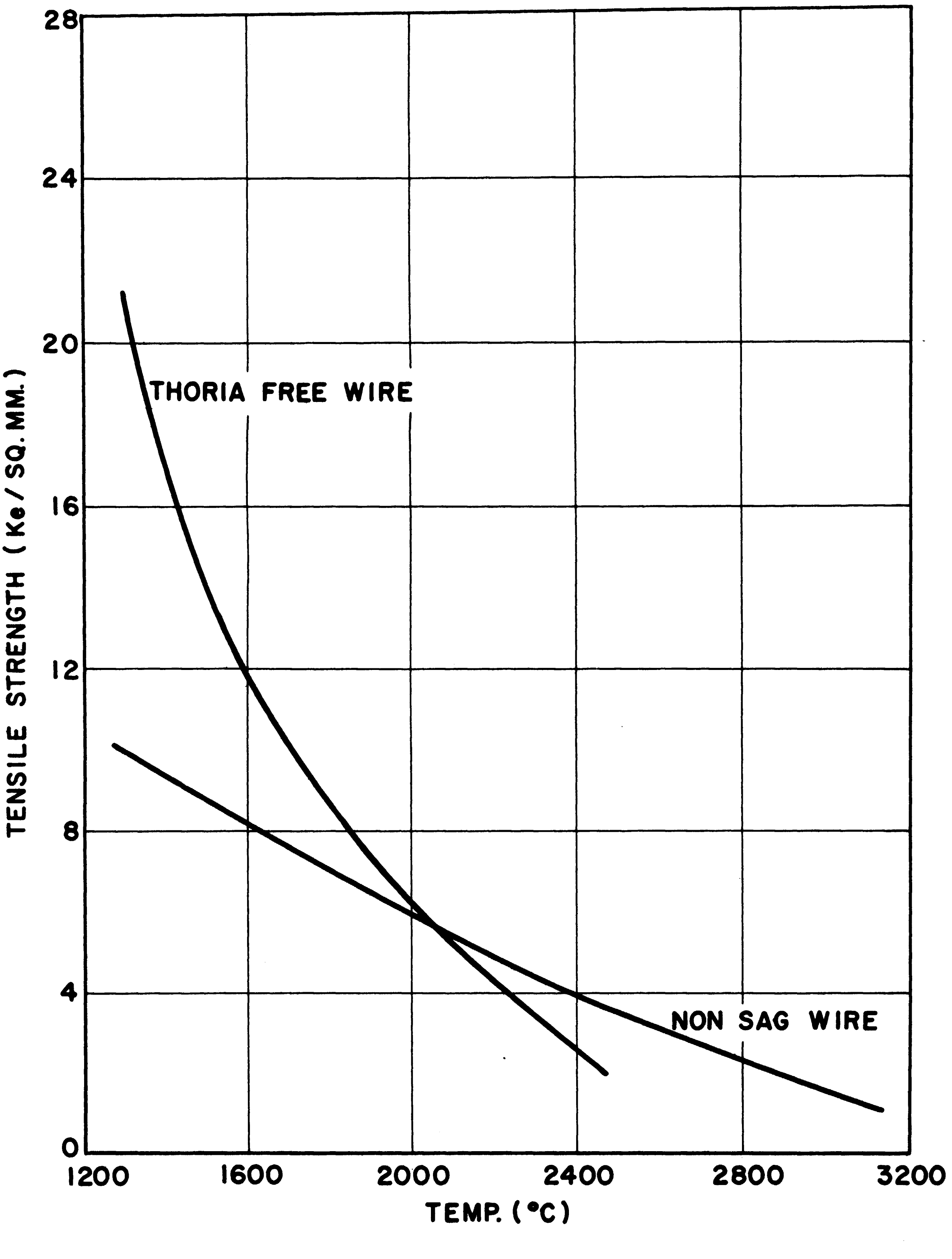
Cal/cm/sec/°C at 20°C	0.38

Specific Heat: (cal/g/°C)

20 - 100°C	3.4×10^{-2}
1000°C	3.65×10^{-2}

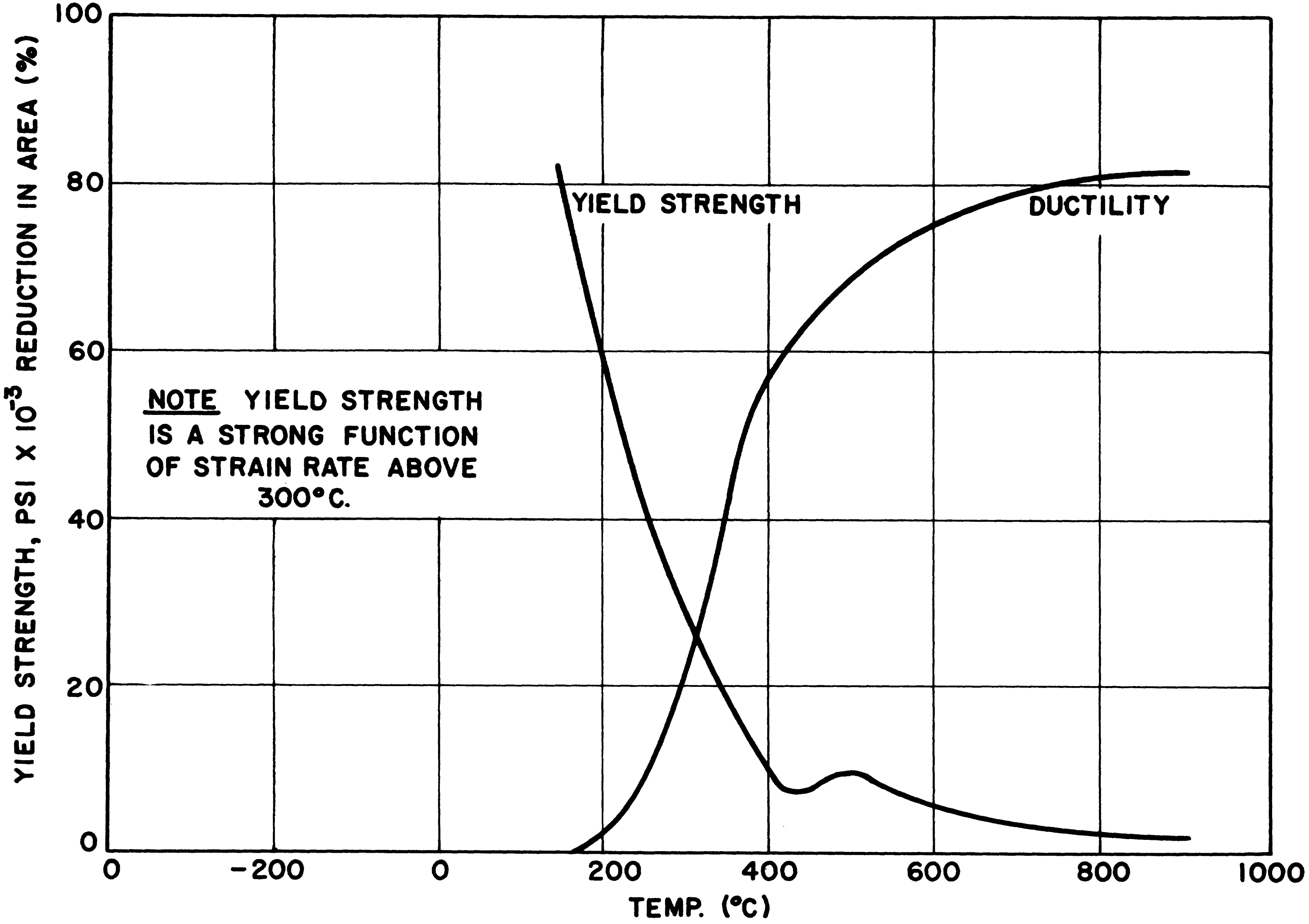
Electrical Resistivity: (microhm-cm)

20°C	5.5
750°C	25.5
1200°C	40
2400°C	85



28
24
20
16
12
8
4
0
TENSILE STRENGTH (Kg/SQ.MM.)
THORIA FREE WIRE
NON SAG WIRE
1200
1600
2000
2400
2800
3200
TEMP. (°C)

Fig. 22



NOTE YIELD STRENGTH IS A STRONG FUNCTION OF STRAIN RATE ABOVE 300°C.

Fig. 23

8. Structures in Tungsten and their Properties

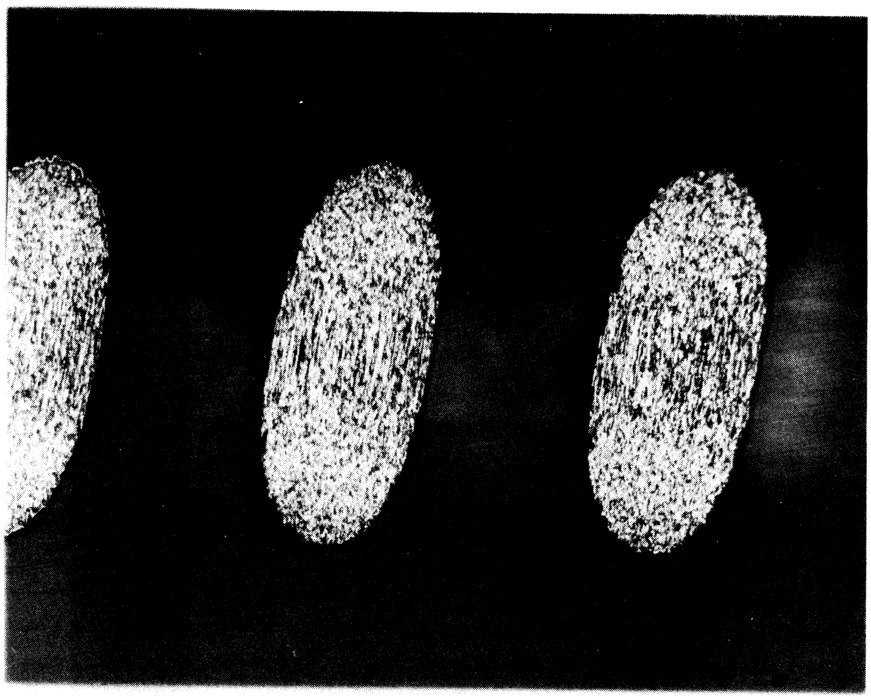
The properties of a tungsten wire are controlled not only by the composition and temperature of the wire, but also by the size and shape of the tungsten grains as revealed by polishing, etching, and viewing under the metallographic microscope. The various structures of interest are illustrated by Figure 24.

Figure 24a represents a cold-worked structure which is typical of metals that have just been cold-rolled or drawn. The grain are elongated and the structure exhibits a fibrous texture. In tungsten, this structure has a high tensile strength and is quite ductile. This structure persists until the metal becomes heated to the recrystallization temperature for a period of time at which point the structure becomes similar to that illustrated in Figure 24b.

When a metal reaches the recrystallization temperature, new, unstressed grains start to form which eventually grow and replace the cold-worked structure. This recrystallization temperature is affected by the degree of cold-work, composition (additions), and time. It can vary from 800°C for pure tungsten to over 2000° for tungsten which contains large amounts of alumina and thoria. If a metal is either held at the recrystallization temperature for a long time or heated to higher temperature, some of the small grains will grow at the expense of others (the process of grain growth) and the structure becomes more coarse as in Figure 24c.

Figures 24b and 24c can be termed annealed structures. Unlike most metals, tungsten at room temperature is very brittle in the annealed condition. This means that the structures illustrated by Figures 24b and c, which are considered desirable in most metals become very detrimental in the case of tungsten as far as resistance to fracture is concerned. The fractures that occur are intercrystalline, that is to say, the fractures occur along grain boundaries. This means that a structure that has a grain-boundary path that runs directly through the whole cross-section of the wire will be very susceptible to fracture. A structure that is fine grained has an easy path of fracture (Figure 25a) as does one in which the grains occupy the whole cross-section of the wire (Fig. 25b). A structure similar to that in Figure 25c would be preferable. The cold-worked structure is, of course, much better than any one of the structures above.

The tungsten in a coiled-coil filament such as that in the type 2416 lamp is not structurally homogeneous after it has once been burned. When a current is passed through the filament there is a temperature distribution set up due to the cooling effect of the leads and the leg inserts

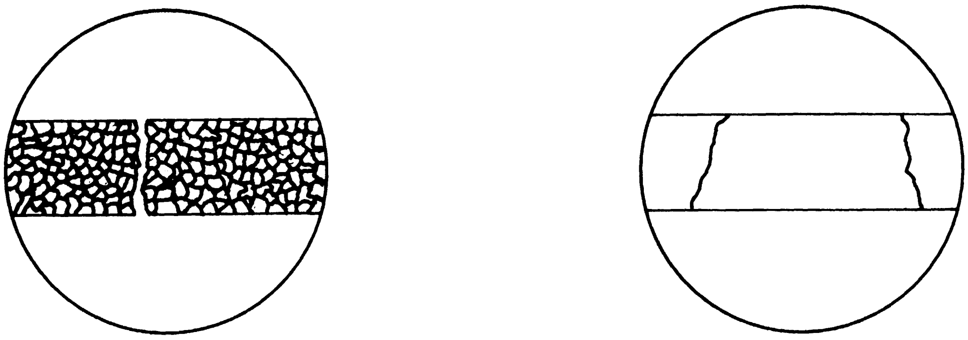


a. Cold-worked Structure. (250X)

b. Fine-grained Structure. (250X)

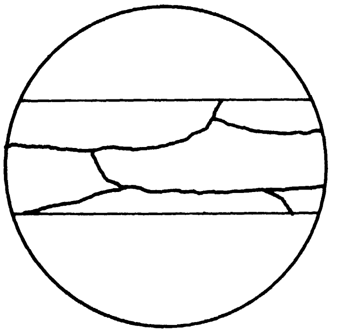
c. Coarse-grained Structure. (250X)

Fig. 24



A. FINE-GRAINED

B. COARSE-GRAINED



C. INTERLOCKING COARSE-GRAINED

Fig. 25

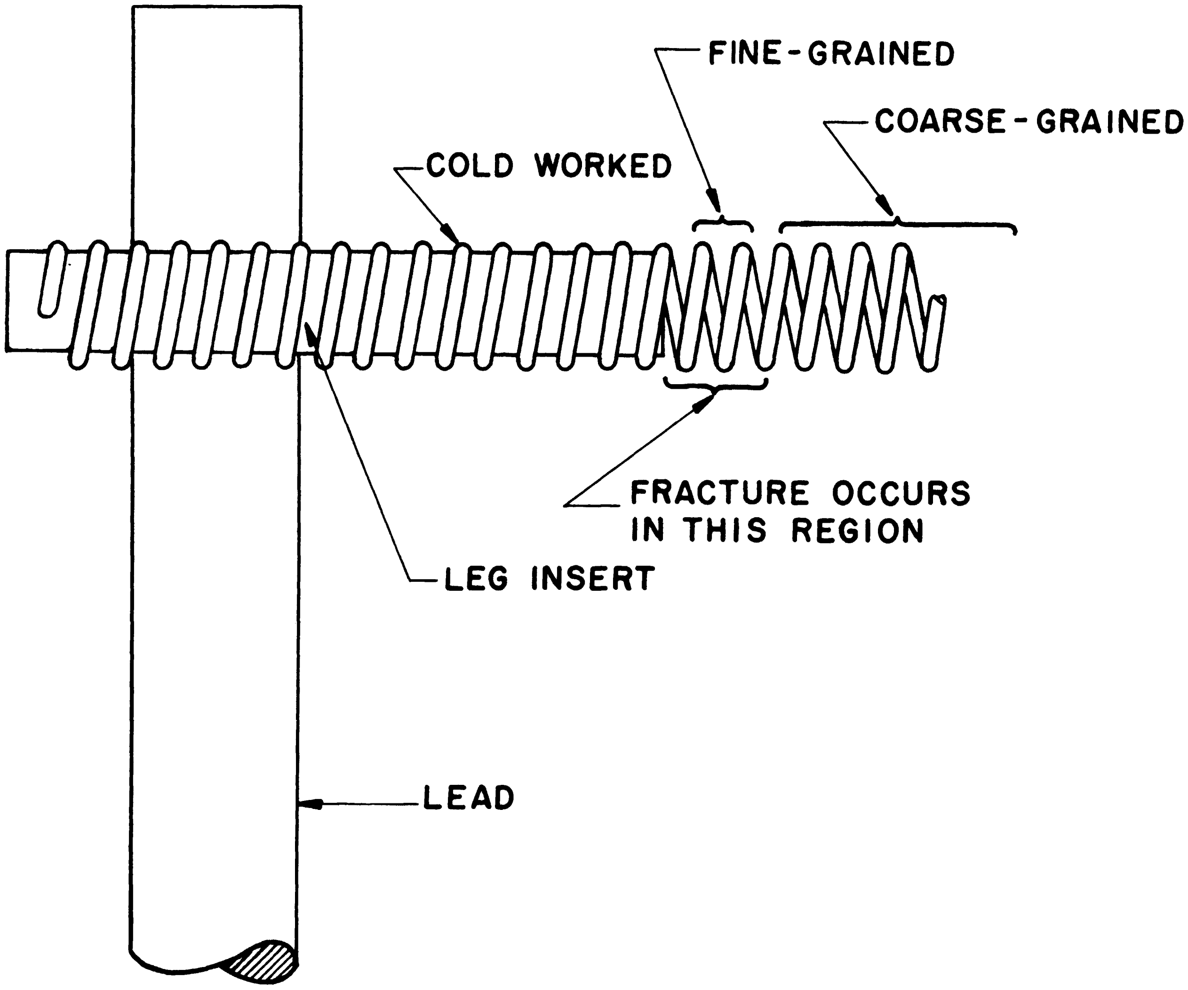


Fig. 26. Metallographic Structures alone Primary Coil of Type 2416 Filament.

(spuds). This temperature distribution is reflected by a distribution in the structures of the various portions of the filament. Figure 26 shows the structures that exist along the primary coil in the vicinity of the leg insert. Figure 27 is a photomicrograph of three successive primary turns of a filament showing the microstructures that exist. In these figures, the turn nearest the leg insert shows a cold-worked structure, and moving out into the incandescent portion of the filament there is a fine-grained zone followed by the coarse-grained region.

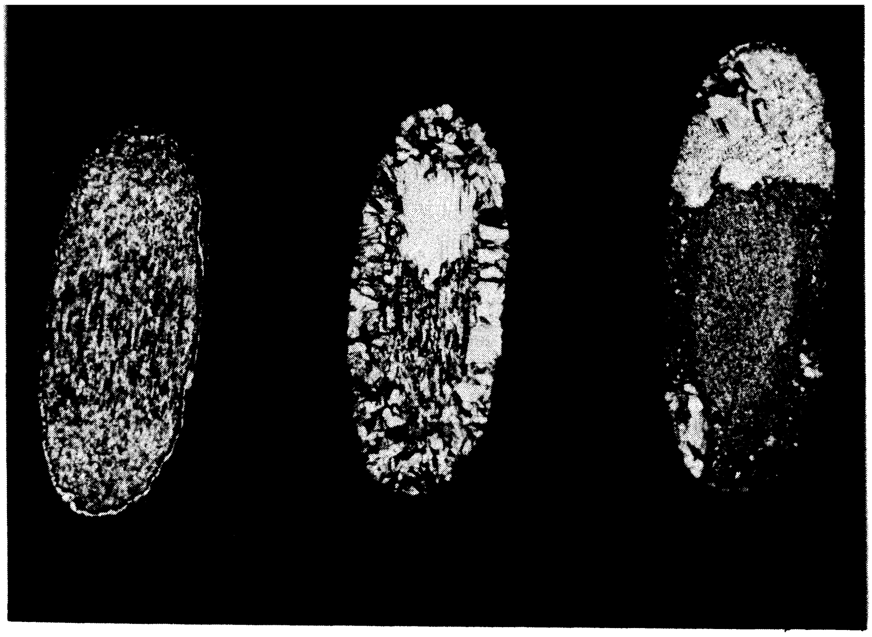


Fig. 27. Three Successive Primary Turns of A Filament after Showing Cold-worked, Fine-grained, and Coarse-grained Structures. (250X)

Filament failures in the type 2416 lamps can be divided into two types: sagging and fracture. Sagging of the filament is phenomenon that occurs when the filament is hot, and is caused by either an instability of structure in the filament or the exceeding of the elastic limit of the hot tungsten.

Fracture occurs in the cold state, usually near the leg insert of the filament. A very large majority of failures seem to occur by fracture in the cold state. This investigation has therefore been mainly concerned with improving the cold vibration resistance of filaments.

Fractures. Cold fractures of tungsten filaments generally occur within one or two primary turns of the leg insert (Figure 26); The structure at this point is generally the recrystallized, fine-grained structure of Figure 24b. Several samples which exhibited cold failures were mounted and polished so that the structure at the fracture could be observed (Figure 28). The metallographic procedure is outlined below.

Metallographic Technique. Tungsten wire filaments were mounted in lucite in a mounting press at 2000 psi and 150°C (Figure 29). They were then rough polished through a series of emery papers to 0 fineness. The specimens were taken from there to a final polishing step using a polish-etch technique outlined by Woods (Linde B abrasive suspended in a solution of potassium ferricyanide and sodium hydroxide). The specimens were then etched and viewed under the metallographic microscope at 100, 250, and 500X. Photomicrographs were made of important features.

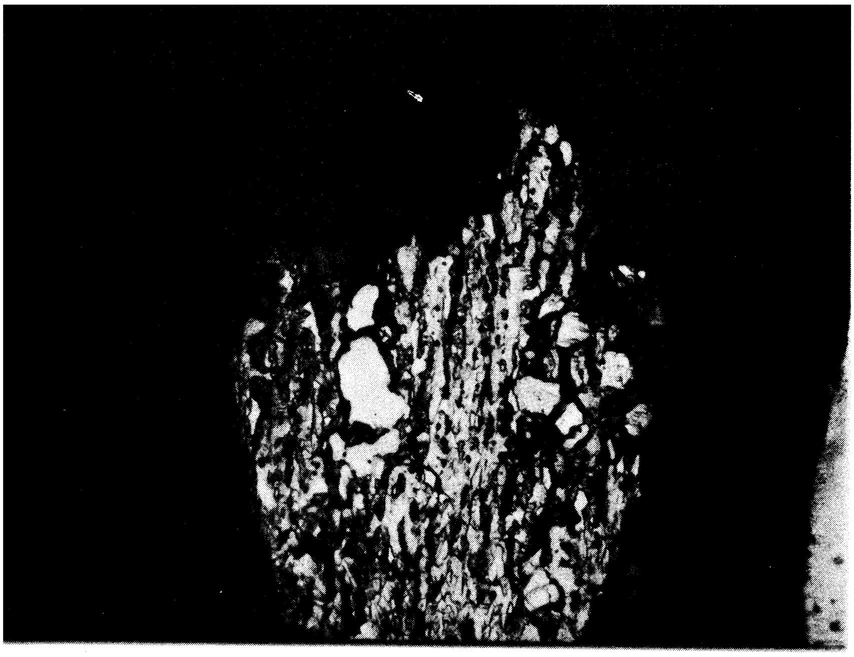
When examing fractures, the filament was carefully mounted so that the plane of polishing was perpendicular to the plane of the fracture (Figure 29). The metallographic procedure outlined above was then followed.

Discussion. It is unfortunate that in the filament the weakest type of structure occurs at the point of maximum flexure (immediately beyond the leg insert). The problem of improving the filament vibration resistance resolves itself into one of separating the point of maximum flexure from the metallurgically weak structure. Several approaches are possible:

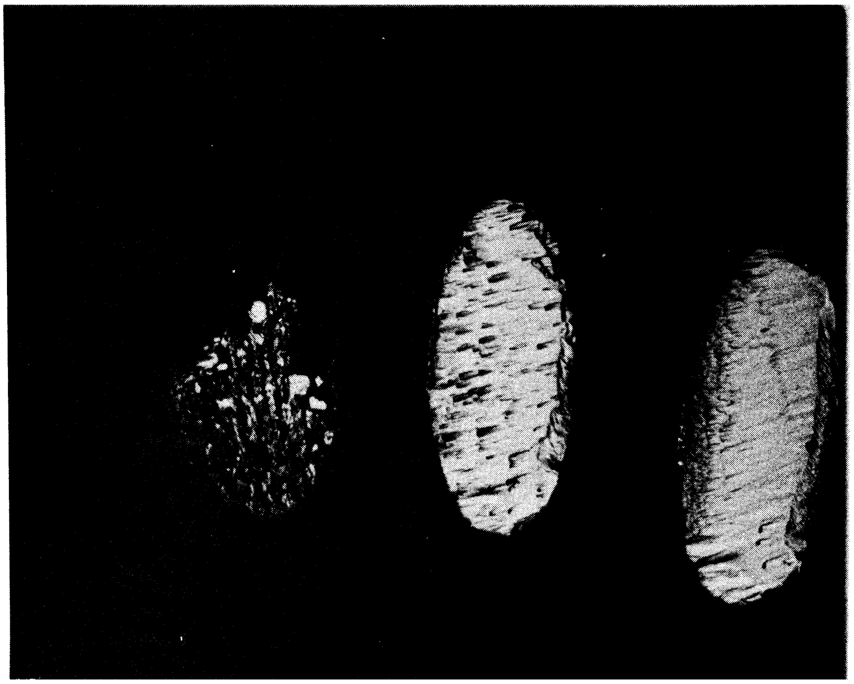
a. The entire filament could be fired at about 2200°C before mounting in such a way as to obtain a structure similar to that in Figure 25c. This structure would then persist in the zone of maximum flexure and constitute an improvement of vibration resistance. One of the main difficulties with this system is that the filament in the fully recrystallized condition is very difficult to handle and to mount.

b. The best structure to have at the point of maximum flexure is the cold-worked structure. To preserve this structure at that point it is necessary to keep the temperature below the recrystallization temperature. This can be accomplished by providing an auxillary conductor which would carry 30-50 percent of the total current in the lamp from the lead to some point perhaps 10-15 turns beyond the end of the leg insert without restricting the motion of the filament in the region of the insert. This conductor could take the form of a slip coil around the primary turns extending from the lead to 10-15 turns beyond the leg insert.

c. The filament itself could be "shock mounted." This could be accomplished by running a ribbon of tungsten from the leads to the filament. The ribbon would have to be of such dimensions



a. Fracture in Sample 921-2 through Recrystallized Region. (500X)



b. Fracture in Sample 921-2. (250X)

Fig. 28

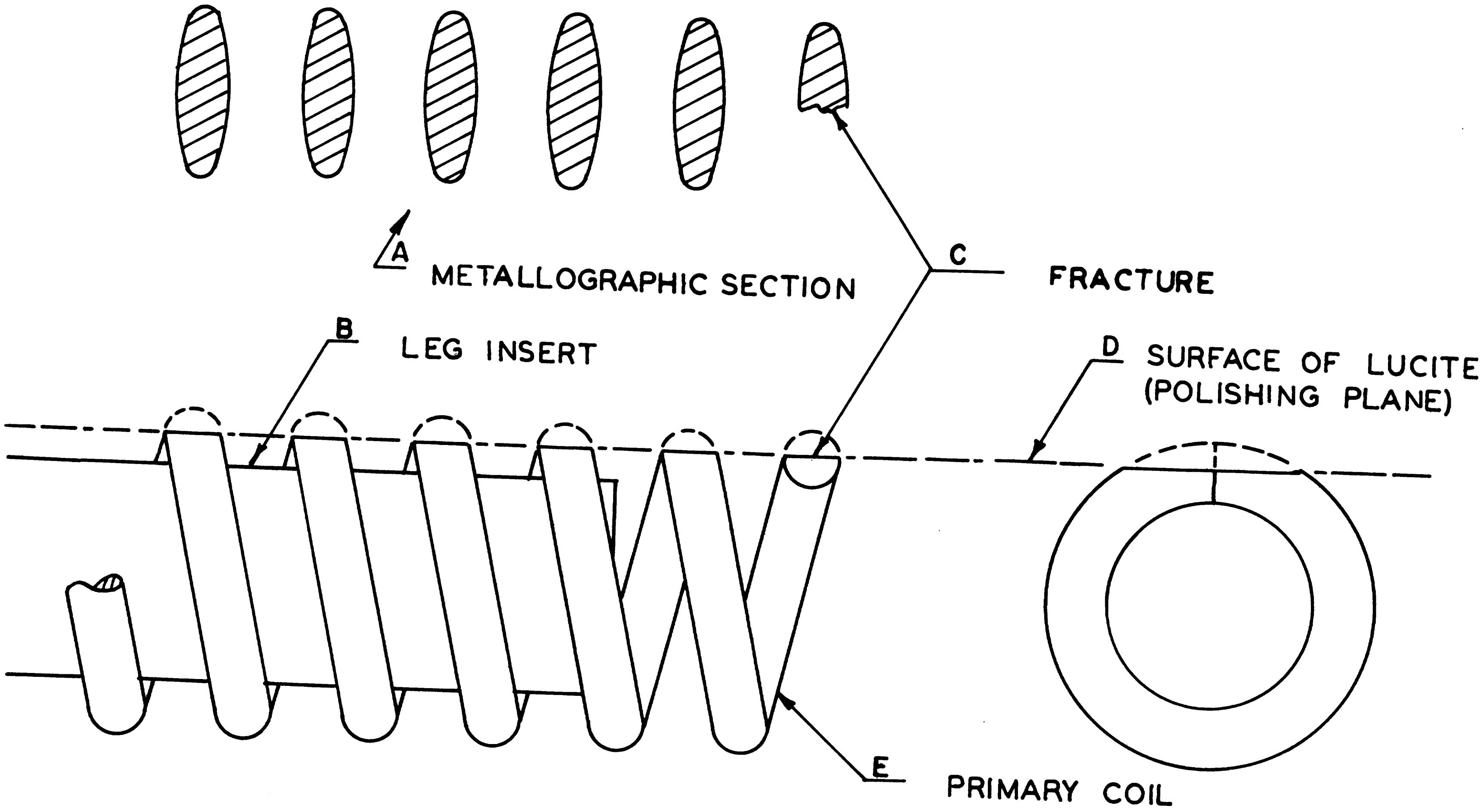

A
METALLOGRAPHIC SECTION
C
FRACTURE
B
LEG INSERT
D
SURFACE OF LUCITE
(POLISHING PLANE)
E
PRIMARY COIL

Fig. 29

as to keep its temperature well below the recrystallization temperature so as to preserve its ductility and yet be thin enough to flex easily. The dimensions of such a ribbon would be about 2 x 20 mils in cross section. Flexure in more than one plane could be obtained by putting a 90° twist in the ribbon.

9. Luminous and Electrical Properties of Tungsten

Resistivity. Tungsten, like most metals, has a positive temperature coefficient. A convenient and sufficiently accurate expression relating resisitivity and temperature is the following:

$$\frac{R}{R_1} = \left(\frac{T}{T_1}\right)^{1.2} ,$$

where R and R_1 are two values of resistivity at the temperatures T and T_1, respectively, in degrees Kelvin.

Filament Radiation. A vacuum incandescent lamp radiates about 93 percent of the power delivered to it. Most of this radiation is in the form of heat, and the size of the glass envelope is roughly governed by the amount of radiant heat reaching it from the filament.

The relationship of radiant power to filament temperature may be conveniently expressed as follows:

$$\frac{J}{J_1} = \left(\frac{T}{T_1}\right)^{X} ,$$

where J and J_1 are the watts per sq cm from the filament at temperatures T and T_1, respectively. The exponents is in the range of 4.5 to 5.1 for the usual temperature range.

Filament Design.[26] Given the watts, P, and the voltage rating, V, of a proposed lamp, the resistance of the filament is given by $R_f = V^2/P$. Knowing the resistance, however, does not fix the filament length and diameter uniquely. Some additional factor such as desired filament temperature must be given. Then J can be determined and $S \approx P/J$ where S is the filament surface in sq cm.

Now, $S = \pi dL$ and $R_f = 4LR/\pi d^2$, where d and L are the diameter and length, and R is the resistivity of tungsten. From these relations,

$$d \approx \sqrt[3]{.4 \frac{Rp}{JR_f}}$$

and

$$L \approx \frac{P}{\pi dJ}$$

These relations are, of course, approximate and would have to be modified cosiderably for a modern coiled-coil design. Nevertheless, they are useful in showing how critical the temperature is and how narrow is the practical range of filament dimensions.

Voltage Effects. Incandescent lamps are very sensitive to changes in voltage above and below their designed voltage. The following relations are commonly accepted:

$$\frac{F}{F_o} = \left(\frac{V}{V_o}\right)^{3.5},$$

$$\frac{E}{E_o} = \left(\frac{V}{V_o}\right)^{1.93},$$

$$\frac{L}{L_o} = \left(\frac{V}{V_o}\right)^{-13.5},$$

where F_o, E_o, and L_o are the values of luminous flux, efficiency, and life, respectively, at design voltage V_o, and F, E, and L are the corresponding values at a different voltage V.

Life, in this case, is associated with the amount of filament evaporation, and has only a very remote bearing on life as affected by vibration.

Life Improvement. To the extent that operating temperature affects the strength of the filament in resisting vibration there is the possibility of increasing somewhat the filament resistance by using more turns of the same size of wire. This might well be explored if all means of strengthening the present filament mechanically or metallugically fail.

To the extent that a heavier filament might increase the life, the possibility of operating at a lower efficiency might be considered. This means dissipating morewatts and may call for an increase in envelope size (a larger bulb) which would be objectionable on several counts.

It seems proper to postpone consideration of changes of this sort until all other possibilities have been exhausted.

BIBLIOGRAPHY

1. J. B. Dickson, "Tail Lamps, Chrysler Design Shock Absorbers," Chrysler Corp. Engineering Tech. Report No. 8103.22, Detroit May, 1944.

2. J. B. Dickson, "Tail Lamps, Rubber Cushion Cemented to Lamp Housing," Chrysler Corp. Engineering Tech. Report No. 8103.24, Detroit, May, 1944.

3. D. R. Hubbard, *Vibration of Lamp Assemblies - Reo Army Truck, M 48*, General Motors Proving Grounds, Milford, Mich. 1952, p.2.

4. D. R. Hubbard, *Vibration of Lamp Assemblies GMC Army Truck, M-135*, General Motors Proving Grounds, Milford, Mich., 1952.

5. D. R. Hubbard, *Vibration of Service Drive Lamp on GMC Army Truck, M-135*, General Motors Proving Grounds, Milford, Mich., 1952.

6. Dudley Mahon, *Tail Lamp Vibration*, Cleveland Tank Plant, Cadillac Motor Car Division, Cleveland, Ohio,1952.

7. "Second Memorandum Report on Project TT1-720E - Electrical Equipment Vibration Test," United States Army - Aberdeen Proving Ground, 1952, (photostat).

8. D. R. Hubbard, *Vibration of Service Drive Lamp on GMC Army Truck, M-135*, General Motors Proving Grounds, Milford, Mich., 1952.

9. Dudley Mahon, *Tail Lamp Vibration*, Cleveland Tank Plant, Cadillac Motor Car Division, Cleveland, Ohio, 1952.

10. J. P. Terry, "Vibration - Ordnance Type Lamps," Engineering Report, Tung-Sol Electric, Inc., Newark, April 11, 1952.

11. Lewis R. Hetzler, "Investigation of the Cause of Filament Failure in Type 2416, 24 Volt Headlamp Bulb," Engineering Report, GMC Truck and Coach Division, Pontiac, Michigan June 2, 1953.

12. "First Memorandum Report on Project TT1-720E - Electrical Equipment Vibration Test," United States Army, Aberdeen Proving Ground, 1952.

"Fourth and Final Memorandum Report, Desert Tests 1953, All-Glass Sealed-Beam Headlamps," United States Army, Aberdeen Proving Ground, Sept. 26, 1953.

"Winter Tests 1953-54, Tail Lamps," United States Army, Aberdeen Proving Ground, March 17, 1954.

"Desert Tests 1952 Experimental Headlamp Seal Beam Units," United States Army, Aberdeen Proving Ground.

13. L. R. Hetzler, "Trip to A.P.G., Aberdeen, Maryland for Conference on Failure of 28 V. DC lamps in Ordnance Vehicles," Report to R. H. Bertsche, GMC Truck and Coach Division, Pontiac, Michigan, April 14, 1953.

14. SAE Handbook, Society of Automotive Engineers, Inc., New York, 1953, p. 794.

15. J. B. Dickson, "Impact Tester for Incandescent Lamps," Chrysler Corp. Engineering Tech. Report No. T 60401.24, Detroit, March, 1944.

16. J. B. Dickson, "Ordnance Lamp Impact Tester Calibration," Chrysler Corp. Engineering Tech. Report No. T 60401.24-01, June, 1944.

17. Lewis R. Hetzler, "Investigation of the Cause of Filament Failure in Type 2416 24 Volt Headlamp Bulb," Engineering Report, GMC, Truck and Coach Division, Pontiac, Michigan, June, 1953.

18. J. B. Dickson, "Tail Lamp Losses," Chrysler Corp. Engineering Tech. Report No. 8103.20, January, 1944.

19. Lewis R. Hetzler, "A Method of Observing Incandescent Lamp Filament Deflection Under Operating Conditions," GMC Truck and Coach Engineering Report, Pontiac, Michigan, October 12, 1953.

20. Bechtold and Shewmon, Westinghouse Scientific Paper No. 1720, (to be published in the Transaction of the AIME 1954.)

21. Bridgeman, Proc. Am. Acad. Sci. , 60, 305, 1925.

22. C. Goetzel, Treatise on Powder Metallurgy, Interscience Publishers, Inc., New York, 1950.

23. I. Isenberg, Physical Review, 83, 627, 1951.

24. C. J. Smithells, Tungsten, Chapman and Hall, Ltd., London, 1952. (Secondary reference)

25. Wright, Proc. Royal Soc., A126, 613, 1930.

26. Moon, Scientific Basis of Illumin. Eng., McGraw-Hill, 1936. Chapt. 6.