A Publication of the

DEPARTMENT OF MECHANICAL SCIENCES and ENVIRONMENTAL ENGINEERING

(NASA-CR-128294) PROGRAM FOR THE EXPLOITATION OF UNUSED NASA PATENTS Final Annual Report, 1 Aug. 1971 - 31 Aug. 1972 R.J. Fay (Denver Univ.) 31 Aug. 1972 116 p CSCL 05A G3/34
N72-32957
Unclas
16362

UNIVERSITY OF DENVER

Denver, Colorado

DRI#2604

Fourth Annual Report (Final)

PROGRAM FOR THE EXPLOITATION OF UNUSED NASA PATENTS

NASA Grant
NGL 06-004-078

August 1, 1971 - August 31, 1972

By
Richard J. Fay

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I. INTRODUCTION

The purpose of this program was to exploit unused NASA patents through the use of a multidisciplinary approach involving faculty students, and research staff. NASA patents were screened for their applicability outside the space program, specific applications were identified, and the technical and commercial feasibility of these applications was established. Also application of this technology by governmental agencies outside the space program was sought.

The program was specifically interested in energy absorbing devices such as those developed for lunar soft landings. These energy absorbing devices absorb large amounts of mechanical energy but are, in general, not reusable. Some of these devices can also operate as structural elements until their structural load capacity is exceeded and they become activated as energy absorbers. The capability of these devices to operate as structural elements and as energy absorbing devices makes them candidates for many applications in the fields of transportation and materials handling safety where accidents take a large toll in human injury and property damage.

The ultimate objective was the commercial application of NASA technology with the university receiving a financial return with which to make the program self-supporting. A unique feature of this program was the interaction of the students with the faculty and the research staff in the solution of technology transfer problems. Students were assigned to groups which worked directly with faculty and research staff members doing mathematical analysis, testing, design, market analysis, business management and financial analysis, library system development, and production analysis. The students derived great benefit from working on real problems while the program benefited from the ideas generated by the students and the work done by them.

During the first year the efforts on the program were directed toward the selection of the type of patents which would be considered, the screening of the patents to determine those having the greatest technical and commercial feasibility for a wide range of applications outside of the space program, and the definition of the general areas of applicability for these patents. Fifty-five patents on energy absorbing devices falling into 18 categories were evaluated. These included 12 NASA patents and 43 competing patents. In addition to this, literature concerning energy absorbing devices and applications was reviewed.

Of the energy absorbing devices evaluated, two devices were considered to embody the combination of features required for a wide range of applications; these are the tube and mandrel (NASA Patent No. 3, 143, 321) and the folding tube (there are no patents on the tube, as considered here, without special end fixtures or preforming). The attractive features of these devices are their simplicity, high stroke to length ratio, low cost per unit of energy absorbed, and their applicability as structural elements.

During the second year the emphasis was placed on activities which would promote the commercial applications of the technology and also secure support from other governmental agencies to study public safety applications for energy absorbing devices. These activities included the following:

1. The identification of companies and governmental agencies operating in the fields of possible application for energy absorbing devices.

2. Visits to companies and governmental agencies to discuss potential applications.

3. Analysis of energy absorber requirements based on information received concerning specific applications.

4. The development of energy absorbers based on the tube and mandrel but having unique features and characteristics required for specific applications.

5. The determination of the cost of producing specific energy absorbers.

6. Basic research on the tube and mandrel and folding tube energy absorbers.

7. The development of a library containing literature in the fields of potential applications.

8. The presentation of papers concerning the work on the project.

During the third year the efforts on the project were devoted entirely to the development of three commercial applications of the tube and mandrel energy absorber which were considered to have the greatest commercial potential. These applications and the industrial clients for which they were developed are the following:

1. An energy absorbing automobile bumper, McCord Corp., Detroit, Michigan

2. A semitrailer support energy absorber; Fruehauf Corp., Detroit, Michigan

3. An elevator buffer: Otis Elevator Co., New York City, New York.

For all three of these applications, energy absorbers based on the tube and mandrel were developed which appeared to be highly satisfactory. As a result, client interest was strong.

During the fourth year prototype development and testing activities supporting the three commercial applications were continued. Follow up contacts were made frequently to maintain client interest in the applications. During the year the Otis Elevator Company under took a broad cost analysis on the tube and mandrel elevator buffer to determine the savings which could be made using it to replace the presently used hydraulic buffers. To support this activity additional tube and mandrel tests were conducted to obtain data which could be used to formulate an improved prediction equation for the resistive force produced by a tube and mandrel energy absorber of a given size. The results of the cost analysis were used by Otis in determining the amount the company could afford to pay for a license to use the tube and mandrel for the application. Also during the year a subsidiary of Otis, Transportation Technology Inc., Denver, Colorado, adopted the elevator buffer for a safety buffer at track spurs in their personal transit system. The buffers are used to provide emergency stopping for 10,000 lb. vehicles traveling at speed up to 10 mph.

After highly successful tests on the semitrailer support energy absorber Fruehauf engineers suggested incorporating the energy absorbing device into the existing semitrailer sand shoe. This made it possible to fit the energy absorbing shoe on any semitrailer without modification. This energy absorbing foot was proposed to Fruehauf

Corporate management who decided that it would be best if the foot were manufactured by the Homan Company, an original equipment manufacturer for the trailer industry. The Homan Company was contacted and found to be enthusiastic over manufacturing and marketing the energy absorbing semitrailer foot. Subsequently Homan took over further prototype development and testing, production planning, and marketing studies.

While Department of Transportation Regulations exclude the use of the tube and mandrel energy absorber on the first generation of energy absorbing automobile bumpers on new cars because it is not self restoring, the bumper project has been continued since it is believed that the future requirements will call for protection at higher speeds. At speeds of 10 to 15 mph, the impact energy is many times as great as it is in the 5 mph impact. In order to provide adequate protection at these higher speeds without large increases in the vehicle weight and cost it will be necessary to use high efficiency energy absorbers such as the tube and mandrel. Therefore it is desirable to develop such a bumper in anticipation of the requirements. Such a bumper could be used in conjunction with a self restoring 5 mph bumper such as that now available on the Saaub automobile. This combination bumper would be self restoring in impacts up to 5 mph but require the replacement of elements after impacts between 5 and 15 mph. The bumper project will continue after the end of this program under the support of the College of Engineering at the University of Denver. The McCord Corporation, Detroit, Michigan, has expressed its interest in the continuation of this project, and concurs with our belief that the future bumper requirements will call for protection from impacts at higher speeds.

This report provides a summary of the major applications efforts on the program over its four year life and discussed the work done during the past year.

II. PROGRAM ORGANIZATION

The organizational structure of the project during the fourth year is illustrated in Figure 2.1. The project was directed by Richard J. Fay acting under Arthur A. Ezra, the Principal Investigator. The program activities included prototype design and development, prototype testing, follow up contacts and license negotiations with clients and educational activities. The educational activities included directing student groups working on research and development projects in support of the project objectives, holding class meetings where outside speakers were heard and oral project reports were given, and maintaining a library of literature relating to the field of energy absorbing devices and their applications. In Figure 2.1 the names are underlined to indicate the principal activity of each staff member.

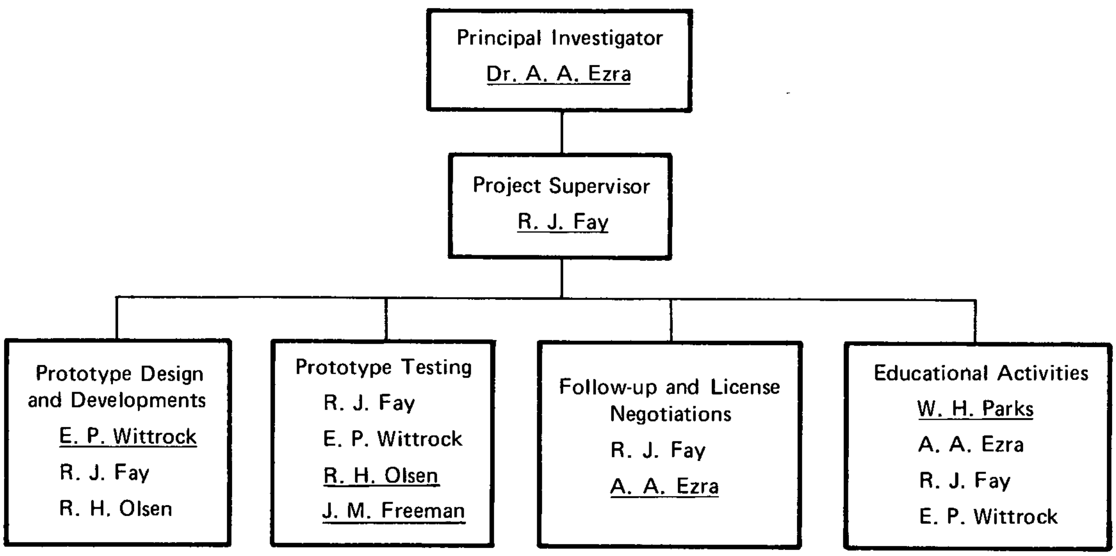


Figure 2.1. Organizational Chart

III. SOLID STATE ELEVATOR BUFFER

1. Summary

An energy absorbing device invented by a NASA engineer has been adapted for use as an elevator buffer by engineers at the University of Denver. The device is known as the tube and mandrel energy absorber and consists of a metal tube which is forced endwise onto a mandrel which expands it and causes it to split and curl. The deformation of the tube material and the friction between the mandrel and the tube absorb mechanical energy. Since the device is simple it appeared to be a possible low cost replacement to the oil buffer which has been traditionally used to stop elevators which overshoot the bottom landing. Prototype buffers for the 3500 lb and 8000 lb capacity elevators were developed at the University of Denver and tested by the Otis Elevator Company. The results of these tests showed that the device can be used as a low cost replacement for the oil buffer. Subsequently Otis conducted a cost study to determine the possible savings to the company if the tube and mandrel buffers were used. The results of these tests were very favorable and license negotiations are under way.

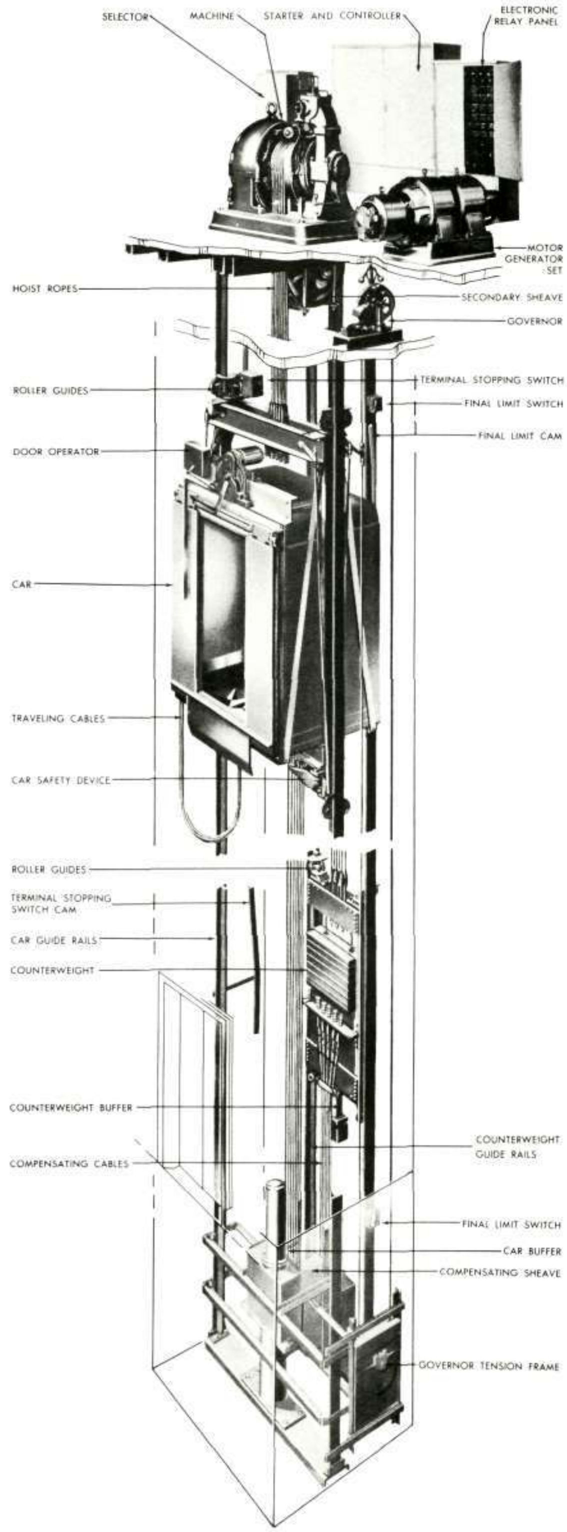
2. Introduction

Elevators are equipped with safety systems which include safety brakes that grip the elevator rails and hydraulic buffers under the elevator car and counterweight. The Otis elevator (Figure 3.1) is protected against free fall due to cable failure by safety brakes which are activated if the elevator speed exceeds a given pre-set value. The elevator is also protected from overshoot of the bottom or top floors due to circuit malfunction, operator error, or cable breakage by the buffers (Figure 3.1). These buffers are designed to bring the elevator to a stop from speeds up to 115 percent of the design speed without injury to the passengers.

Hydraulic buffers are specified in the "American Standard Code for Elevators" for elevators traveling 200 fpm or faster. Also the performance of these buffers is specified in the code. The specification is as follows: "Oil buffers shall develop an average retardation of not more than 32.2 fps/sec and shall develop no peak retardation greater than 80.5 fps/sec having a duration exceeding one-twenty-fifth of a second with any load in the car from rated load to a minimum load of 150 lbs when struck with the initial speed of not more than 115 percent of rated speed. Oil buffers (see Figures 3.2 and 3.3) are designed so that the same buffer can be used for a wide range of loads. This facilitates use of one buffer with a wide range of car weights and capacities, with the car either full or empty. The ratio of the weight of the full car to the empty car is usually 3:2; however, it is frequently as high as 2:1.

Since the oil buffer is an expensive device which is only used occasionally, the Otis Elevator Company considered the possibility of replacing some of the oil buffers with simple low cost energy absorbers which would be discarded after use. The NASA tube and mandrel energy absorber is being considered for this application. This device was invented by McGehee (Pat. No. 3,143,321) and consists of a tube which is deformed by forcing it endwise onto a mandrel which expands it causing it to split and curl. The deformation of the tube and the friction between the tube and the mandrel absorb energy. Subsequent development work at the University of Denver has yielded an improved version of this device which uses mild steel welded tubing and a mandrel having a simple conical geometry.[1,2,3*] This energy

* The superscripts are the numbers of References at the end of this report.



A.I.A. File 33B

Figure 3. 1. Otis Passenger Elevator

OTIS OIL BUFFERS (SPRING RETURN TYPE)

Otis Spring-Return Oil Buffers are designed to bring elevator cars to a smooth stop if they overtravel the landing at the lower terminal. They are built to absorb the impact of a fully loaded car descending at full rated speed.*

Otis Spring-Return Buffers have been tested and passed by the U. S. Bureau of Standards as complying with all the requirements of the American Standard Safety Code for Elevators.

*Oil buffers are not designed to stop falling cars. In the remote possibility that a car should fall, special "safeties" are provided to stop the car before it reaches the buffer.

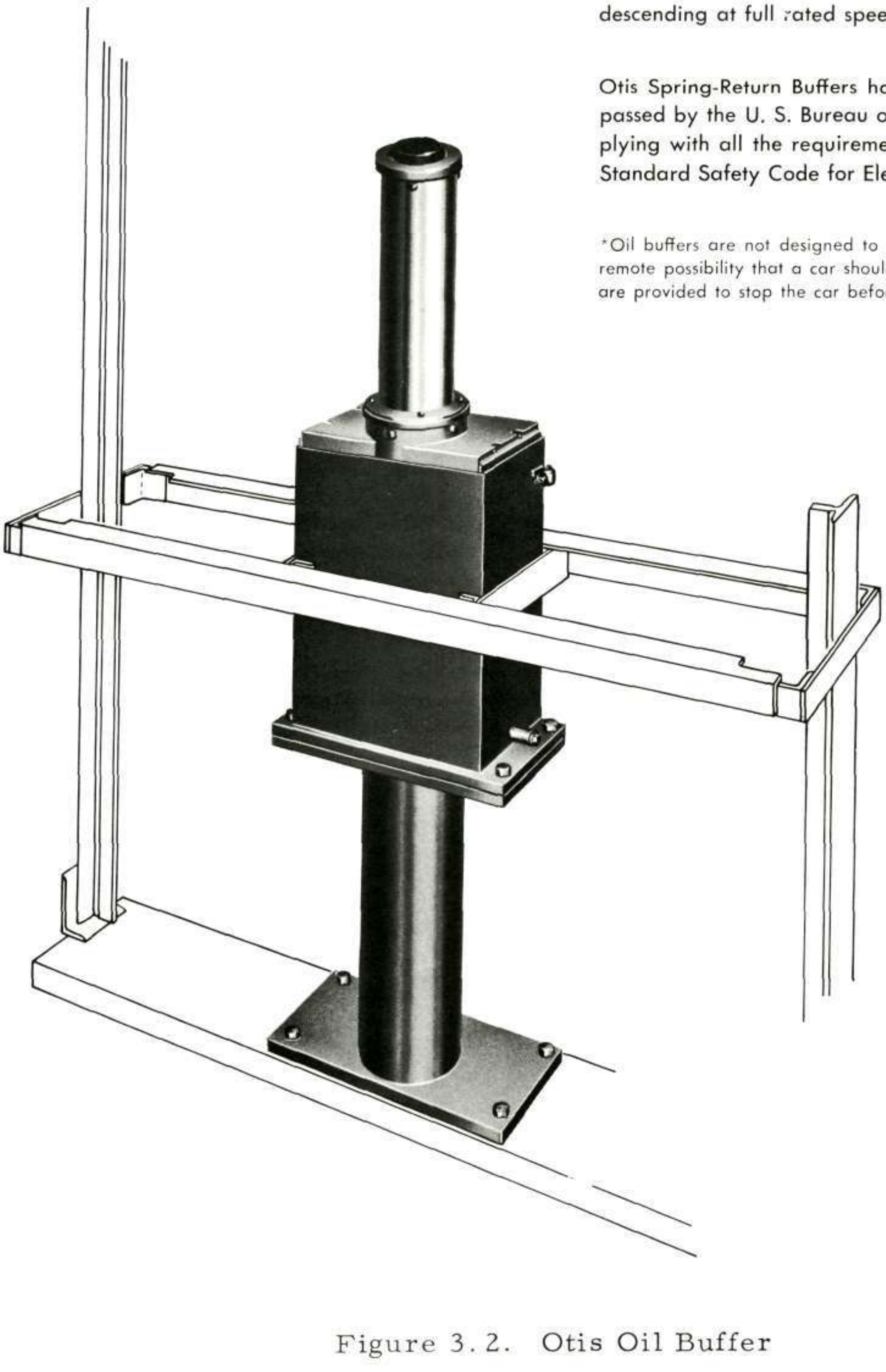


Figure 3.2. Otis Oil Buffer

OTIS OIL BUFFERS (SPRING RETURN TYPE)

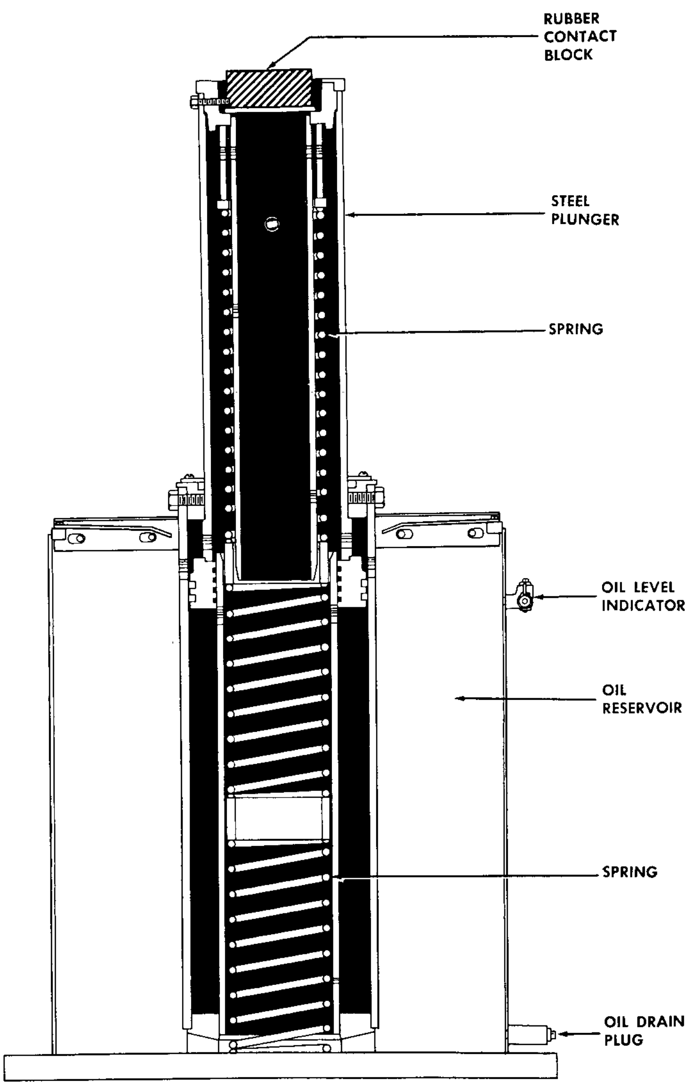
OPERATION

1- If the descending elevator car overtravels the lower landing, a heavy steel plate under the car frame strikes the rubber contact block on the top of a steel plunger. This rubber block absorbs the first shock of contact.

2- Further descent of the car drives the steel plunger into the oil filled inner cylinder of the buffer. This forces the oil through the escape holes in the side of the cylinder, and produces sufficient oil pressure to retard the descent of the car and bring it to a smooth stop.

3- When the car is lifted from the buffer, a compression spring returns the plunger to its normal position at the top of the cylinder. This permits the oil to flow from the reservoir back through the escape holes into the inner cylinder and the buffer is again ready to function.

4- Otis Oil Buffers are entirely self-contained. Their operation is completely automatic and mechanical, and does not depend upon any controlling mechanism.



OTIS ELEVATOR COMPANY

Figure 3.3. Otis Oil Buffer

absorber is illustrated in Figure 3.4. A typical force-deflection curve is shown in Figure 3.5.

This section summarizes the work done on the elevator buffer. A more detailed account of this project is found in reference 3.

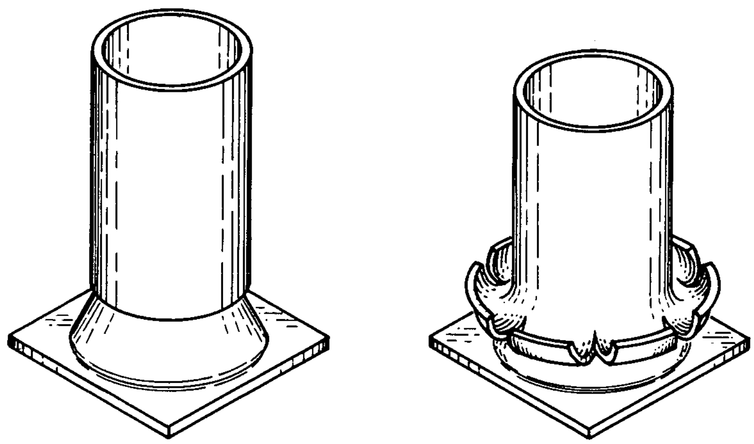


Figure 3.4. Tube and Mandrel Energy Absorber

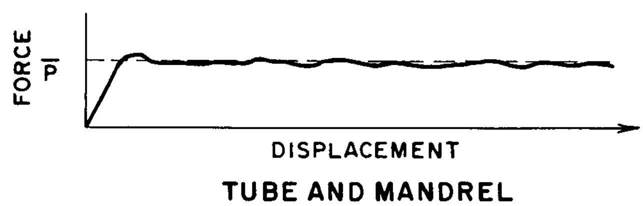


Figure 3.5. Force-Deflection Curve for Tube and Mandrel Energy Absorber

3. Buffer Requirements

The requirements for an elevator buffer can be determined by a simple dynamic analysis. Consider an elevator of weight W traveling at a velocity V_0 just prior to striking a buffer having a stroke S and an average retarding force F.

After striking the buffer the elevator is slowed by the buffer retarding force. The instantaneous velocity while the elevator is acted on by the buffer is V.

The entire kinetic energy of the elevator car is assumed to be absorbed by the buffer since friction forces are small. This gives

$$K.E. \;=\; W\, V_0^2/2g = FS \qquad (3.1)$$

Summing the forces and applying Newton's Law we obtain

$$\Sigma F \;=\; F - W = Wa/g \qquad (3.2)$$

where g is the acceleration due to gravity and a is the deceleration of the elevator.

The force F is nearly constant for the tube and mandrel (solid state buffer). According to the "American Elevator Code" the average value of a must not exceed g, i.e., 32.2 feet/sec^2. This imposes a limitation on the value of F since

$$F \leq 2W_e \qquad (3.2a)$$

where W_e is the empty weight of the elevator. If the maximum allowable value of F is used in Equation (3.1) the stroke for the fully loaded elevator is given by

$$S \;=\; W_f V_0^2/4g\, W_e \qquad (3.1a)$$

where W_f is the weight of the fully loaded elevator. In the case where $W_f/W_e = 2$, Equation (3.1a) can be simplified to

$$S \;=\; V_0^2/64.4 \qquad (3.1b)$$

This equation gives the same values for the minimum strokes as are given for oil buffers in Table No. 201.4a of the elevator code. This table is reproduced below. In this table V_0 is taken as 115 percent of design speed. The line of oil buffers presently being offered by Otis Elevator Company is presented in Table 3.1.

Table No. 201.4a from the "Safety Code for Elevators"

Rated Speed in Feet Per Minute	115% of Rated Speed in Feet Per Minute	Minimum Strokes of Oil Buffers in Inches
200	230	2-3/4
225	259	3-1/2
250	288	4-1/4
300	345	6-1/4
350	402	8-1/4
400	460	11
450	517	13-3/4
500	575	17
600	690	24-3/4
700	805	33-1/4
800	920	43-3/4
900	1035	55-1/2
1000	1150	68-1/2
1100	1265	83
1200	1380	98-1/2
1300	1495	115-1/2
1400	1610	134-1/2
1500	1725	154
1600	1840	175
1800	2070	222
2000	2300	274

Some information of actual elevators is given in Table 3.2.

TABLE 3.1

STROKES OF OTIS OIL BUFFERS

Buffer Stroke (in.)	Rated Speeds (FPM)
8-1/4	200- 350
11	350- 400
17	400- 500
24-3/4	500- 600
33-1/2	600- 700
43-3/4	700- 800
68-1/2	800-1000
84	1000-1140

TABLE 3.2

SOME TYPICAL OTIS ELEVATORS

Weight (lbs)				
Empty W_e	Full W_f	W_f/W_e	V_0 = 115% of Rated Speed (FPM)	F = Max. Ave. Buffer Force (lbs)
7,000	10,500	1.5	405	14,000
7,000	10,500	1.5	700	14,000

4. Solid State Elevator Buffer

The NASA tube and mandrel energy absorber (Pat. No. 3, 143, 321) is a very simple device capable of absorbing large amounts of mechanical energy. The specific energy of this device per pound of tube has been found to be as high as 33, 000 ft-lb/lb.[1] An improved version of this device has been developed at the University of Denver which is suitable for commercial applications. The improvements include a replacement of the curved mandrel with one having a simple conical shape and the use of electric welded mild steel tubing. This tubing has a longitudinal grain flow which encourages the proper fracture formation and is inexpensive.

The prototype tube and mandrel elevator buffer is shown in Figure 3. 6. A steel cap is used on the tube to support a rubber bumper like that used on the oil buffers.

The oil buffer produces a retarding force which is a function of the elevator speed. Therefore, the retarding force is initially very high and then falls very rapidly as the elevator velocity is reduced. This gives a force-deflection curve having the appearance of the one shown in Figure 3. 7. Because of this velocity sensitivity, the same buffer can be used for different elevator weights and speeds. The effect of increasing the weight of the elevator will be to broaden the peak of the force-deflection curve thereby absorbing more energy in the retarding process. Some typical results obtained from an Otis oil buffer are presented in Table 3. 3. It can be seen in this table that the buffer satisfied the code requirements for elevators designed to operate at 1000 FPM with weights ranging from 2500 to 10, 500 lbs. The stroke of the buffer, 68-1/2", is consistent with the "Safety Code for Elevators." In order to perform these same functions with a tube and mandrel buffer, two different sizes of tubes would be required. One for 2500 lb loads and the other for the 9000 to 10, 500 lb loads. However, it was shown earlier that for a given elevator the tube and mandrel buffer would have the same minimum stroke as indicated in the "Safety Code for Elevators" for the oil buffers.

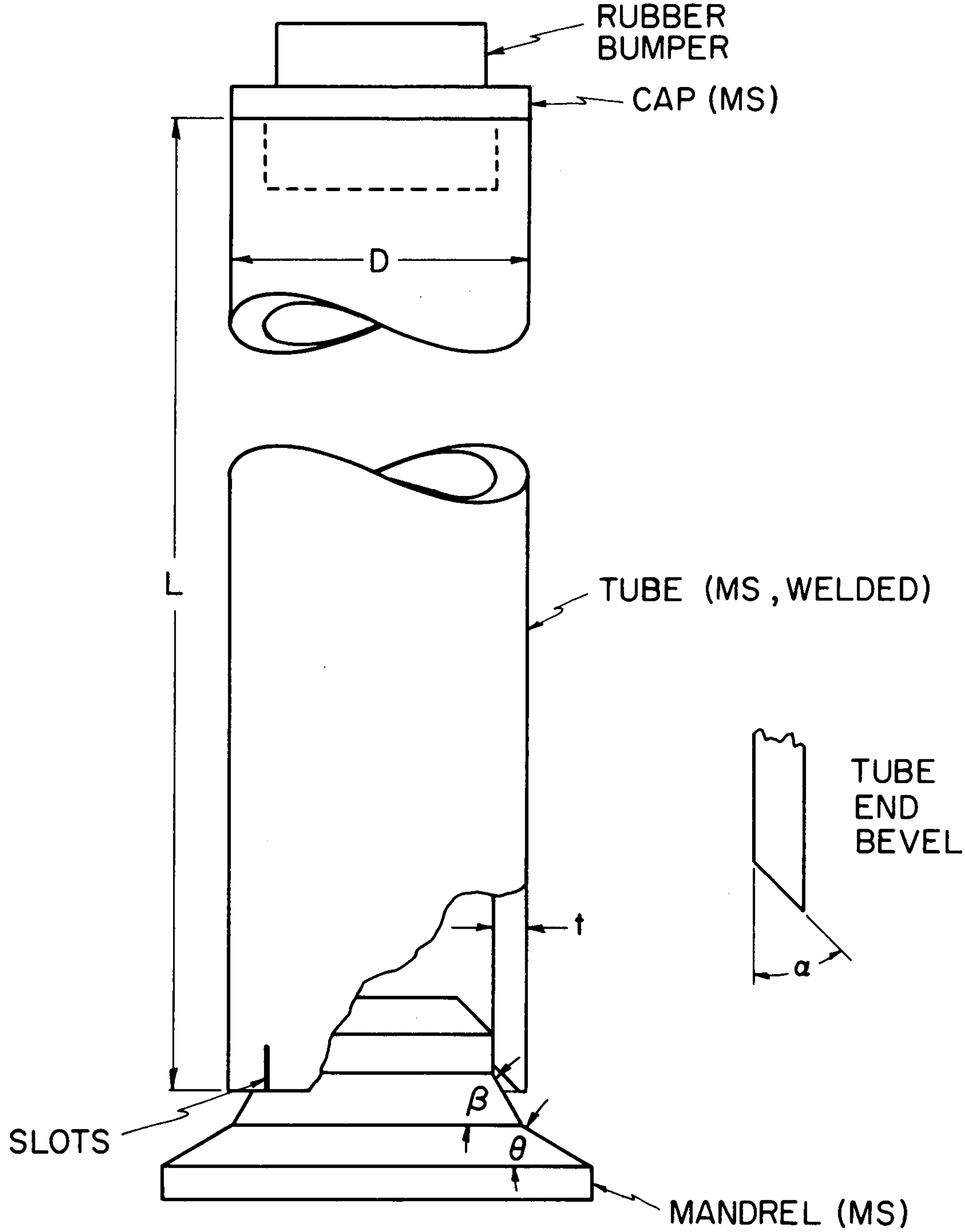


Figure 3.6. Solid State Elevator Buffer

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TABLE 3.3

TYPICAL OIL BUFFER PERFORMANCE DATA

Computed Critical Retardation Values

Stroke: 68-1/2 in. Graduated Cylinder Part No: 350 PA_{15}
Rated Car Speed: 1000 FPM
Rated Load: 2500 lbs to 10,500 lbs

Test Sequence No.	Test Condition			Retardation Data							Remarks
					Peaks Exceeding 80.5 Ft/Sec^2						
	Load Lbs	Speed FPM	Spark No.	Average Based On Stroke Ft/Sec^2	Critical and Adjacent Values (Calculated at Sparks)				Duration Sec		
18	2,500	1146.34	1	26.80	27.38	101.25	98.63	78.00	.035		
		1136.76	2	27.72	64.50	106.50	77.25	61.50	.025		
21	9,000	1149.68	1	30.43	57.75	57.75	65.25	58.50	No Peaks		
		1147.82	2	31.29	57.00	62.25	67.50	47.25			
20	10,000	1158.21	1	30.69	68.25	82.50	78.75	33.75	.011		
		1152.38	2	30.81	78.00	97.50	58.50	20.25	.022		
19	10,500	1150.19	1	30.58	73.50	82.88	91.13	78.00	.034		
		1152.46	2	30.89	74.25	89.25	96.00	59.25	.033		

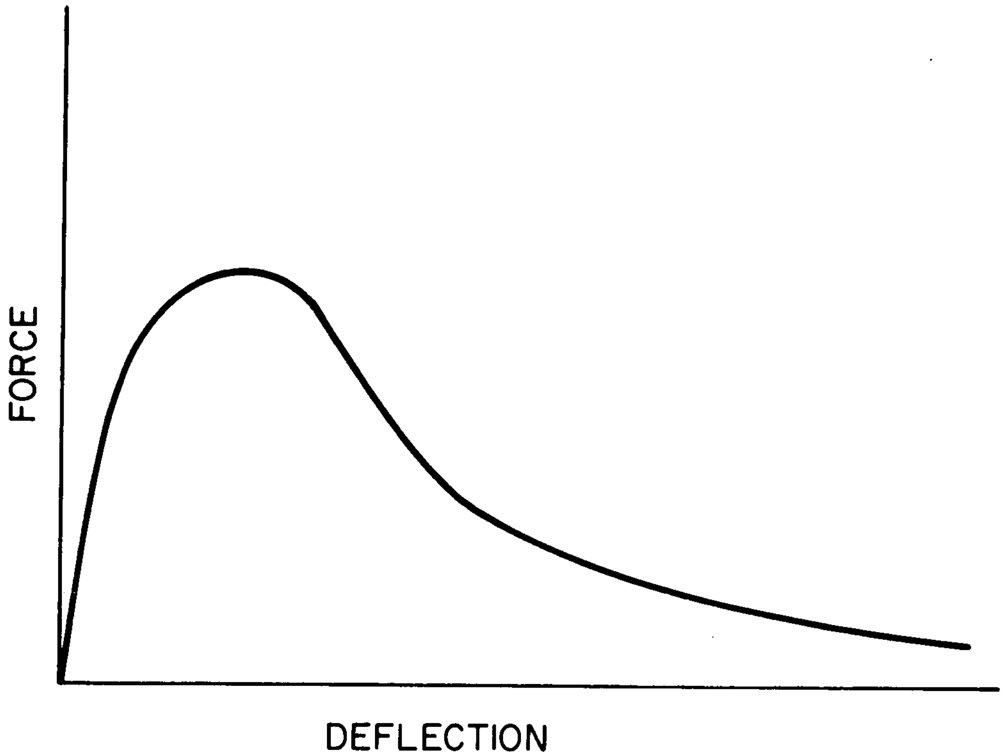

Figure 3.7. Typical Force-Deflection Curve for an Oil Buffer

The tube and mandrel has some important advantages. These include a smaller overall length since the stroke to length ratio is nearly equal to 1. This may be of value in reducing depth of the elevator shaft or in allowing a higher speed elevator to be installed in an existing shaft. The nearly constant force deflection curve will produce a stop which is more comfortable than that produced by the oil buffer. Significant differences exist between the tube and mandrel and the oil buffer in the area of complexity and cost. The tube and mandrel buffer has only a fraction the number of parts the oil buffer has and these parts are less complicated. As a result, the tube and mandrel can be made for a fraction of the cost of the oil buffer.

The tube and mandrel buffer can not be inspected by operating it since it must be replaced after operation. However, once the device has been proven, a tube and mandrel buffer can be given an adequate inspection visually. This would result in a reduction in the labor cost in performing the annual inspection.

Since the tube and mandrel buffer requires replacement after operation an alarm system would be required to signal the need for replacement. The buffer could be made with some extra stroke so that it could take a light bump without the need for replacement. Also it might be that the shorter length of the device would give the elevator more room for stopping beyond the bottom landing and reduce the frequency of the light bumps. A typical solid state elevator buffer is shown in Figure 3.8. The buffer after operation, is shown in Figure 3.9.

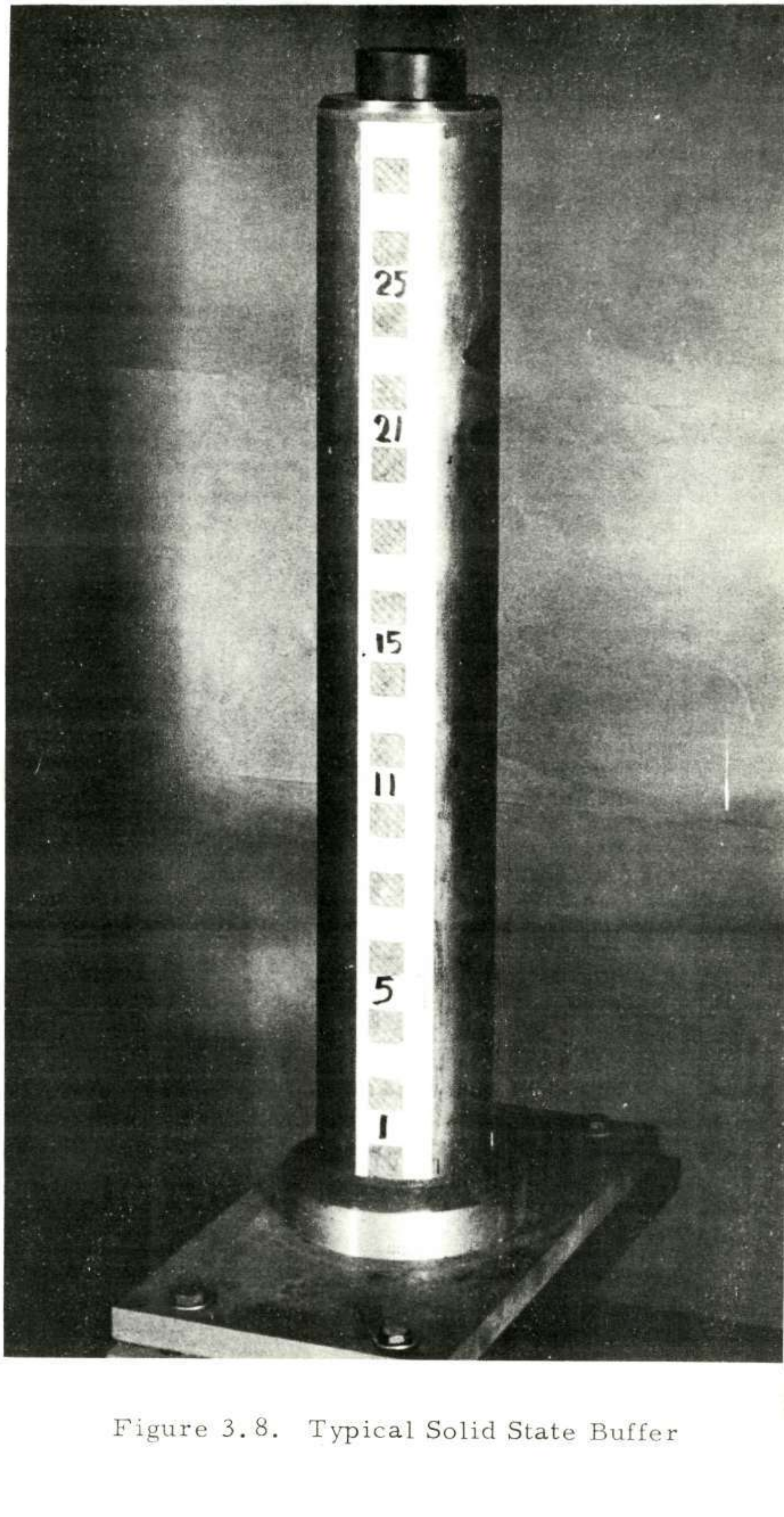

Figure 3.8. Typical Solid State Buffer

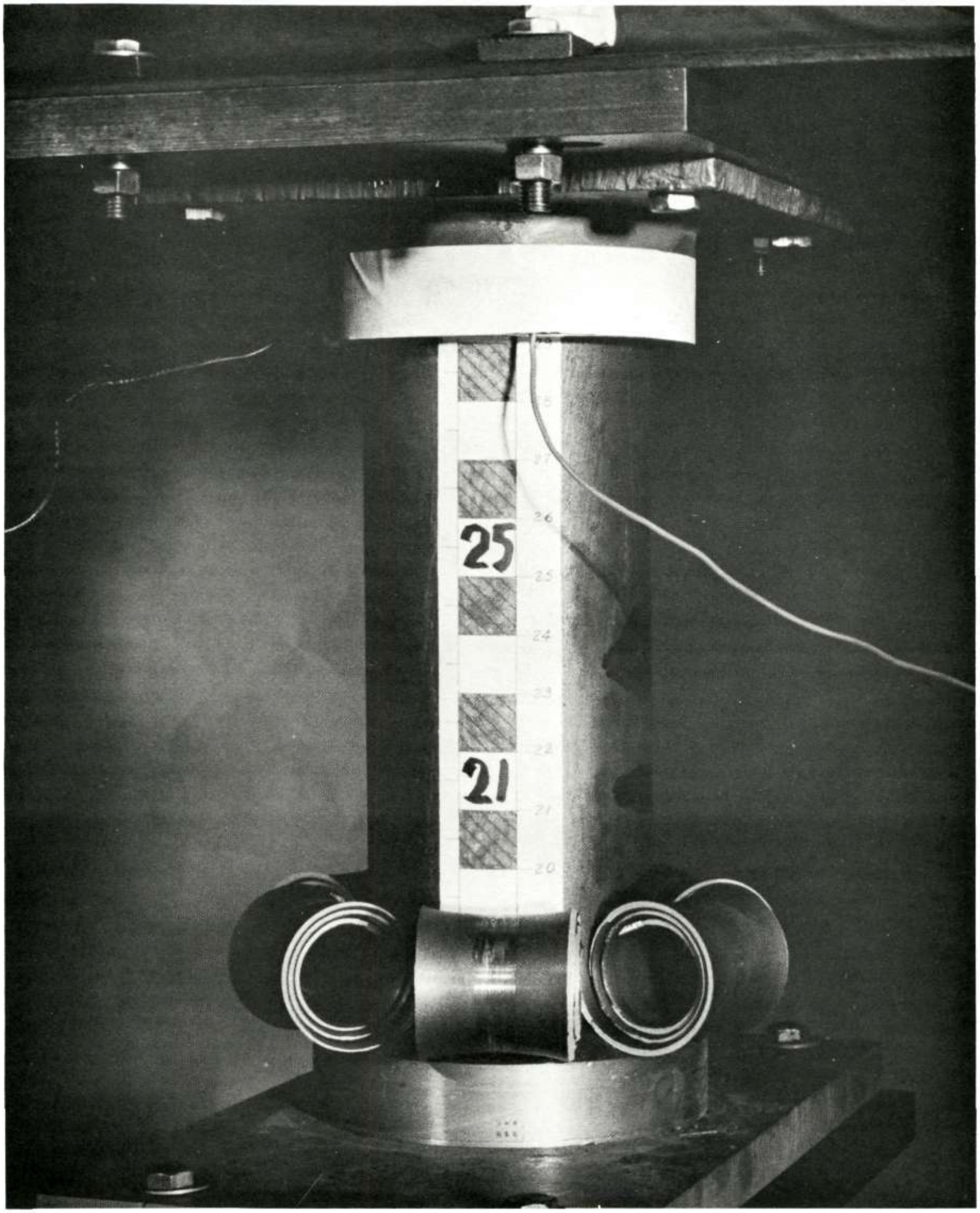

Figure 3.9. Typical Solid State Buffer After Operation

5. Solid State Buffer Operation

The prototype solid state buffer was subjected to a series of dynamic tests by engineers at the Otis Elevator Company Yonkers Works, Yonkers, New York.[3] The performance of the buffers in these tests indicated that the buffer could be designed to work satisfactorily in this application. The desired operating force for the 5" O.D. by 11 gage wall buffer tube is 14,000 lb for the elevators described in Table 3.2. This will give a retardation of 32.2 fps/sec on an elevator with a 7,000 lb weight and a retardation of 10.73 fps/sec on an elevator with a weight of 10,500 lb. While the average buffer force should be near 14,000 lb, a somewhat lower value is acceptable if the stroke is adequate so that all of the kinetic energy of the elevator can be absorbed.

In general the operating force obtained in the tests at Yonkers was somewhat below 14,000 lb. The results of these tests are shown plotted in Figure 3.10. Here the average operating force is plotted as a function of accumulated stroke since several tests were conducted on some of the tubes, each adding to the total stroke of the tube. This plot shows that, except for the tests in which there was excessive mandrel surface damage, the operating force ran at approximately the desired value. The mandrels used in these tests were made of mild steel and were subject to wear and damage by the tubes. The tests made with the surface hardened mandrels are all lower than the others and in the desired range.

These tests demonstrated that this simple low cost device could be designed to replace the oil buffers presently used on elevators.

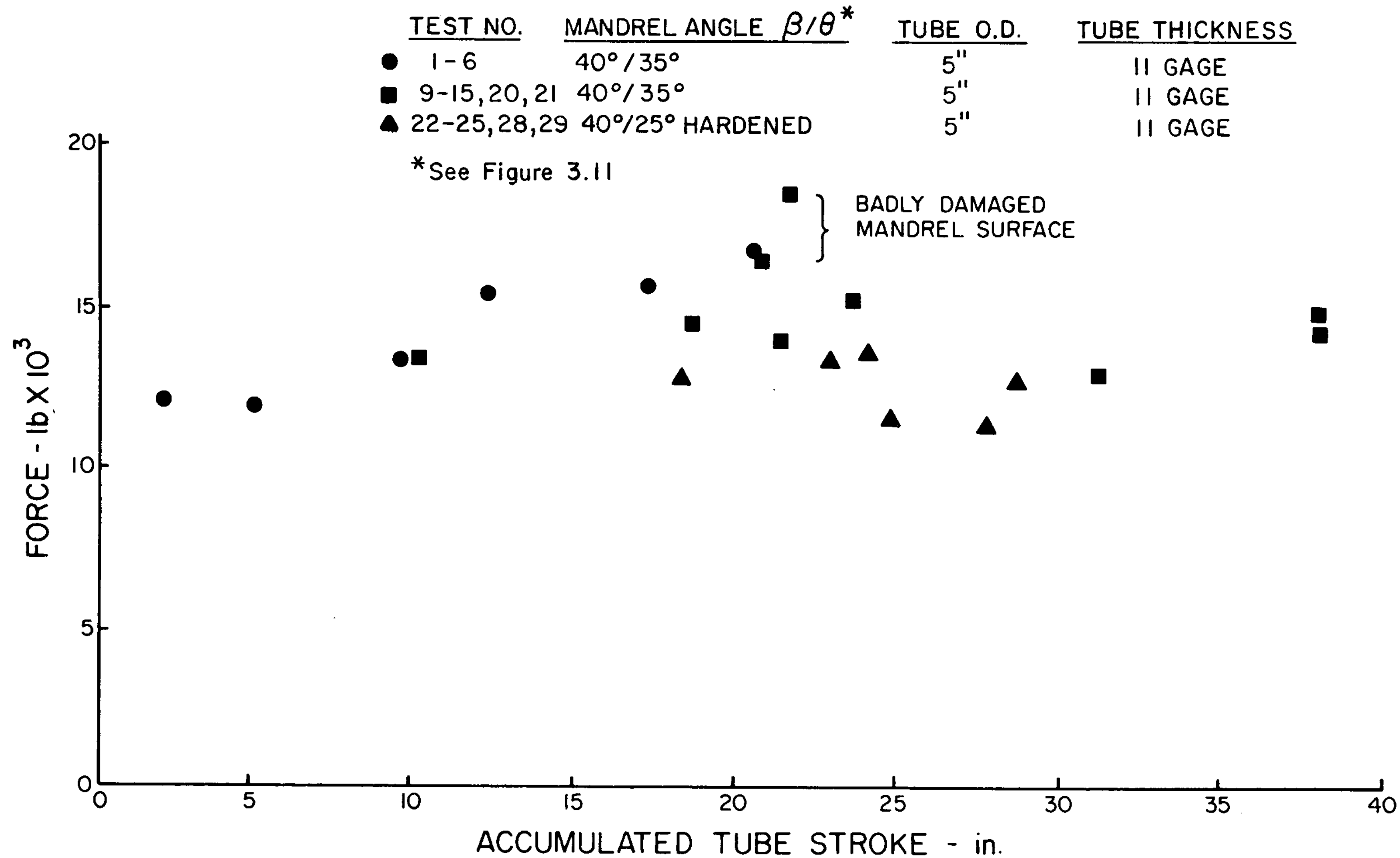

Figure 3.10. Plot of Buffer Test Data

6. Cost Analysis

In order to establish the potential savings to be made out of the use of the buffer on elevators, Otis has made a cost study taking into account the cost of development of the elevator buffer, the cost of tooling and manufacture, the cost of efforts to have the elevator code revised to accept the buffer, and other costs. The results of this study are very favorable.

7. Conclusions

The tube and mandrel energy absorber has been proven to be a practical low cost alternative to existing elevator buffers. Negotiations are in progress to license Otis to exploit this NASA patent in the elevator field and in the rapid transit areas described in the next section.

IV. PERSONAL RAPID TRANSIT CAR BUFFER

1. Summary

The tube and mandrel elevator buffer described in the previous section was adapted for use as a spur track buffer for a personal rapid transit system by engineers at the University of Denver and Transportation Technology Inc. The device is known as the tube and mandrel energy absorber and consists of a metal tube which is forced endwise onto mandrel which expands it and causes it to split and curl up. The deformation of the tube material and the friction between the tube and mandrel absorb mechanical energy. The device is ideally suited for this application since it is extremely simple, highly reliable, and very compact.

2. Introduction

The tube and mandrel elevator buffer was adapted for use as a spur track buffer in the personal rapid transit system developed by Transportation Technology Inc., Denver, Colorado, an affiliate of the Otis Elevator Company. This personal rapid transit system, illustrated in Figure 4.1, utilizes small cars which will carry six to ten people, therefore, the word personel. These cars are computer controlled so that any car can be directed to any point in the system. The rider pushes a button indicating his desired destination and waits for a personal transit vehicle to dock at his station. He then rides the vehicle alone or with other people, depending on the density of the traffic, to his desired destination, possibly with intermediate stops. In other words, the system is used much the same as an elevator. The computerized control allows the system to be flexible, able to handle fluctuating loads over the entire system.

The tube and mandrel elevator buffer is used at the end of track spurs to bring the vehicle to a safe stop in the unlikely event that the automatic braking system fails to operate. The vehicle is powered by a linear induction motor and is suspended by air levitation. Some braking is done by the motor but the main braking effort in quick stops is accomplished by turning off the levitation air and allowing the vehicle to slide along the track on its skids. The buffer is designed to stop the vehicle, which will weigh between 7800 lbs (empty) and 9400 lbs (full at speeds up to 10 mph, in a distance of 4 feet). The buffer can be seen at the end of the track spur in Figure 4.2. This photograph and the one presented in Figure 4.1 were taken of the TTI exhibit at Transpo-72, Washington, D.C., May 27 - June 4, 1972.

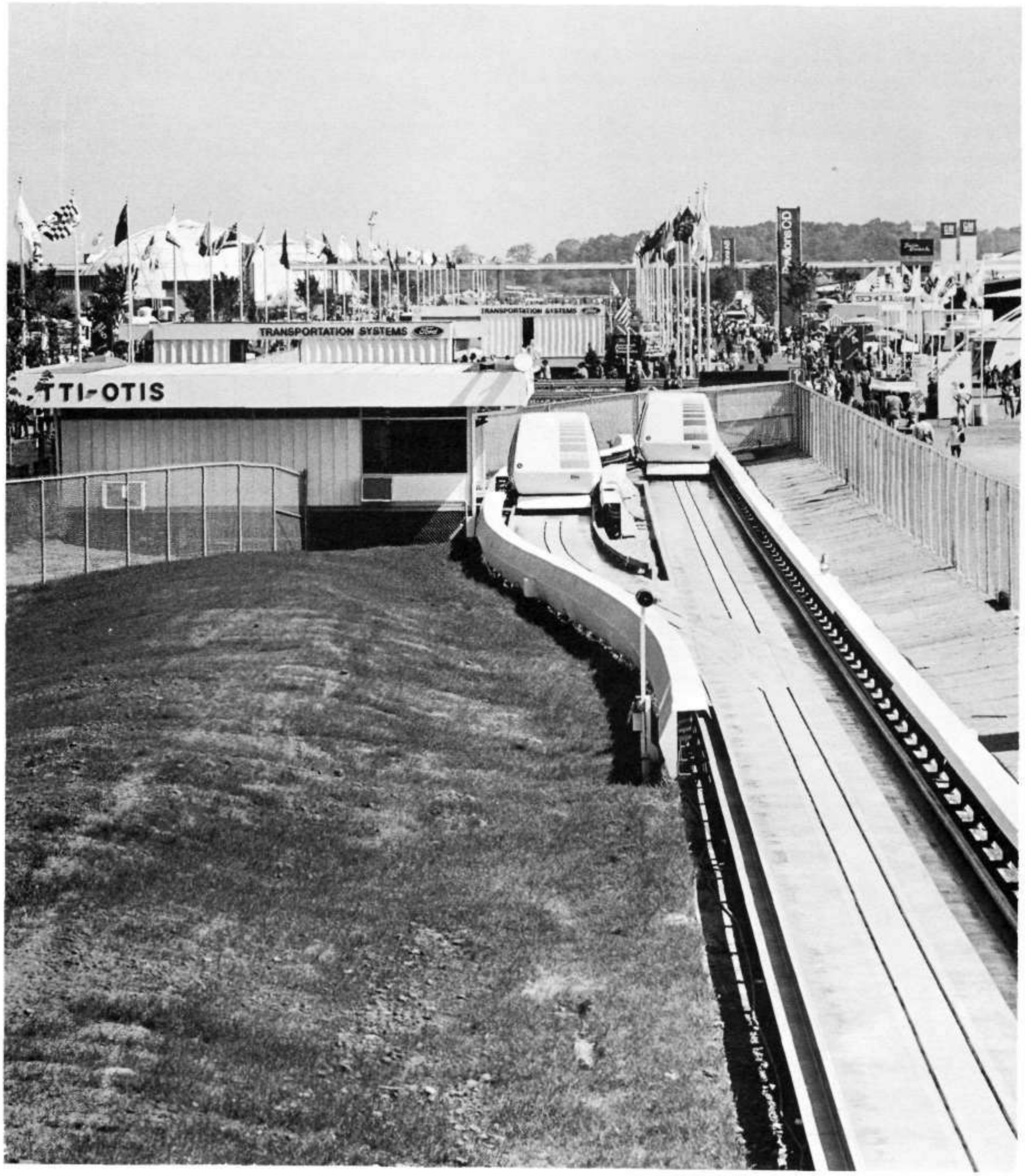

Figure 4.1. Photo of TTI Personel Rapid System

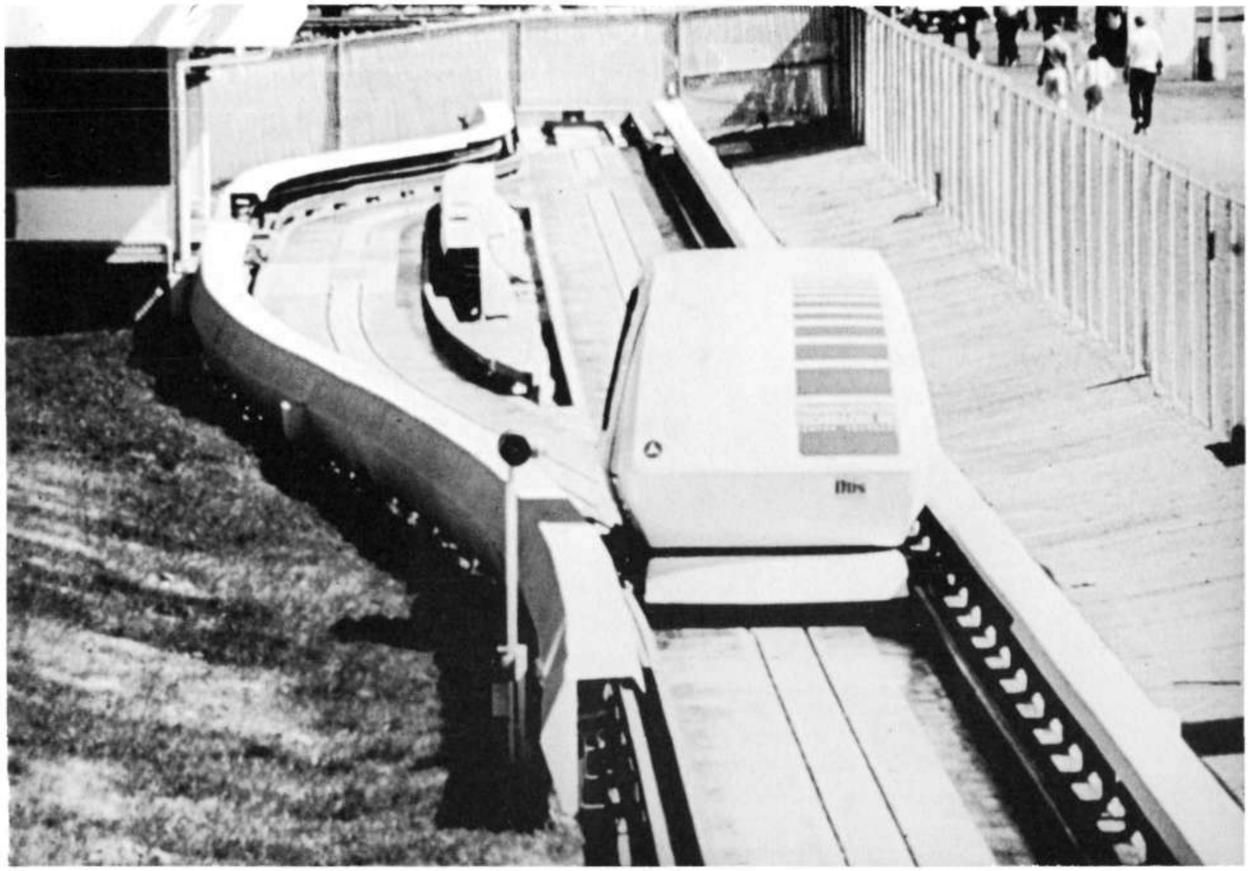

Figure 4.2. Photo of TTI System Spur and Buffer

3. Requirements

The requirements for the transit car buffer established by Transportation Technology were that it must stop the fully loaded (9400 lb) car at speeds up to 10 mph in a distance of not more than 5 feet, with the acceleration during the stop not exceeding an average of 1 g (32.2 fps) on the empty (7800 lb) car. From this the force requirements for the buffer were determined by a simple dynamic analysis. Consider a transit car of weight W impacting the buffer with velocity V_0. The vehicle is brought to rest by a resistive force F over a stroke S, thus expending the kinetic energy of the moving vehicle in doing work on the buffer. This is described mathematically as

$$KE = WV_0^2/2g = \int F ds = \text{Work} \tag{4.1}$$

Application of Newton's Law gives

$$F = aW/g \tag{4.2}$$

where a is the acceleration on the vehicle produced by the resistive force of the buffer. Since the tube and mandrel energy absorber produces a nearly constant resistive force, the acceleration, a, is nearly constant during the stop and a function of W. The acceleration is therefore largest on the lightest car, i.e., the empty one (7800 lbs). With F taken as a constant equation 1 may be rewritten

$$WV_0^2/2g = FS. \tag{4.3}$$

For a given value of the resistive force, F, the stroke, S, is a function of the weight, W, and is therefore greatest when W is greatest, i.e., when the car is full (9400 lbs).

From the above, it can be seen that the maximum average resistive force which can be produced by the buffer is 7800 lbs. Over a five foot stroke, 39,000 ft/lb of energy would be absorbed. The kinetic energy of the 9400 lb fully loaded vehicle at 10 mph (14.7 fps) is 31,500 ft lb. Therefore, a resistive force of 6300 lbs is adequate. Consequently the requirements are satisfied by a buffer having a resistive force of between 6300 and 7800 lb and a stroke of five feet.

4. Buffer Design

The buffer designed to meet the transit vehicle requirements is illustrated in Figure 4.3. The tube is welded cold rolled 1010 steel (flash controlled) 3-3/4" O.D. with a 0.063" wall. On the mandrel end of the tube are six evenly spaced 1/2" deep saw cuts to provide sites for crack initiation and to control the starting load. The mandrel is a dual taper design with a 45° upper slope for starting the tube and a 32° lower slope for expanding and curling the tube during the remainder of the stroke. Typical static test results for this buffer are presented in Figure 4.4

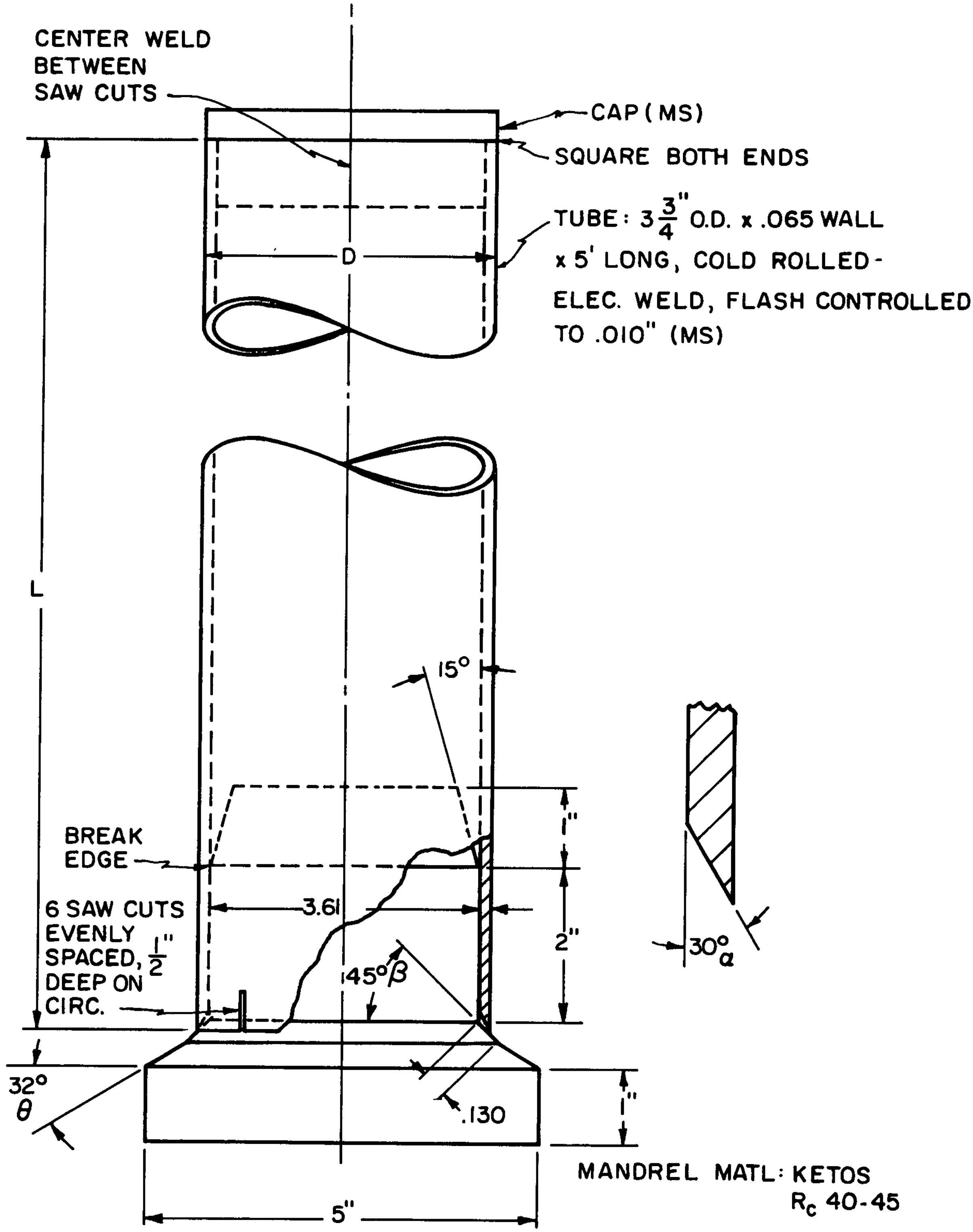

Figure 4.3. Phototype Rapid Transit Vehicle Buffer

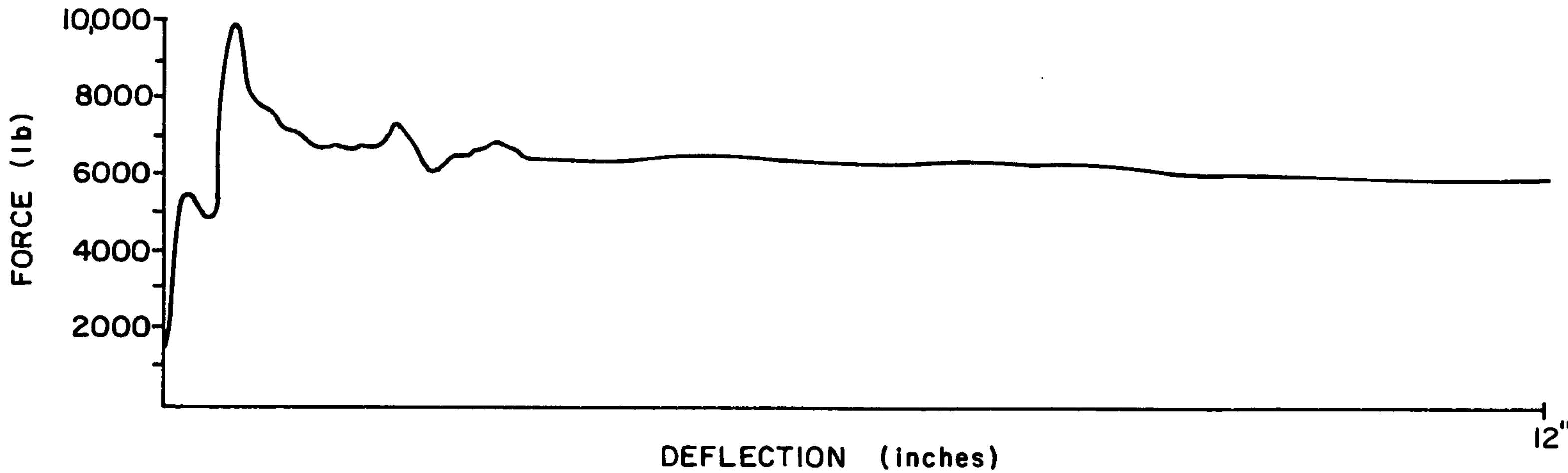

Figure 4.4. Typical Static Test Results for Prototype Buffer

5. Dynamic Tests

A series of dynamic tests were conducted with the prototype transit car buffer by the Otis Elevator Company at its test facility, Yonkers, New York. The results of these tests are summarized in Table 4.1. The test set up is illustrated in Figure 4.5. It is a specially designed test elevator for testing elevator buffers. It consists of an elevator frame without car or doors on which weights may be added to give the desired weight. The elevator achieves its operating speed in free fall after being released by a specially designed mechanism from a predetermined height.

The instrumentation used on the tests consists of a system for measuring the velocity of the elevator, a system for recording elevator position-time data during the free fall and the buffer operation, and a method for determining the instant of contact between the elevator and the top of the buffer. The velocity measurement is made with a Weston Tach-Generator mounted on the elevator with a friction wheel operating on a stationary rail. Its output is recorded by a CEC oscillograph. The output of the tach-generator is proportional to the speed of rotation and therefore, proportional to the speed of the elevator. The elevator position-time information during the drop and the operation of the buffer is taken by means of a Cenco synchrous spark generator which puts out sparks at 60 cycles per second. These sparks jump from a stylus mounted on the elevator to a long stationary rail fitted with a specially made paper tape. A series of small holes are burned in the tape by the sparks, thus recording the position of the elevator at 60 intervals per second. The output of the spark timer is also recorded by the oscillograph so that the paper tape data can be synchronized with the other data. A contact switch in series with a power supply is used to send a signal to the oscillograph indicating the instant of contact of the elevator with the buffer.

The results of the dynamic tests at Otis Elevator Company are tabulated in Table 4.1. It can be seen here that the three tests at 1060 fpm (12 mph) gave a higher than desired resistive force. At first it was thought that the buffer was too stiff and would have to have its resistive force lowered. However, Transportation Technology engineers decided, upon rethinking the problem, that they favored this stiffer buffer since the acceleration on the empty vehicle during a stop would average less than 1.25 g's and also the stiffer buffer would offer a greater margin of safety. It was therefore decided to take the prototype buffer as tested for the final design.

TABLE 4.1

DYNAMIC TEST DATA

Date	Test No.	Com'l. Tubing	Mandrel Angle (Degrees)	Test Load (Lbs)	Nominal Striking Velocity (fpm)	Overall Buffer Length (Inches)	Reduced Buffer Length (Inches)	Buffer Stroke (Inches)	Average Buffer Resistive Force (Lbs)	Peak Buffer Resistive Force (Lbs)
	1	3.75 OD × .065 wall			474	63-5/8	57- 5/8	6	6975	9,075
	2	cold rolled elec. welded. Flash con-	45°/32°		489	63-5/8	57-13/16	5-13/16	7315	10,055
1/17	3	trolled to .010	Hardened	2835	1067	63-5/8	40- 5/16	23- 5/16	9335	13,395
	4	C-1010 C.R. Stl.	RC46-50		1078	63-3/4	40	23- 3/4	9235	11,835
	5				1064	63-5/8	41- 1/2	22- 1/8	9535	13,405

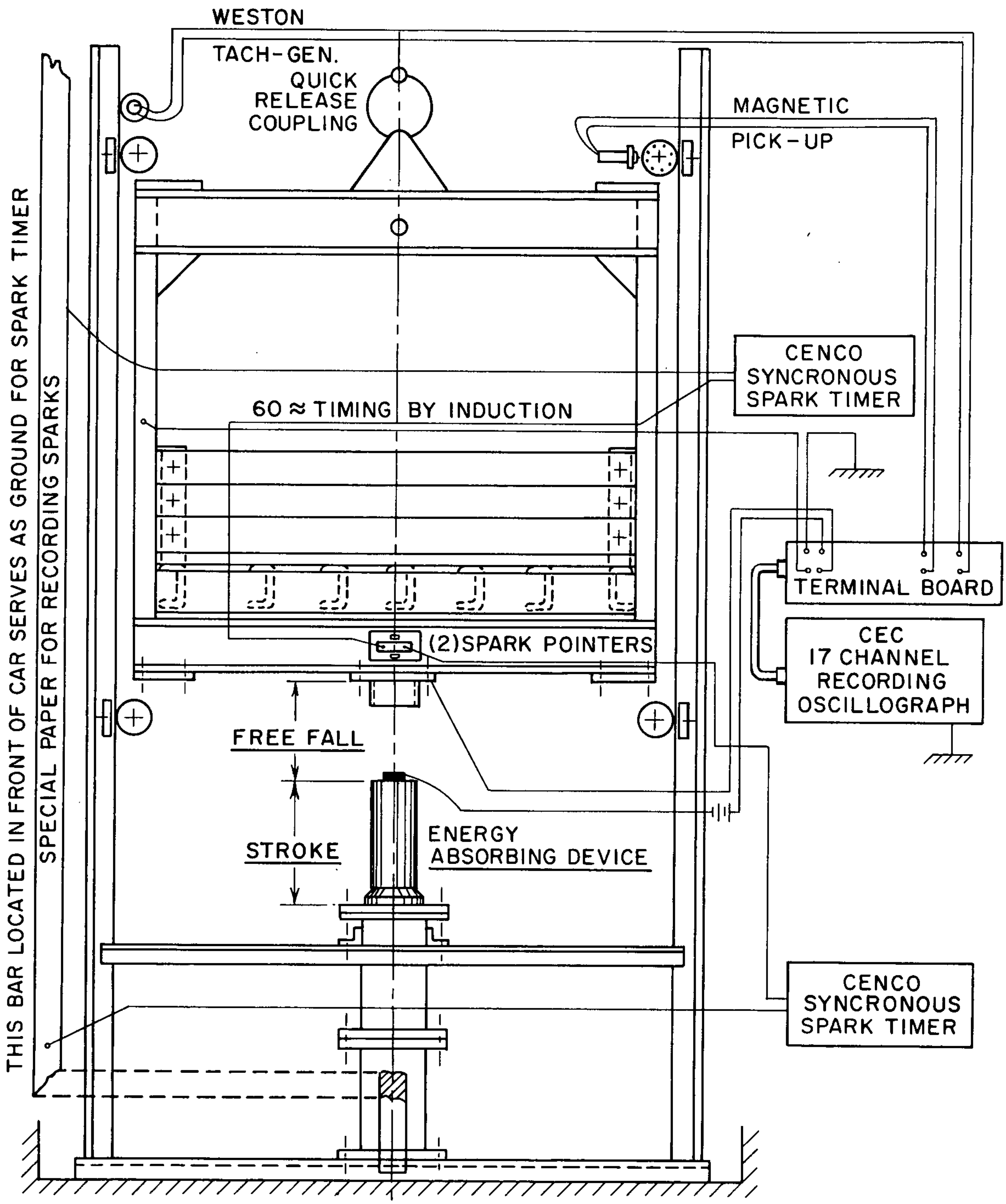

Figure 4.5. Otis Test Set Up

The results of later work revealed that the increase in the resistive force of the buffer in the higher speed impacts is due to frictional effects between the mandrel surface and the inside of the tube. If, in place of the molydisulfide grease lubricant used on the above tests, the mandrel and the entire inside of the tube are painted with aluminum paint the resistive force will be much less sensitive to the impact velocity. In other tests using the painted surfaces very little difference was observed between the static test results and tests at impact speeds up to 80 fps.

6. Buffer Installation

The design of the installation of the buffer by Transportation Technology engineers is shown in Figure 4.6: The installation differs a little from the elevator application. Here a guide is required on the end of the buffer to insure axial motion of the buffer tube.

7. Conclusions

The tube and mandrel is an ideal energy absorber for this type of application because of its low cost, high efficiency, and its small size. It is believed that the buffer could also be used on larger systems of the same type and on railroad spurs.

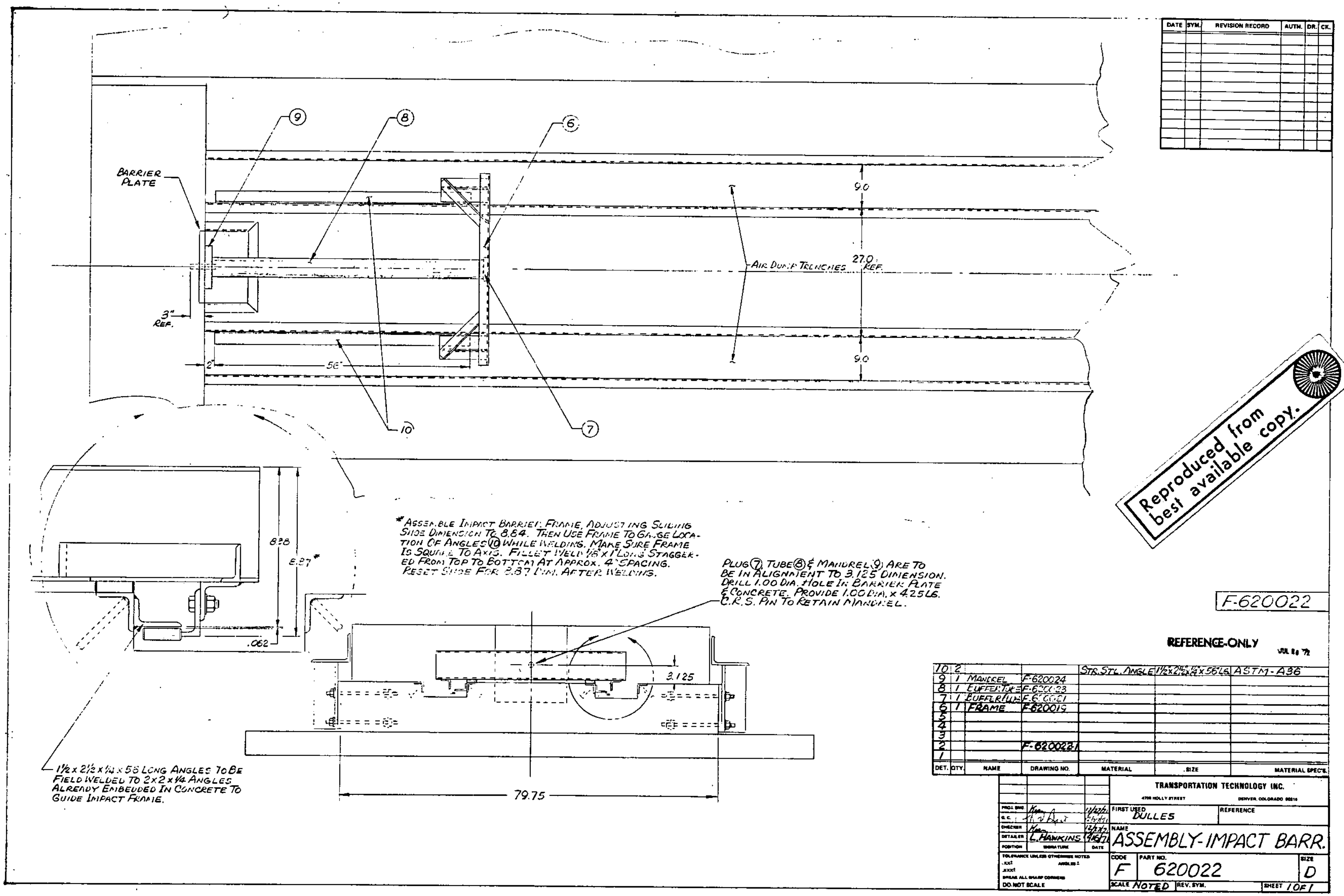

Figure 4.6. Drawing of Buffer Installation in Transportation Technology Personal. Rapid Transit System Spur.

V. SEMITRAILER SUPPORT ENERGY ABSORBER

1. Summary

An energy absorbing device invented by a NASA engineer (McGehee, Patent No. 3, 143, 321) has been adapted for use in the front support structure of semitrailers to protect the trailer and support from damage due to accidental drops. The energy absorber, known as the tube and mandrel, consists of a metal tube which is forced endwise onto a mandrel which expands it causing it to split and curl. The deformation of the tube material and the friction between the mandrel and the tube absorb energy. It was found that the tube could be welded to the mandrel so that the energy absorber could function as part of the structure under normal loading; larger than normal loads shear the welds and cause the energy absorbers to be activated. In actual tests with fully loaded Fruehauf Model F trailers the energy absorbers have given satisfactory performance for normal pullout drops with up to 14-1/2" clearance between the supports and the pavement.

A prototype sand shoe, utilizing this energy absorber, has been developed which can be used to replace the standard sand shoe used on semitrailers without trailer modification. This sand shoe can be used on new trailers and as a replacement on existing trailers. The Homan Company, Cincinnati, Ohio, an original equipment manufacturer for the trailer industry, cooperated with the University of Denver and the Fruehauf Corporation, Detroit, Michigan, in the development of this device. Homan plans to produce the energy absorbing sand shoe and sell it to trailer manufacturers and truck fleet operators.

2. Introduction

Semitrailers are equipped with a front support structure so that they can stand alone. This structure is equipped with retractable lower legs which terminate at wheels or sand shoes. The sand shoes are generally preferred since they provide more contact area than the wheels and do not sink down in asphalt pavement. When the trailer is hooked up to a tractor the lower legs are retracted so that the clearance between the shoes or wheels and the pavement is 12 to 15 inches. Truck drivers refer to the front support structure as the "landing gear," and for good reason, since frequently the trailer is unhooked and the tractor driven off without the support structure being lower completely. This results in a drop of the trailer, and, in many cases, damage to the support and to the trailer understructure.

3. Previous Work

The Fruehauf Corporation, Detroit, Michigan, suggested the possibility of incorporating the NASA tube and mandrel energy absorber (McGehee, Patent No. 3,143,321) into the lower support legs to protect the structure and the trailer from such damage, see Figures 5.1 and 5.2. Subsequently the University of Denver and the Fruehauf Corporation worked together on the development of this energy absorber[2,3]. This program resulted in the development of a prototype energy absorber which worked very well in conjunction with the Fruehauf Briskin sand shoe shown in Figure 5.3. In actual tests with a fully loaded Fruehauf Model F trailer this energy absorber protected the trailer in a series of pull out drops with up to 14-1/2" of clearance between the sand shoes and the pavement.

a. Trailer Support Energy Absorber Requirements

In general it is required that the energy absorbers protect a fully loaded Fruehauf Model F (40 ft long) trailer from damage in a drop of 6" onto concrete pavement with a burning rubber tractor start. Also the support leg must be able to resist the normal operating loads including small drops (up to 1 or 2"), tensile loads imposed by retracting the lower support legs when the wheels or shoes are frozen to the pavement, and transverse loads imposed by sliding the wheels or shoes on the pavement during hookup. Figure 5.4 presents Fruehauf test results concerning the strength of the front support structure. It can be seen here that an axial load of 54,000 lbs on the leg can be tolerated by the leg without yielding. If the wheels are removed from the system, the leg can tolerate loads up to 70,000 lbs. Also the legs are capable of resisting bending loads of up to 12,500 lbs when fully extended.

In addition to structural requirements, the energy absorbers for this application must satisfy certain size requirements. First, the overall length of the lower leg (including wheels or pads) must not be increased more than about 4" with the addition of the energy absorber since any increase in the overall length of the lower support leg will reduce the total clearance between the wheels or shoes and the pavement when the leg is retracted. Also the energy absorber should be nearly the same dimensions as the bottom of the support leg so that mounting is not a problem and so that the leg has a relatively normal appearance with the energy absorber installed on it. In addition to these requirements the energy absorber should be low in cost and highly reliable.

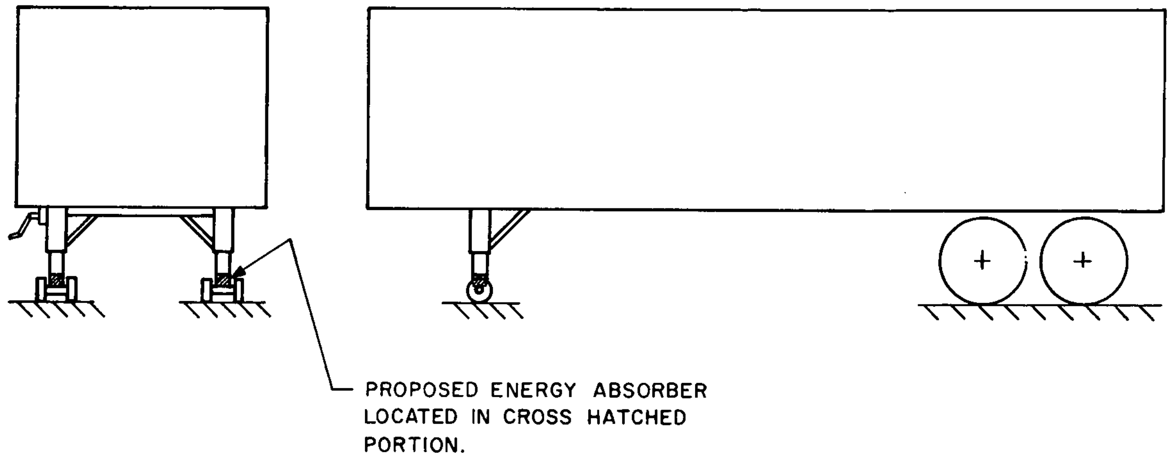

Figure 5.1. Proposed Application of Energy Absorbers to Semitrailers

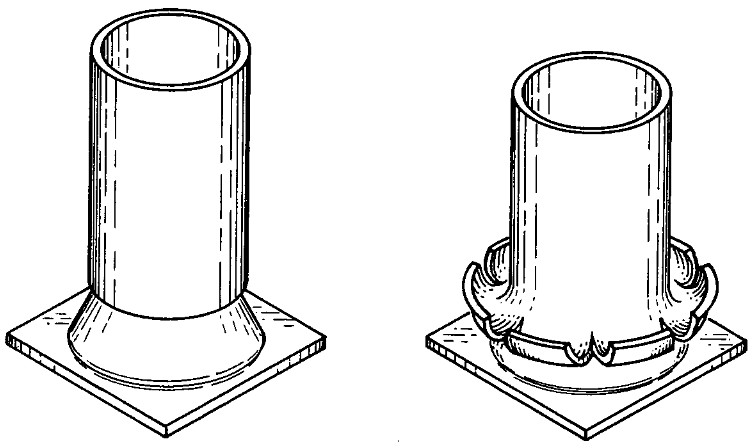

Figure 5.2a. Tube and Mandrel Energy Absorber

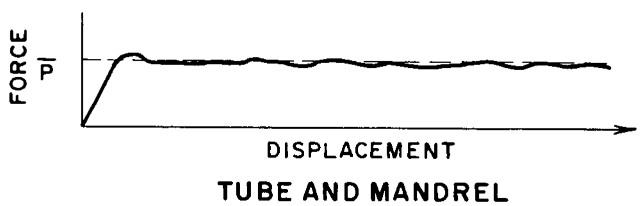

Figure 5.2b. Force-Deflection Curve for a Tube and Mandrel Energy Absorber

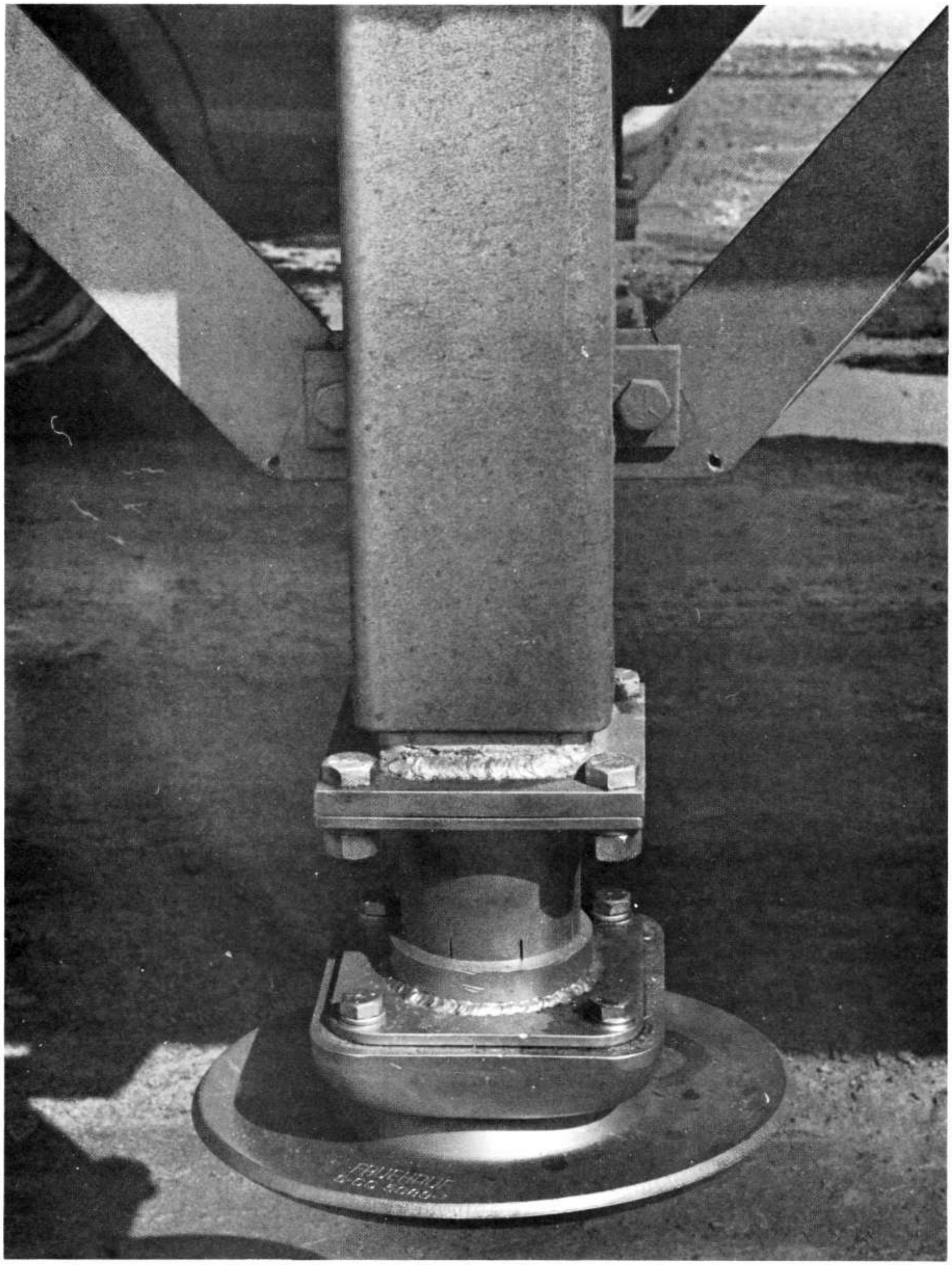

Figure 5.3. Energy Absorber Installed With Briskin Sand Shoe

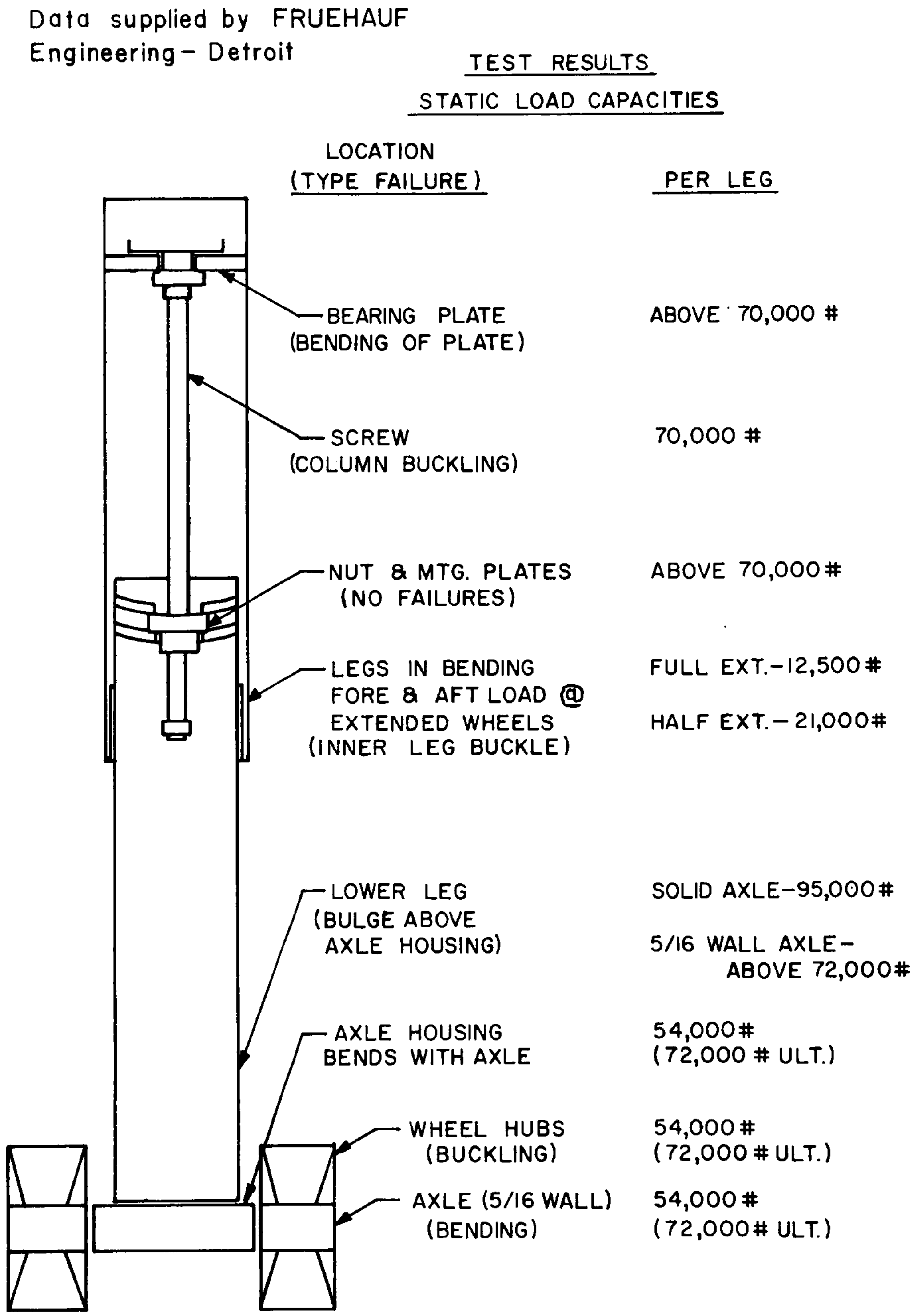

Figure 5.4. Test Specifications for Fruehauf Trailer Support Structure

It has been determined that a drop of up to approximately 8" during uncoupling does not result in free fall of the front of the trailer but rather the fifth wheel tilts when the pivot is in front of the front corner of the trailer and the corner slides down it[2]. This results in a somewhat lower impact velocity for the support legs than would be achieved in free fall. It can be shown mathematically, considering the tractor and trailer as a coupled dynamic system with two degrees of freedom, that the vertical velocity V of the front corner of the trailer at impact between the shoes and the pavement is given by

$$V = \frac{2}{3}\left\{S_1\left(\frac{F_t - F_f}{M_t}\right) + S_2\left[\frac{3R_L\,(WR_c\beta + R_L F_t\gamma)}{MR_c^2\beta + 3R_L^2 M_t\gamma}\right]\right\}^{\frac{1}{2}} \qquad (5.1)$$

The nomenclature used here and in the following equations is given in Table 5.1 and Figure 5.5. It follows that the rotational velocity ω_1 of the trailer at shoe impact is given by

$$\omega_1 = \frac{V}{R_L} \qquad (5.2)$$

Using this, the constant resistive force required to bring the trailer to rest in a given stroke is given by[2]

$$F = \frac{\omega_1^2 MR_c^2}{2S} + \frac{M_g R_c}{R_s} \qquad (5.3)$$

It has been assumed here that the resistive force produced by the energy absorber will be constant since the constant force energy absorber absorbs the maximum possible amount of energy within the constraints of a maximum allowable stroke and a maximum allowable resistive force[1, 2]. Using Equation 5.3 with the tractor and trailer data given in Table 5.2, assuming a drop of 6", and assuming an energy absorber stroke of two inches, F = 74,000 lbs. This is the total force on the front support of the trailer so two energy absorbers each having an average resistive force of 37,000 lbs would be required.

Equations 5.1 and 5.3 rely on the assumption that the front corner slides all the way down until the shoes or wheels impact the pavement. To determine the impact velocity for a situation in which the drop height is sufficient to result in some free fall after the front

TABLE 5.1

TRACTOR AND TRAILER PARAMETERS USED IN VELOCITY AND FORCE EQUATIONS (also see Figure 4.5)

e	=	Overall efficiency of tractor gear train
F_f	=	$\mu_1 P_1$
F_t	=	TGe/r
G	=	Tractor gear reduction
g	=	Acceleration due to gravity (32.2 ft/sec^2)
M	=	Trailer mass (slugs)
M_t	=	Tractor mass (slugs)
P_1	=	Downward force of trailer on fifth wheel (lb)
r	=	Radius of tractor wheels (ft)
S_1	=	Distance from trailer kingpin to front corner of trailer (ft)
S_2	=	Distance tractor moves while front corner of trailer slides down tilted fifth wheel (ft)
S	=	Energy absorber stroke (ft)
T	=	Maximum tractor engine torque (ft-lb)
W	=	Weight of trailer
β	=	$\tan\theta - \mu_1$
γ	=	$\mu_1 \tan\theta + 1$
μ_1	=	Coefficient of friction between trailer and tractor fifth wheel
θ	=	Tilt angle of fifth wheel (deg)

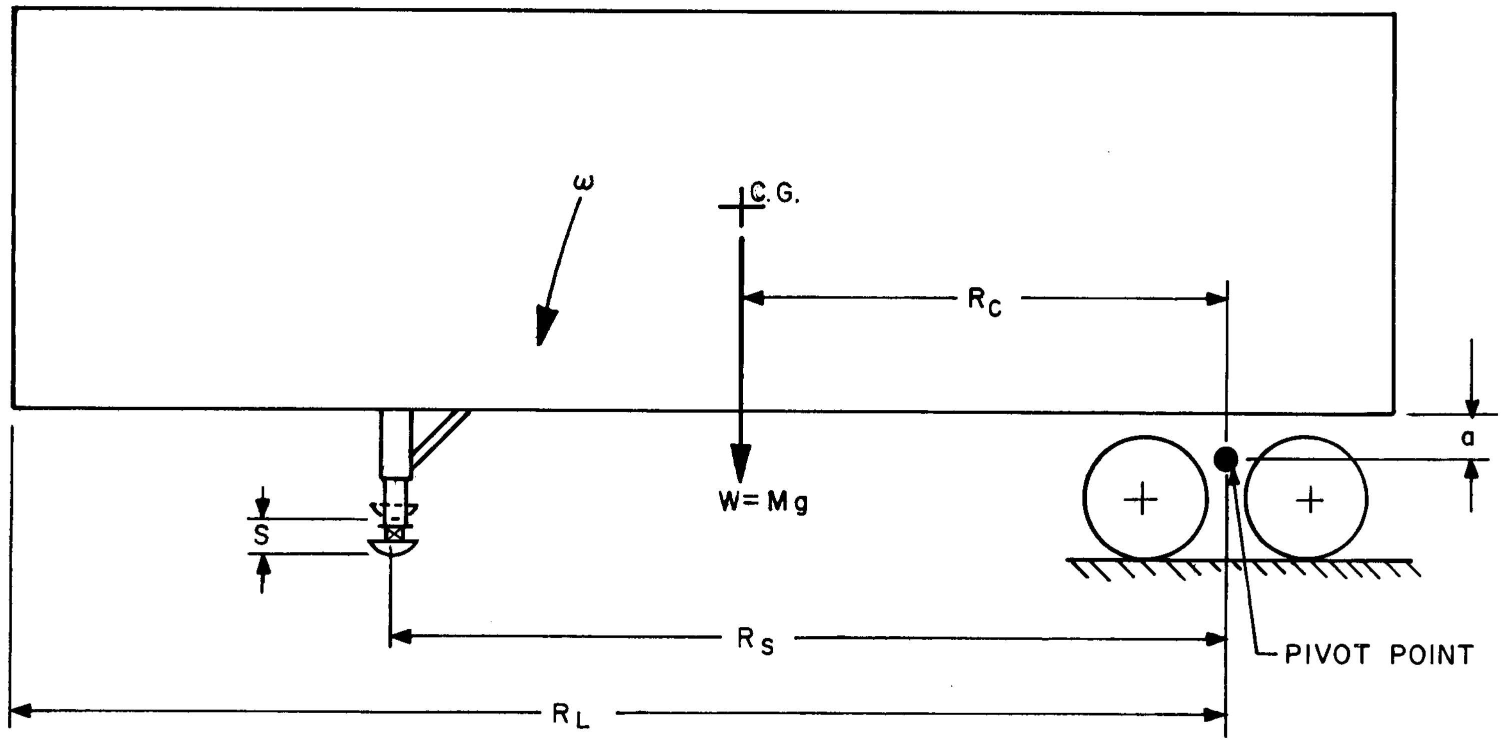

Figure 5.5. Definition of Trailer Parameters Used in Velocity and Force Equations

TABLE 5.2

DATA FOR A TYPICAL TRACTOR-TRAILER COMBINATION

Engine Horsepower		275 bhp @ 2300 rpm
Max. Engine Torque	T	700 ft/lb @ 1600 rpm
Max. Torque Rating on Clutch	T_c	1200 ft/lb
Truck Weight	W_t	13, 105 lbs
Rear Wheel Radius	r	43.5 in. (neglecting tire deflection)
Max. Gear Reduction	G	60:1
Assumed Coefficient of Friction for Trailer on Fifth Wheel, Typical	μ_1	.1
Assumed Gear Train Efficiency	e	65%
Loaded Trailer Weight	W	57, 500 lbs
Trailer Dimensions	R_c	218 in.
	R_s	360 in.
	R_L	487 in.
Pull-out Distances	S_1	2.3 ft
	S_2	2 ft

corner leaves the ramps behind the fifth wheel or in the case in which the ramps are at a different angle than the tilted fifth wheel the equations would have to be revised.

b. Trailer Energy Absorber

Previously the tube and mandrel energy absorber had been demonstrated to give a nearly constant force-deflection curve.[1,2] It was also shown that the energy absorber could be made entirely from mild steel and that a mandrel with a conical shape could be used. This made the energy absorber practical for many applications since it could be made from commercially available tubing and the mandrels could be mass produced from mild steel. Therefore, the tube and mandrel energy absorber seemed ideally suited for use in the support structure except that the device was made of two separate parts and as such was unable to resist, as a unit, the tensile and sending forces which are imposed on the support leg. Several rather complex schemes involving additional parts internal to the energy absorber were conceived to provide it with this desired capability. However, each of these made the device so complicated and potentially expensive to produce that they were discarded as unworkable. Finally it was observed that the use of mild steel for both the tube and the mandrel made it possible to join them together by arc welding such that the weld would be sheared by a sufficient axial compressive load; otherwise the tube and mandrel would behave as a structural element, resisting axial and transverse loads such as those imposed on the trailer leg.[2,3]

The first prototype of the trailer energy absorber is shown installed in Figure 5.6.[3] This energy absorber was designed to be activated by a load of 50,000 lbs and to provide a constant resistive force of 35,000 to 40,000 lbs. It consisted of a length of 1010 steel DOM tubing and a mild steel mandrel having a taper of 22°. The tube was welded to the mandrel inside with 8 small fillet welds. The energy absorber was equipped with flanges top and bottom for the purpose of bolting it to the lower support leg and to the wheels or shoes. Static tests on this device produced the results shown in Figure 5.7. This prototype was found to give excellent results when used in conjunction with a sand shoe as shown in Figure 5.8. However, it was unsatisfactory when used in conjunction with the wheels as shown earlier (Figure 5.6).

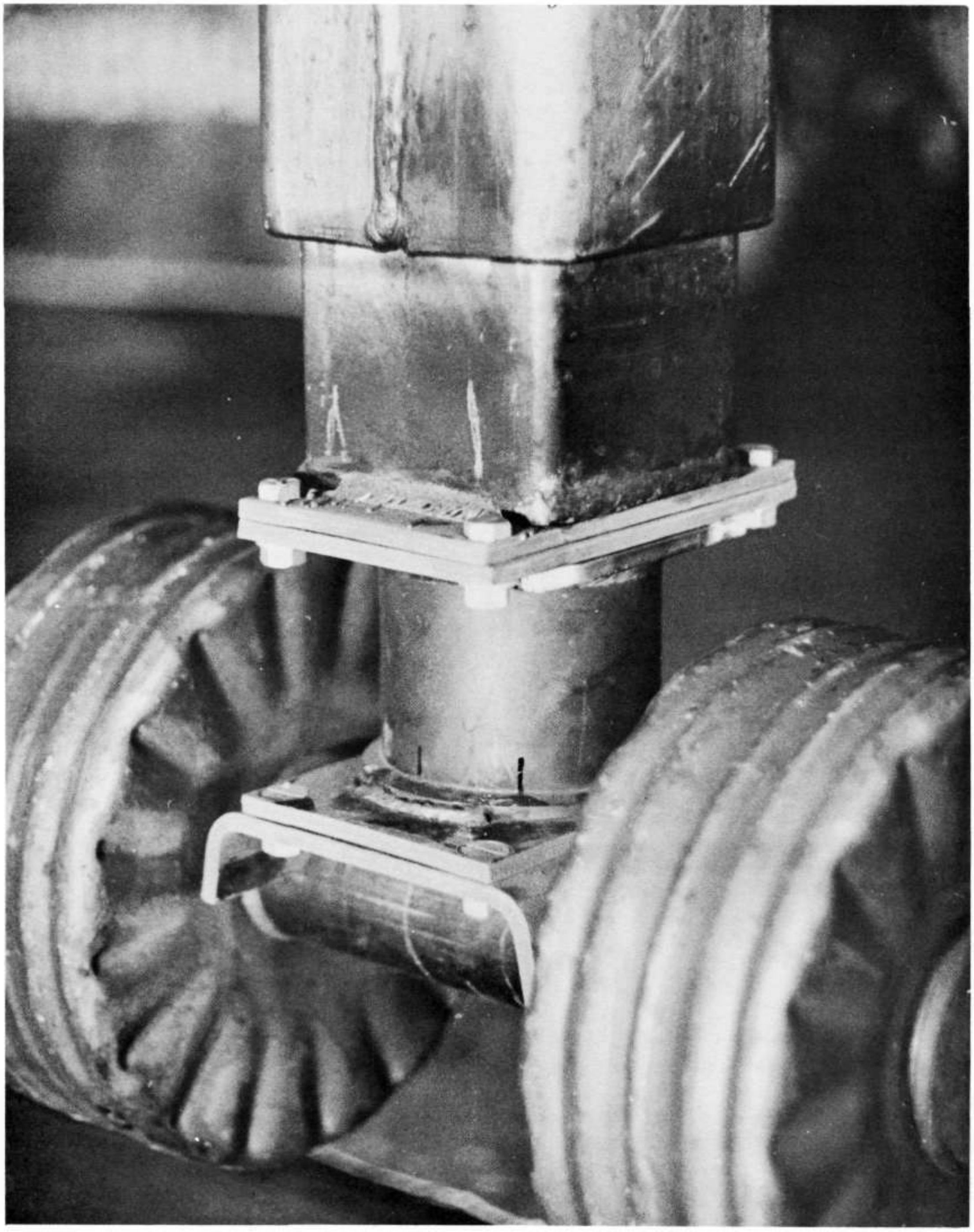

Figure 5.6. Prototype No. 1 Installed

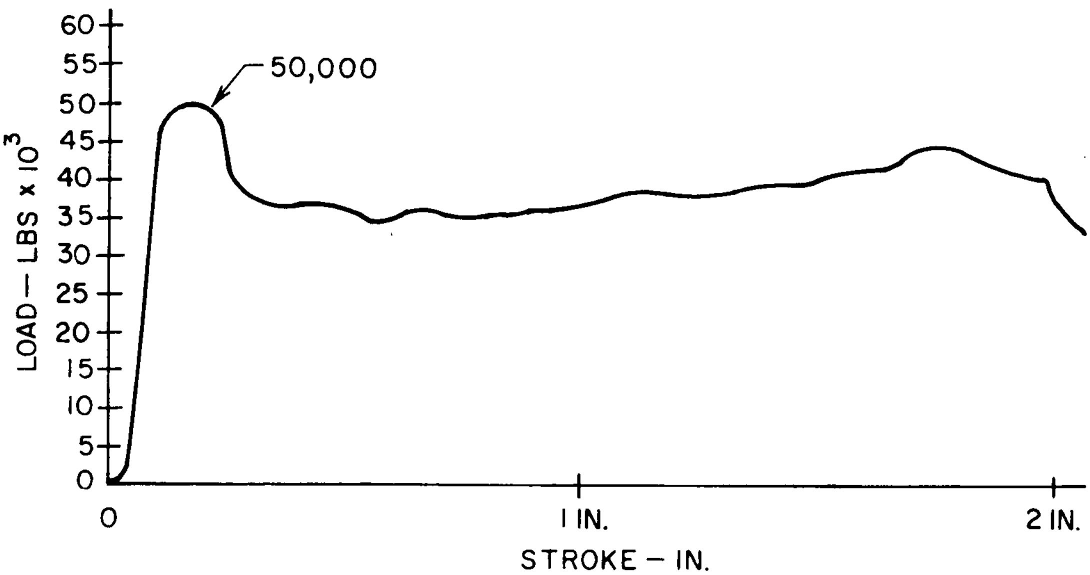

Figure 5.7. Force-Deflection Curve for Prototype No. 1

The energy absorbers were subjected to two series of tests in which they were installed on Fruehauf Model F trailers loaded with 35,000 lbs of concrete. These trailers were dropped from heights of up to 14-1/2" onto concrete pavement. The earlier results of these tests led to the development of Prototypes No. 2 and No. 3. These prototypes are quite similar to Prototype No. 1 but they use a different type of mild steel tubing (API-5L Type B) and a different welding pattern (Prototype No. 3 is the same as No. 2 except for the welding pattern).[3] Energy absorber Prototype No. 3 is shown after a 14-1/2" drop in Figure 5.9. This drop with a fully loaded trailer consumed the entire 3" stroke of the energy absorbers but the trailer was protected from damage. The designs of Prototypes No. 2 and No. 3 are discussed in more detail later in connection with the prototype tests.

The shoes used with the energy absorbers are known as the Briskin Sand Shoe and are made by the Fruehauf Corp. The shoes were made so that they could be attached by the same axle used for the wheels but were modified for attachment to the energy absorbers. These shoes are unique in that they are made like a ball joint so that they can tilt to align themselves with the surface of the pavement.

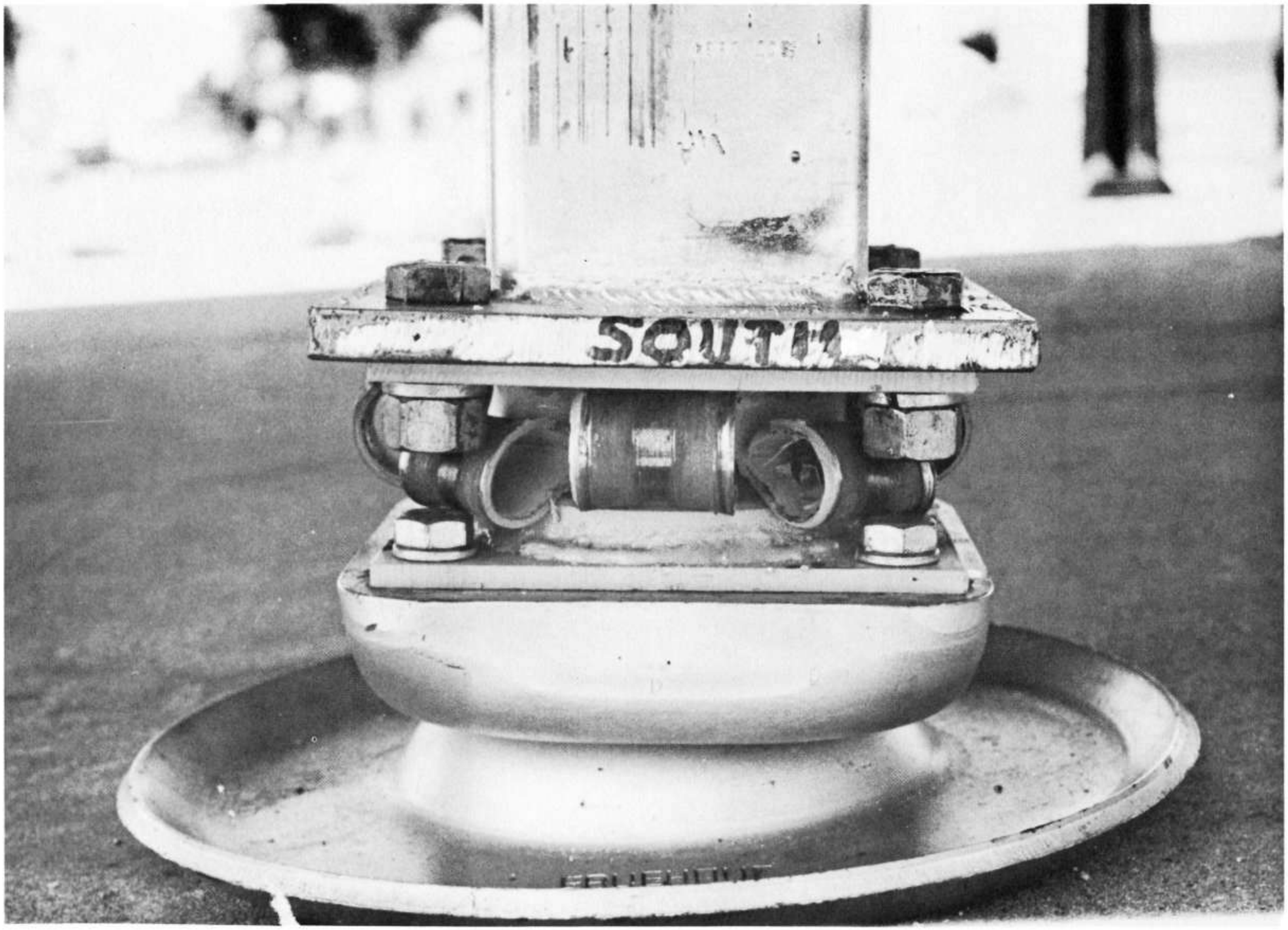

Figure 5.8. Energy Absorber Installed With Sand Shoe

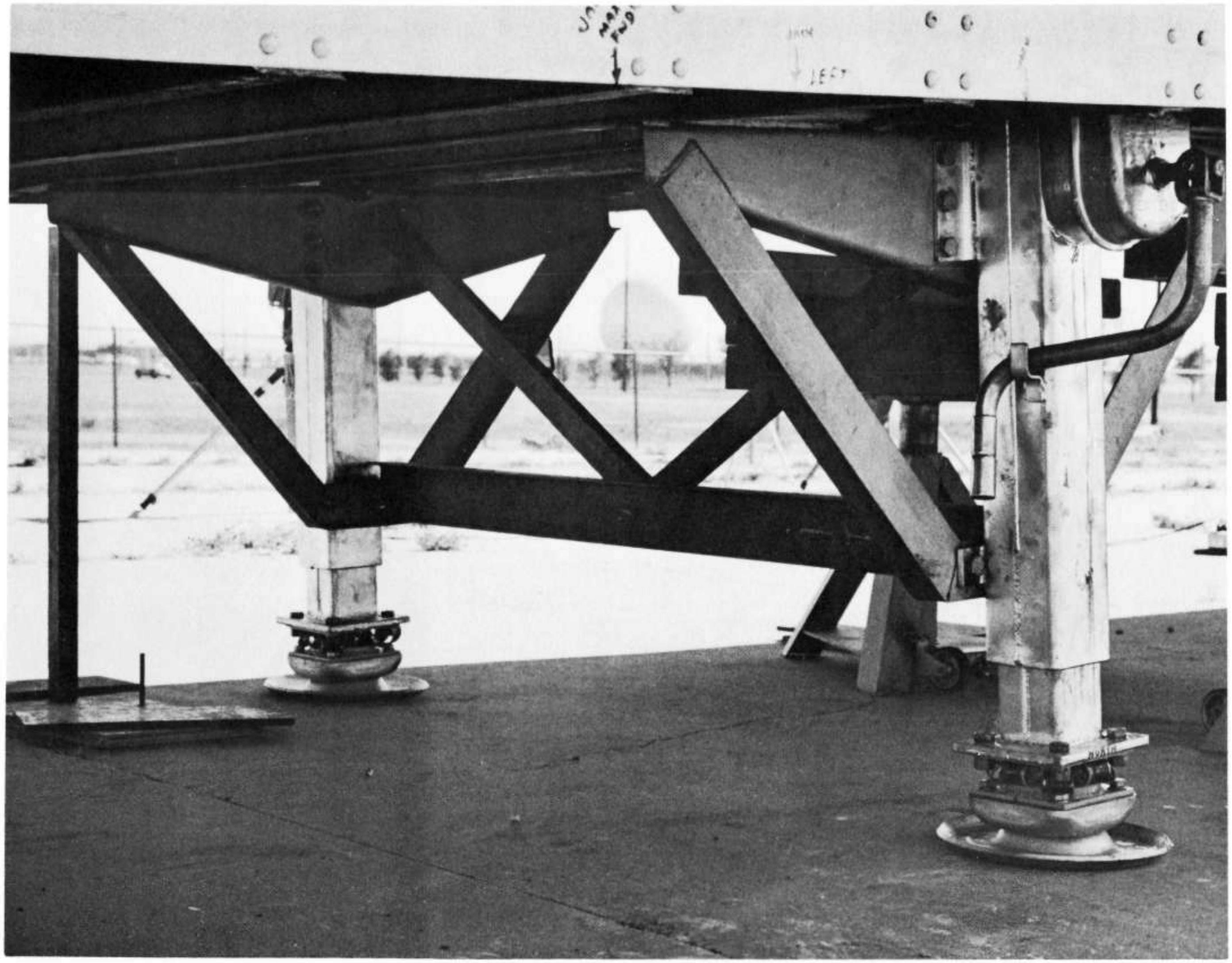

Figure 5.9. Trailer Support and Energy Absorbers After 14-1/2" Drop With Loaded Trailer

c. Prototype Tests

After the prototypes were found to meet all the trailer requirements in static tests two series of trailer tests were conducted. The first series was conducted at the Fruehauf Corporation headquarters, Detroit, Michigan and included six tests involving the leg configuration shown earlier in Figure 5.6 and one test with the same leg and energy system but without the wheels. The second series of tests was conducted in Denver at Buckley Air National Guard Base by the University of Denver and involved the leg configuration shown previously in Figure 5.8 using the Briskin Sand Shoe.

i. Test Series No. 1 (Detroit)

This series of tests was conducted by the Fruehauf Test Engineering Department using a full size Fruehauf Model F trailer loaded with concrete blocks weighing 35,000 lbs, and a GMC Model 7000 tractor, see Table 5.3. The test setup and load distribution in the trailer were as shown in Figure 5.10. Trailer and tractor data are given in Table 5.3. The trailer was dropped by driving the tractor out from under it with the trailer wheels blocked on the first test and the axles chained in place on the other tests. The general procedure followed by the driver of the tractor was to rev the engine up to 1800 rpm and then hold this engine speed while releasing the clutch (the tractor was driven in 2nd gear).

The test series results are summarized in Table 5.4. The energy absorbers used in Test 1 were designed to activate 30K (30,000 lb). Tests 5 and 7 gave the best results in this series. Test 5 was a 3" drop; the operation was somewhat nonsymmetrical, however, with the right side skewed forward and the left side skewed back. The force-time and deflection-time are shown in Figure 5.11. The force required for activation of the device is in the design range of 50-60K. The average operating force of 25K is a little below the design range of 30-40K due to the nonsymmetrical operation. The results of Tests 1, 4, 5 and 6 indicated that the pilot on the mandrel was not a sufficient stabilizer to correct for eccentricities in the loading. Also, these tests indicated that the support and energy absorber system possessed an instability such that once nonsymmetrical operation was initiated, it would continue and worsen. Therefore, it was decided to conduct Test 7 with the wheels removed and with the flat plate under the mandrel forming the bottom of the support leg. This was done because it was believed that this

TABLE 5.3

DATA FOR TRACTOR-TRAILER COMBINATIONS
USED IN DROP TESTS

		Detroit Tests	Denver Tests
Engine Horsepower	H	250 @ 2400 RPM	196 @ 2800 RPM
Tractor Weight (lbs)	W_t	14,000	17,500
Tractor Mass (slugs)	M_t	435	545
Rear Wheel Radius (in.)	r	21.6	21.2
Gear Reduction	G	33:1	42:1
Assumed Coeff. of Friction for Trailer on Fifth Wheel, Typical	μ_1	.1	.1
Assumed Gear Train Efficiency %	e	65	65
Loaded Trailer Wt (lbs)	W	46,000	46,440
Loaded Trailer Mass (slugs)	M	1,430	1,440
Trailer Dimensions:			
Pivot to C o G (in.)	R_C	151	151
Pivot to Support Legs (in.)	R_S	212	212
Pivot to Front End of Trailer (in.)	R_L	343	343
Pull-out Distances (in.)	S_1	32	32
	S_2	14.7	17.5
Stroke of Energy Absorber	S		
Tilt Angle of Fifth Wheel (deg)	θ	15	15

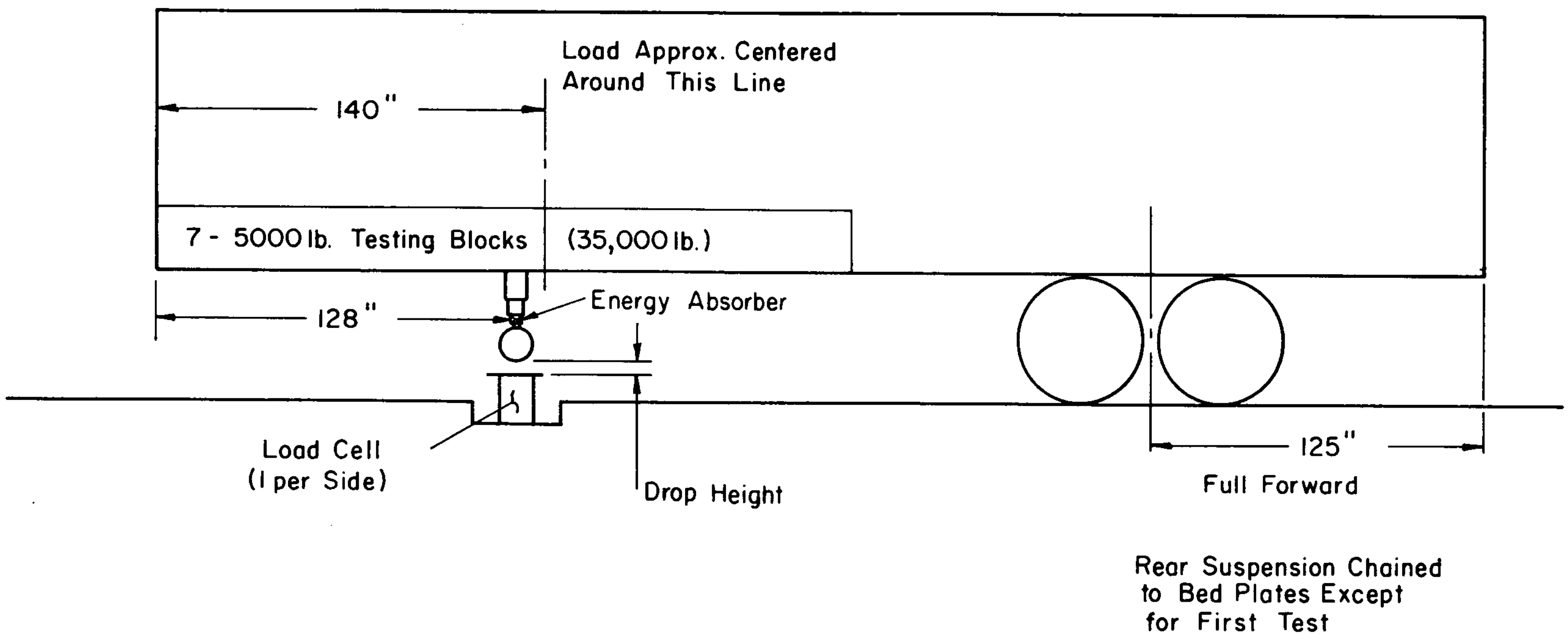

Figure 5.10. Diagram of Test Series No. 1 Set Up

TABLE 5.4

RESULTS OF TRAILER TEST SERIES NO. 1 (DETROIT)

Test No.	Energy Absorber Design			Drop Height	Remarks
	Activation Force	Operating Force	Stroke		
1	30K	30K	2"	1"	Nonsymmetrical operation of energy absorbers. Accidental drop of approx. 8" during lift was cushioned by further deformation of the tubes.
2	50-60K	30-40K	2"	1"	Energy absorbers not activated.
3	50-60K	30-40K	2"	2"	Front side of right side energy absorber shows very slight deformation.
4	50-60K	30-40K	2"	2-1/2"	Energy absorbers activated, right side was very nonsymmetrical in operation.
5	50-60K	30-40K	2"	3"	Energy absorbers activated but operation was nonsymmetrical.
6	50-60K	30-40K	2"	3-1/2"	Wheels kicked out (bolts sheared) and let the trailer fall. Cushioning was provided by further deformation of tubes.
7	50-60K	30-40K	3"	4"	Wheels were removed for this test. Absorbers activated and worked well.

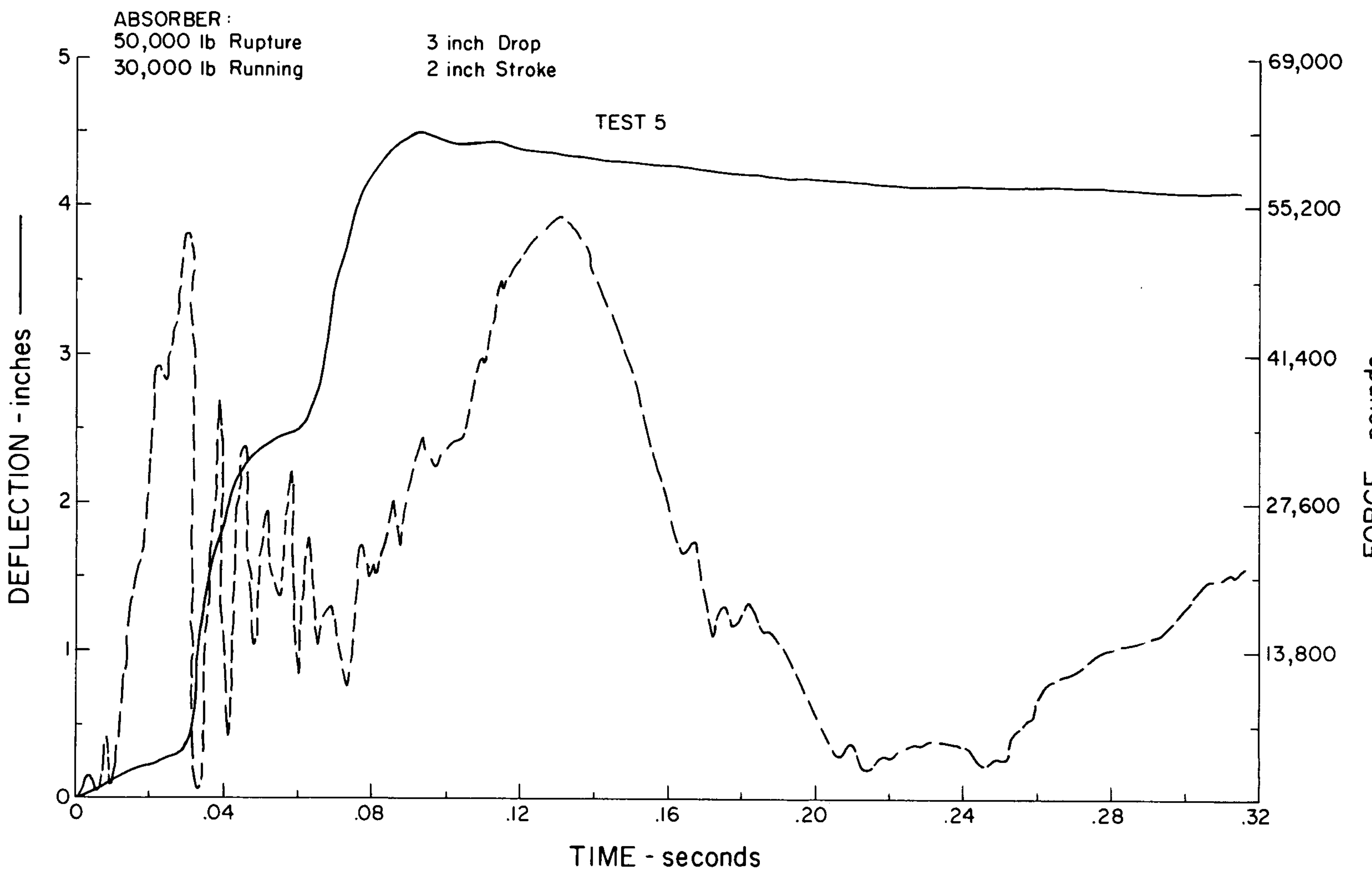

Figure 5.11. Force-Time and Deflection-Time Record for Test 5, Series No. 1

would form a self-stabilizing system with the forces between the foot plate and the drop platform acting to stabilize the system during operation. The results of this test were very encouraging as shown in Figure 5.5. Both energy absorbers operated symmetrically to stop the trailer after a 4" drop in 2" of stroke.

ii. Test Series No. 2 (Denver)

Test Series No. 2 was conducted to determine the performance when using the energy absorbers with a special design of shoe known as a Briskin Sand Shoe. This shoe is made like a ball joint and is able to align itself with the surface of the pavement.

This series of tests was conducted by the University of Denver at Buckley Air National Guard Base and was designed to correspond as well as possible with the tests conducted previously in regard to test method, trailer type, and trailer loading. The test setup is illustrated in Figure 5.12. Tractor and trailer data are given in Table 5.3. The basic differences between this series of tests and the first series was that they were conducted outside on a concrete pavement with no restraint on the axles of the trailer (only the trailer brakes prevented motion of the trailer), the tractor used was somewhat different, and the tests were conducted with Briskin Sand Shoes on the supports rather than wheels (see Figure 5.8). The difference in tractor type was of necessity rather than choice. The tractor used in these tests was a government vehicle assigned to the Denver Research Institute, University of Denver and was therefore available for use on this project at a low cost. While not being identical to the one used in Detroit, it managed to do the job quite well after some modification; tractor data is given in Table 5.3.

The trailer was dropped as before by driving the tractor out from under it. However, in this series of tests the trailer wheels were held only by the trailer brakes. The general procedure followed by the driver was to rev the engine up to 1800 rpm and then release the clutch while pushing the gas pedal to the floor. This tractor did not have the horsepower of the one used in the first series of tests so to compensate for this the pullout was done in first gear. Measurements taken later of the impact velocity of the trailer leg indicated that the pullout was as fast as in the other tests. In one test a slow pullout was used to simulate actual field conditions.

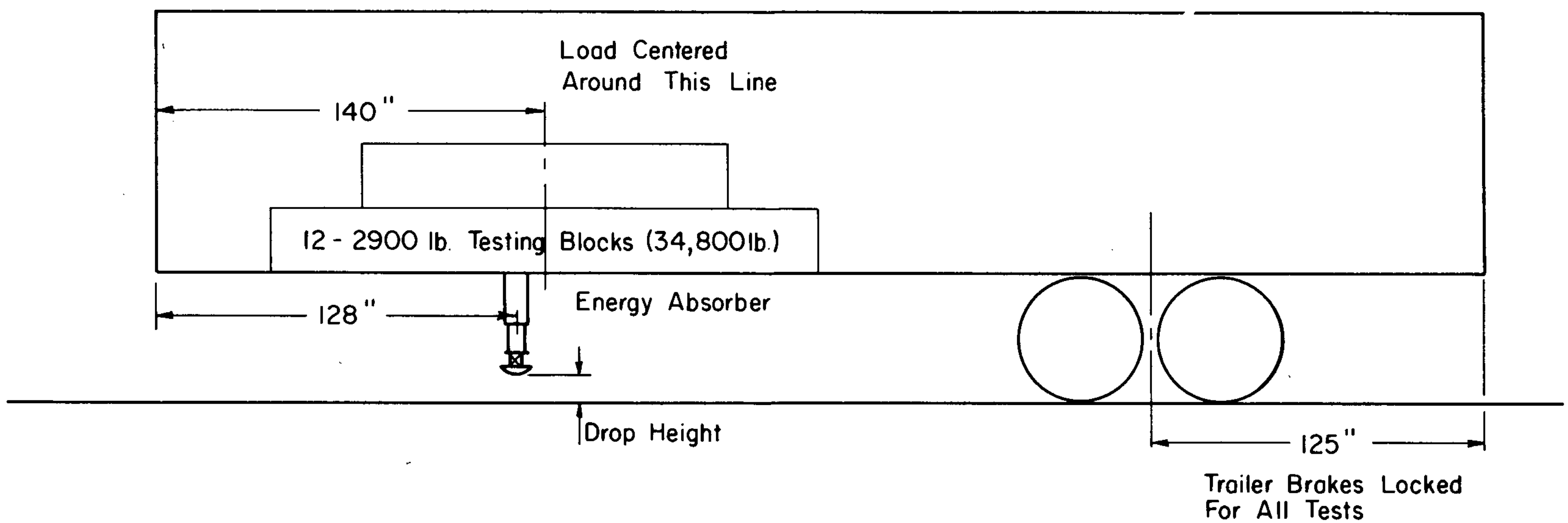

Figure 5.12. Diagram of Test Series No. 2 Set Up

The results of these tests are summarized in Table 5.5. The energy absorbers used in Tests 1-5 were made the same as those used in Test Series No. 1. The first two tests were one and two inch drops and produced predictable results in that the energy absorbers did not activate. In Test 3, a 4" drop, the energy absorbers activated and operated symmetrically. However, two unexpected things happened; first, the energy absorbers stroked 2.5" rather than 1.5 to 2" as expected and second, the rear cross member on the tractor frame hooked the trailer kingpin and pulled the trailer ahead sharply. In spite of these difficulties, the test was considered successful since it indicated that the combination of the energy absorber and the Briskin Sand Shoe would produce the desired results even if the trailer were pulled while the energy absorber was operating and perhaps work even if the trailer had some forward motion at the time of shoe impact. The test did some damage to the lower support legs; they were bent where they fit inside the upper legs. The energy absorber functioned in a symmetrical fashion in spite of the rather severe duty imposed by the hooking of the trailer pin. The tractor frame was longer and the rear frame member was higher than normal for a semi since the tractor was a military vehicle and designed for a multitude of applications. The frame was modified so that it was the normal configuration for a semi-tractor. This involved shortening the frame and installing a Mack Truck rear frame member with a drop center.

The stroke of the energy absorbers in Test 3 was excessive and it was found that the energy absorbers were activating at 65,000 lbs indicating that too much weld was used. Also, the energy absorbers were found to be significantly different than that those used previously with a large curl radius and an operating load on the order of 15K. It was found that the tubes used for the previous energy absorbers were 1010 DOM rather than 1018 as was indicated by the supplier. It was also learned that 1010 DOM is only available by special purchase in large quantities.

A search yielded API-5L Type B line tubing which seemed to be suitable. Some of this tubing was obtained and tested and proved to possess the desired characteristics. These included a hardness of R_B 70-75, a buckling load of 90,000 lbs for a short segment of 4" O.D. tube with a 0.137" wall, and the formation of small curls when tried on a mandrel with a 30° taper. The energy absorber was redesigned using

TABLE 5.5

RESULTS OF TRAILER TEST SERIES NO. 2 (DENVER)

Test No.	Energy Absorber Design: Activation Force (lbs)	Operating Force (lbs)	Average Stroke (in.)	Drop Height (in.)	Remarks
1	50K	30-40K	0	1	Energy Absorber did not activate. No damage to trailer.
2	50K	30-40K	0	2	Energy Absorber did not activate although paint cracked around bottom of tube. Forward weld on north side of angle from braces pulled loose from parent metal. Not repaired.
3	50K	30-40K	2.5	4	Trailer pin caught on rear cross member of tractor pulling trailer forward and bending the lower leg section of the supports. Support legs removed for repairs. No other damage to trailer.
4	50K	30-40K	0	3	Energy Absorber did not activate. No damage to trailer. Using repaired legs. Very difficult to crank in high gear, low gear satisfactory.
5	50K	30-40K	0	3	Energy Absorber did not activate. No damage to trailer.
6	50K	30-40K	2	4	Prototype No. 2 Energy Absorbers were used and activated nicely with a high degree of symmetry but lower legs were bent back slightly where they contact upper leg.
7	50K	30-40K	0	4	Added ramps behind fifth wheel - standard equipment on many trailers. No Energy Absorber activation due to trailer sliding down ramps. Support legs switched after test to opposite sides of trailer to place bend in lower legs toward front of trailer. Ramps removed.
8	50K	30-40K	1-1/8	4	Energy Absorber activated and ran well, but noted slight bend in south leg only. The leg was installed with welded joints rotated 90° from normal position. This leg was changed for next test to place weld in correct position, as per normal factory assembly.

TABLE 5.5 (Continued)

Test No.	Energy Absorber Design: Activation Force (lbs)	Operating Force (lbs)	Average Stroke (in.)	Drop Height (in.)	Remarks
9	60K	30-40K	0.83	4	Energy Absorber activated Damage at angle with connection to leg noted. Possibly some damage to screws which raise legs as they are now difficult to crank in low gear.
10	60K	30-40K	0.46	4-1/2	Energy Absorber activated slightly. No additional damage to trailer noted. Uniform stroke.
11	45-50K	30-40K	1.64	4	Reduced weld strength. Energy Absorber activated and ran as desired. No damage to trailer except for slight dent in right, lower support leg where it contacts the upper support leg. Dent in lower leg probably due to Energy Absorber not stroking parallel, front to rear. This can probably be taken care of by using 6 welds (3/8" long by 1/8") located symmetrically about the circumference of the Energy Absorbing tube, facing the front of the trailer and 2 welds (1/8" long by 1/8") symmetrically facing the rear of the trailer.
12	45-50K	25-30K	0	1	This test used the Prototype 3 Energy Absorbers. New legs installed for this test.
13	45-50K	25-30K	.92	4	Energy Absorbers activated and stroked as expected. These were the same energy absorbers used in Test 12 above. It was noted after this drop that the cranking mechanism would not operate properly in high gear but worked well in low. Examination revealed the damage was confined mainly to the leg which contains the gearbox. The exact nature of this damage was not determined.

TABLE 5.5 (Continued)

Test No.	Energy Absorber Design: Activation Force (lbs)	Operating Force (lbs)	Average Stroke (in.)	Drop Height (in.)	Remarks
14	45-50K	25-30K	3	14-1/2	This test was conducted to simulate an accidental drop. Ramps were installed behind the fifth wheel to allow the trailer to slide from the fifth wheel to the ramps, down the ramps, and then free fall 6" after leaving the end of the tractor. No trailer damage noted.
15	45-50K	25-30K	0	1	Energy absorbers did not activate, no damage to trailer
16	45-50K	25-30K	0	2	Energy absorbers did not activate, no damage to trailer.
17	45-50K	25-30K	0.5	3	Symmetrical operation - worked good.

API-5L line and designated Prototype No. 2. This energy absorber produced the force-deflection curve shown in Figure 5.13 when tested statically.

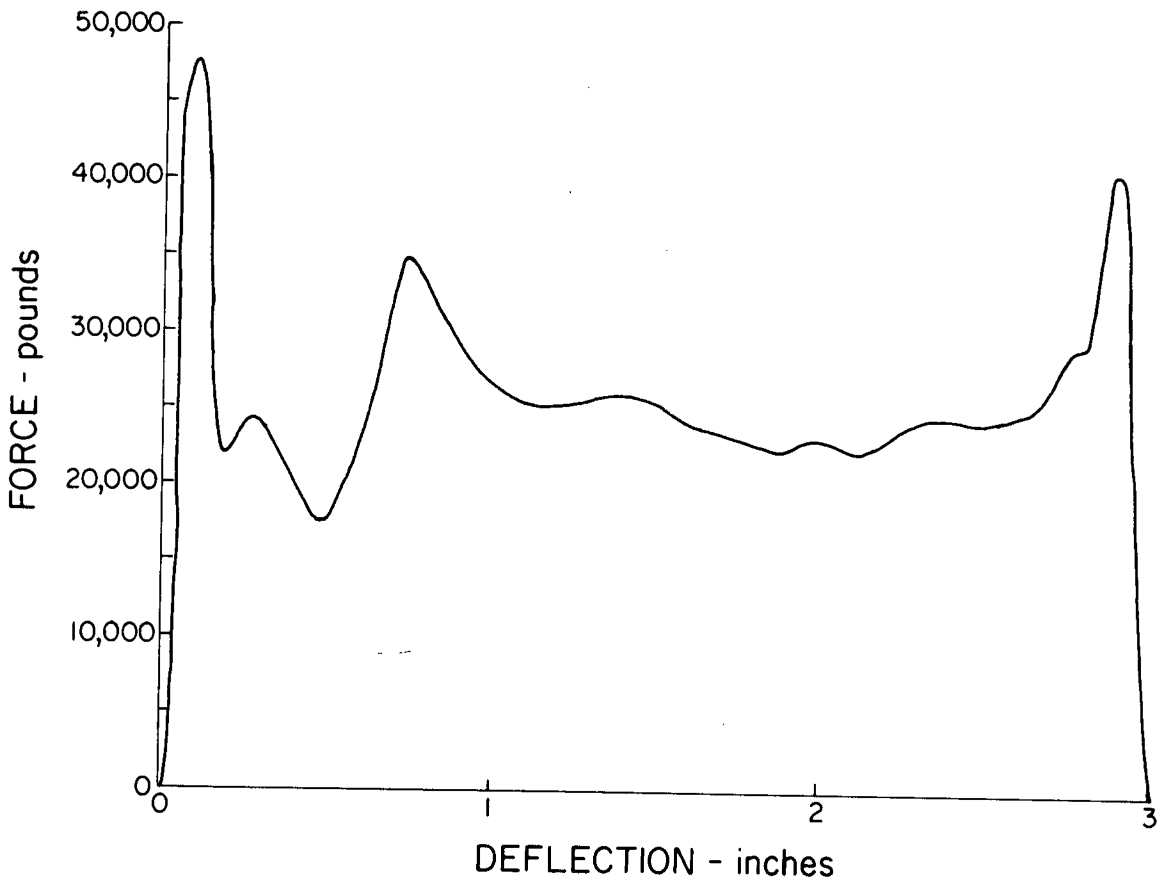

Figure 5.13. Static Force-Deflection Curve for Prototype No. 3

Prototype No. 2 energy absorbers were tested dynamically in Trailer Test 6 (Table 5.5) and worked very well as can be seen in Figure 5.14. However, the lower legs of the trailer, especially the right one were dented slightly. The left leg was given a small dent in the back where it fitted inside of the upper leg and the right lower leg suffered similar but more obvious denting. The legs did not seem to be damaged seriously enough to need replacement; instead they were exchanged with each other so that the dents in the legs were in the front rather than in the rear. A review of the high speed films (slow

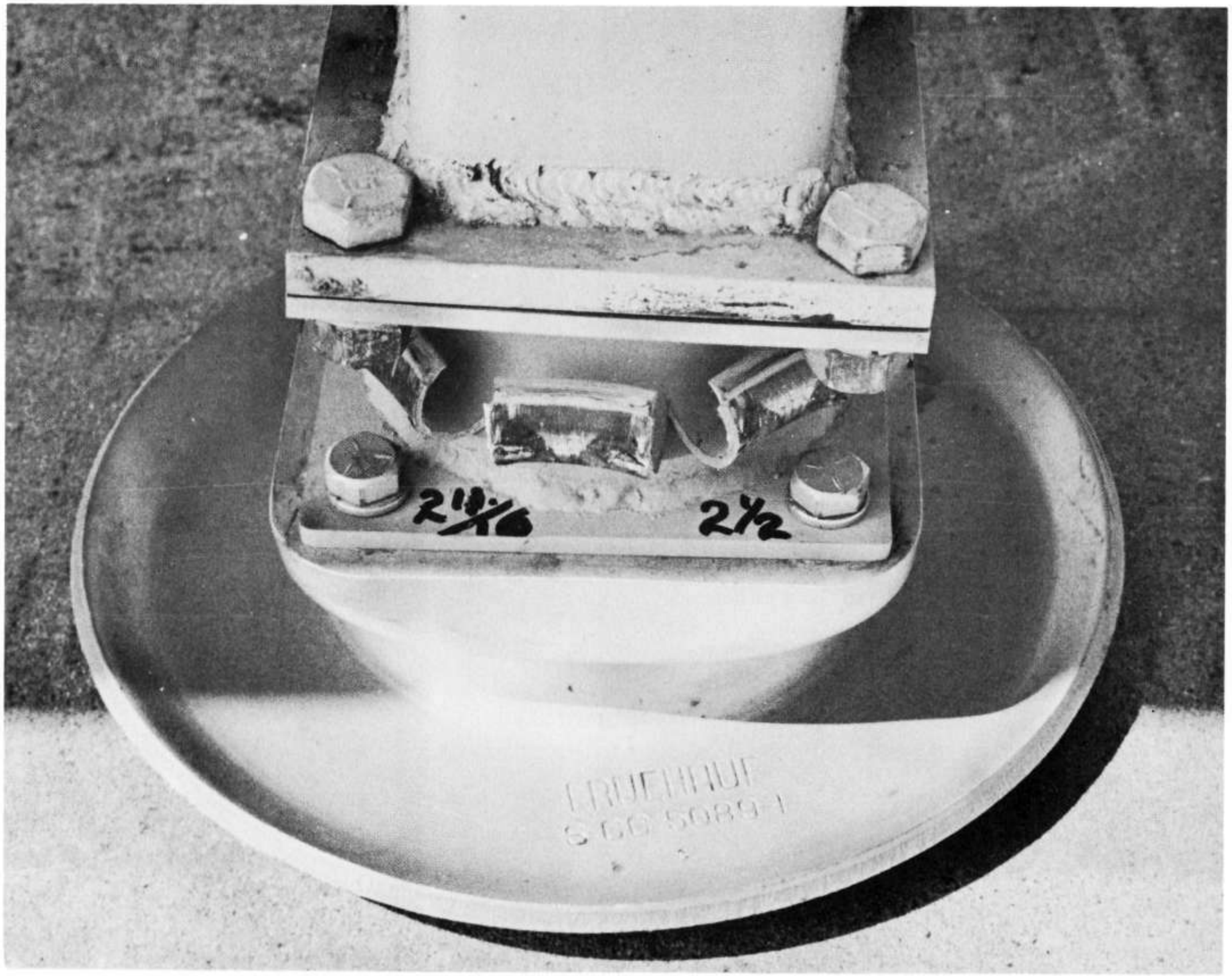

Figure 5.14. Prototype 2 Energy Absorber After a 4'' Drop

motion) showed that the trailer actually moved forward approximately 1.5'' during the drop. Subsequent analysis proved that the trailer movement is due to flexibility of the rubber parts in the suspension system. The legs are square tubing which is formed by welding two channels together. For maximum strength the legs should be oriented so that the welds are in the back and front rather than on the sides. Ordinarily this is done, since the factory attaches the axle tubes to the bottom of the legs in the appropriate direction; however, in our case when the legs were repaired after Test 3 one lower leg was improperly assembled. This leg received the worst denting in Test 6.

It was observed that many tractors are equipped with ramps on the frame behind the fifth wheel. For Test 7 similar ramps were fitted to the tractor; these are as illustrated in Figure 5.15. In this test everything was done as had been done in Test 6 with the exception of the ramps. The drop did not achieve sufficient velocity to activate the energy absorbers. Although this was not what was looked for, the information gained was especially valuable later on in Test 14, a 14-1/2''

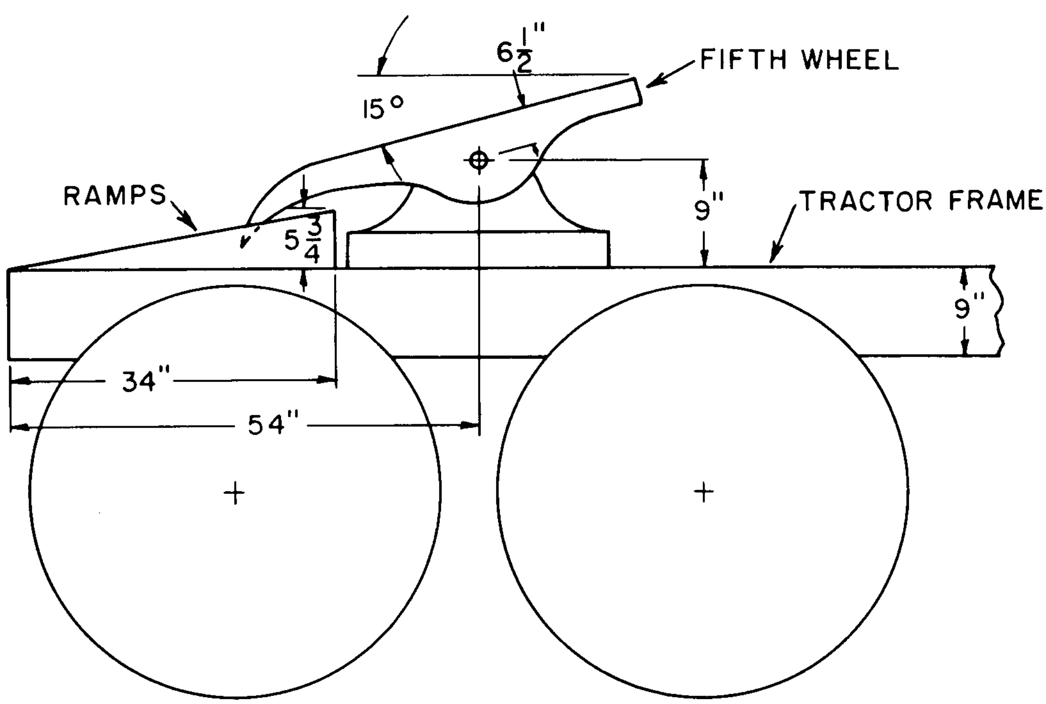

Figure 5.15. Tractor Ramps and Fifth Wheel

drop. For Test 8 the ramps were removed and the fifth wheel raised 2". Also for this test the welds between the tubes and mandrels were made stronger than before so that the stroke of the energy absorbers would be smaller. As seen in Table 5.5 the stroke was 1-1/8" and the operation was similar to that obtained in Test 6. A lower leg having improper orientation was dented while the other one exhibited no damage. After this test this leg was removed and rotated to the proper orientation. The energy absorbers used in Test 9 and 10 were found to have too high a starting load due to too great a weld strength. It was observed that the energy absorbers all had a slight tendency to deflect more in the front than in the rear due to the angle of the support leg with the pavement. To cause the energy absorber to operate more the same in the front and back, the welds were modified slightly with the welds orientated so that two smaller welds straddle the rear center line of the tube. This energy absorber was designated Prototype No. 3 and tested in Trailer Test No. 10. The energy absorber deformation in this test was very symmetrical on both legs. For Tests 12, 13, and 14 the trailer legs, both upper and lower, were replaced with new ones. These tests included a 1" drop which resulted in no energy absorber activation, a 4" drop which resulted in very symmetrical operation with an average stroke of 0.92", and a drop of 14-1/2" which resulted in a stroke of 3". The 14-1/2" drop was made in a manner closely simulating an accidental drop with the legs retracted. Here the tractor, equipped with ramps behind the fifth wheel as illustrated in Figure 5.15, was driven out slowly and the trailer allowed to fall. Both energy absorbers operated symmetrically and were consumed completely as shown in Figure 5.9. The drop amounted to 8-1/2" of sliding down the tilted fifth wheel followed by a 6" free fall. Trailer damage as a result of this drop was difficult to detect. The trailer showed no evidence of side wrinkling and very little if any permanent set in the trailer floor beams of bending of the support braces.

The lower support legs are equipped with a mechanism which lowers and retracts them. This mechanism is crank operated and has two gear ratios which are selected by moving the crank shaft axially. It was found that this mechanism was difficult to operate in the highest gear ratio after the Test 13 (4" drop). This was apparently due to misalignment of the gears caused by some deformation of the internal parts of the mechanism. After the 14-1/2" drop the retracting mechanism was still operable in the lowest gear.

4. Second Generation Prototypes

Fruehauf product development engineering considered the results of these tests in conjunction with user requirements and came up with the second generation prototype design illustrated in Figure 5.16. Here the energy absorber is incorporated into the standard sand shoe. The beauty of this design is that it can be used in place of the standard sand shoe with no trailer leg modifications required since it is attached with the standard axle tube. In the energy absorbing sand shoe the load is carried from the leg through the axle tube and then through the energy absorber to the bottom plate of the shoe. The sand shoe is free to pivot on the axle tube. Slots are provided on the side members of the shoe so that the axle tube is free to move downward as the energy absorber is deflected. The energy absorbing sand shoe has the standard 5'' height from the centerline of the axle tube to the pavement. This provides for a 2-1/2'' energy absorber stroke (4'' of stroke was required to protect the trailer from a normal pull out 14-1/2'' drop).

The Fruehauf prototype energy absorbing sand shoe was tested on a Fruehauf Model F trailer at the University of Denver and found to perform very well (Table 5.5, Tests 15, 16, and 17). A photo of the University of Denver version of this sand shoe which was tested is shown in Figure 5.17; a sketch of the shoe is shown in Figure 5.18.

Fruehauf product development engineering presented this design to corporate management and suggested that the company produce the sand shoes and offer them as standard equipment on Fruehauf trailers and as a replacement part for existing trailers. Corporate management decided that rather than offer them as standard equipment, these sand shoes should be offered as an option. They also decided that the shoes should be manufactured by an original equipment manufacturer.

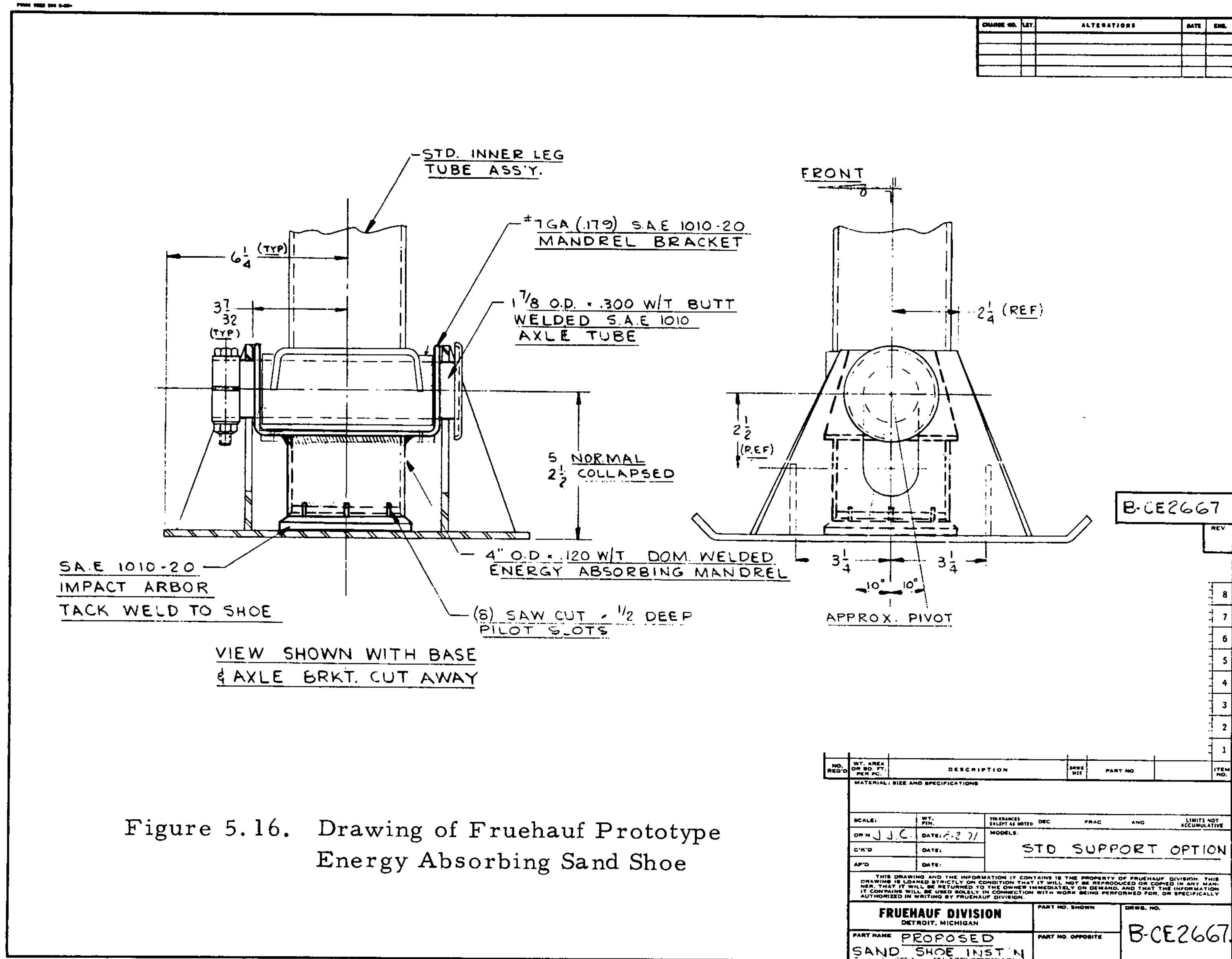

Figure 5.16. Drawing of Fruehauf Prototype Energy Absorbing Sand Shoe

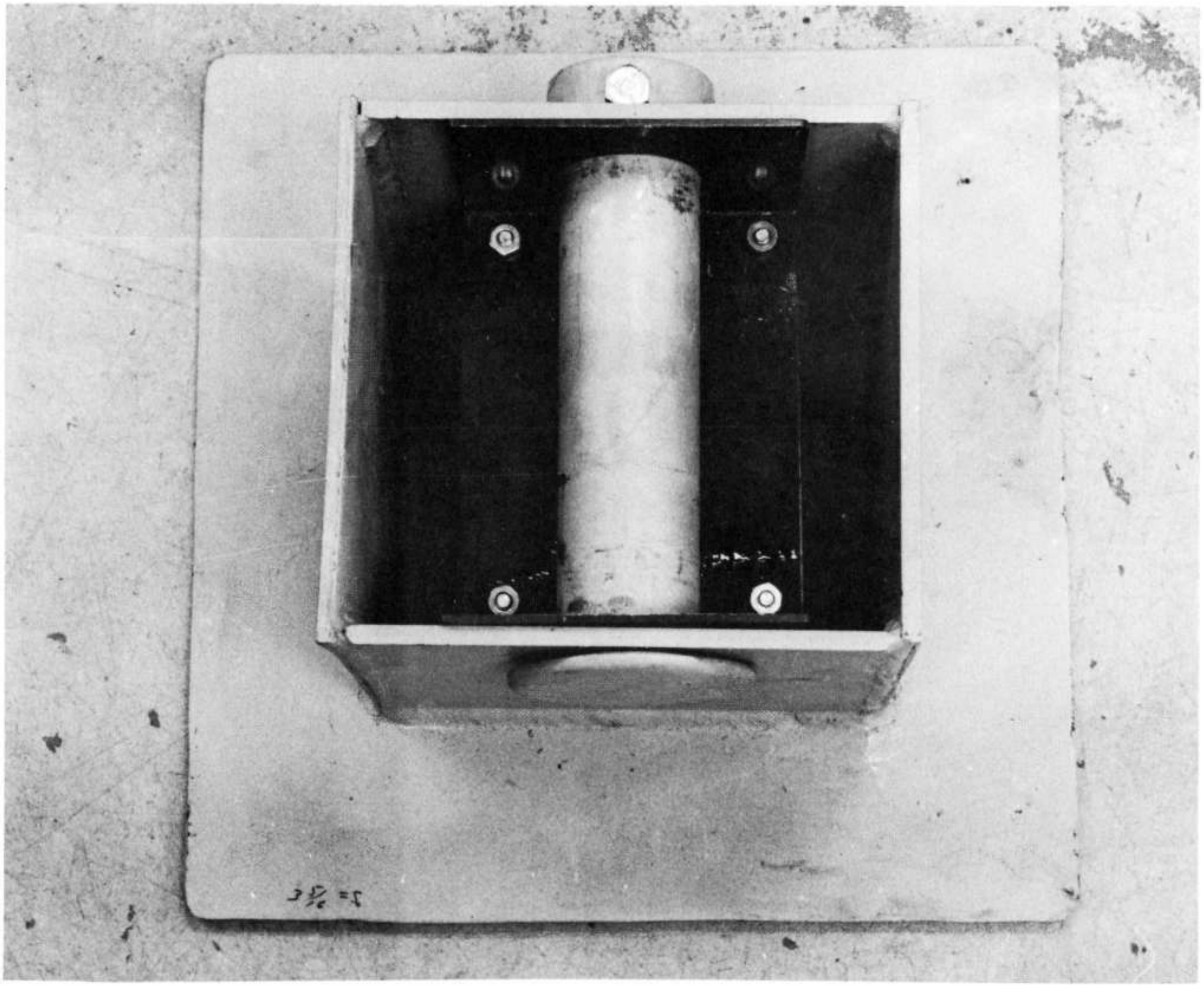

Figure 5.17. Photo of University of Denver Version of Fruehauf's Energy Absorbing Sand Shoe Design

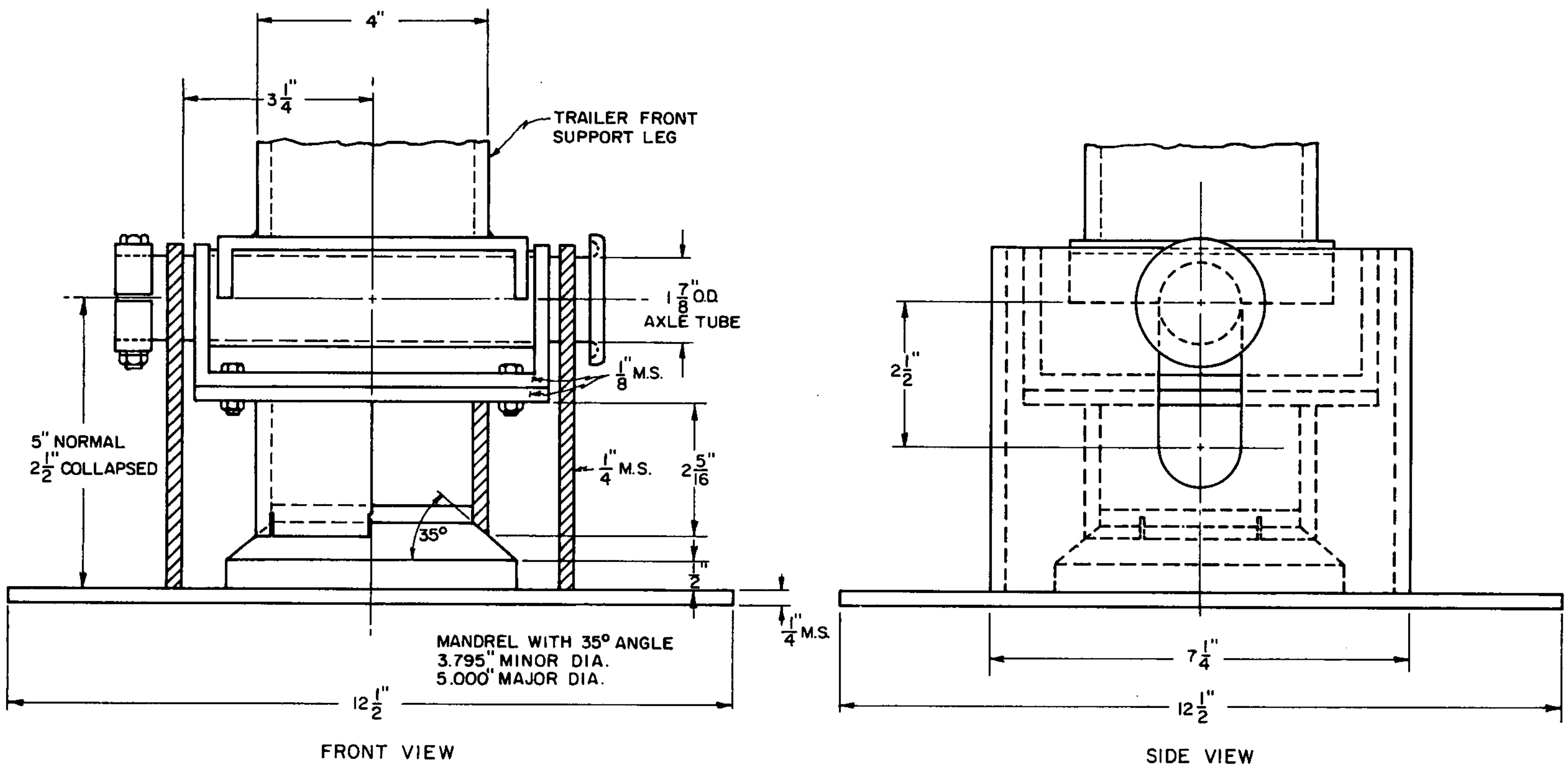

Figure 5.18. Drawing of the University of Denver Version of Fruehauf's Energy Absorbing Sand Shoe

5. Joint Program with Homan and Company

Through Fruehauf, contact was made with Homan and Company, Cincinnati, Ohio, a leading original equipment manufacturer for the trailer industry. From the begining Homan was extremely interested in the prospect of manufacturing and marketing the energy absorbing sand shoe. The transfer of this project from Fruehauf to Homan offered the advantage of greater market potential since Homan sells to all of the trailer manufacturers and to fleet operators as well. After some engineering and manufacturing analysis Homan came up with the simplified prototype shown in Figures 5.19 and 5.20.

At the present time Homan is doing more engineering work on the sand shoe and making design modifications which will lower the cost of manufacture. Prototype testing has been scheduled and fleet testing is planned.

6. Conclusions

The Homan prototype (based on the Fruehauf design), because of its low cost (little more than the cost of the standard sand shoe) and its ready applicability to existing semitrailers without leg modification, will probably find wide acceptance with fleet operators, who deal directly with Homan. Trailer manufacturers will also be able to offer the Homan shoe as an option on new trailers. The market potential is large. It includes the 50,000 new trailers sold in the U.S. annually and the several hundred thousand existing trailers in the U.S., as well as those in foreign countries.

Negotiations on a license for this application are in progress.

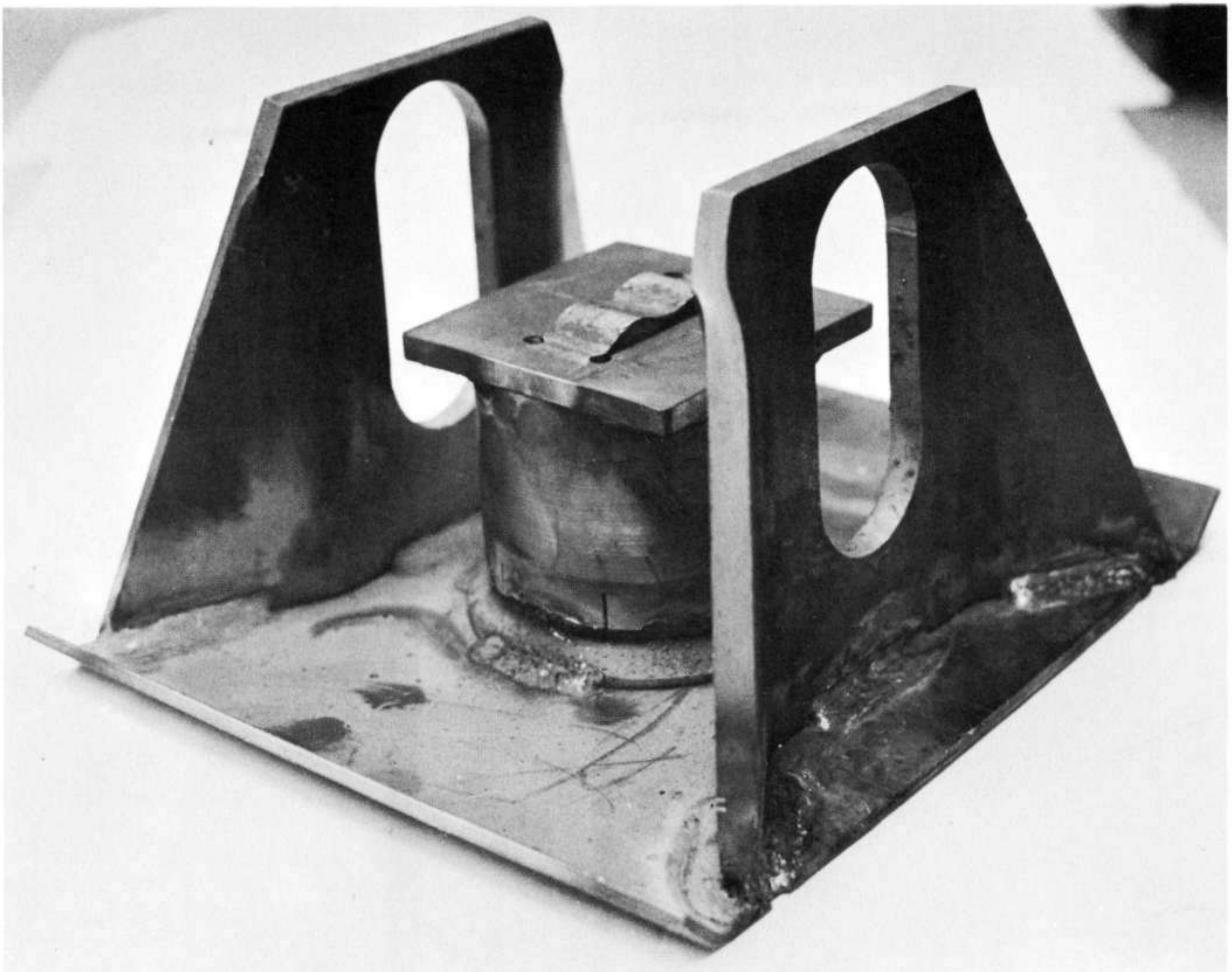

Figure 5.19. Photo of Homan Prototype Energy Absorbing Sand Shoe

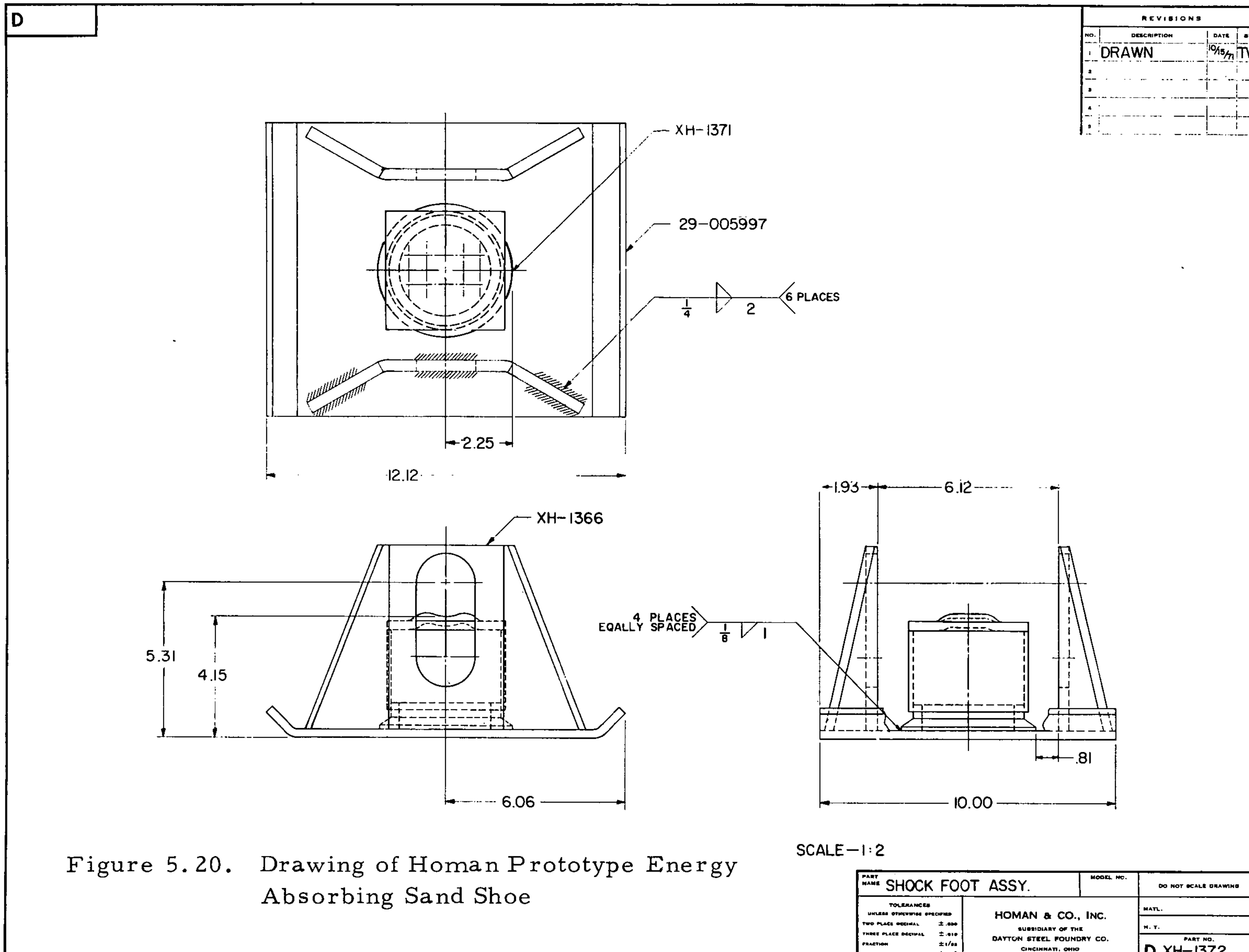

Figure 5.20. Drawing of Homan Prototype Energy Absorbing Sand Shoe

VI. ENERGY ABSORBING AUTO BUMPER

1. Summary

In a cooperative effort between the McCord Corporation, Detroit, Michigan, the Battelle Memorial Institute, Columbus, Ohio, and the University of Denver, a 5 mph energy absorbing automobile bumper was developed.[3] This bumper utilized the NASA tube and mandrel energy absorber (McGehee, Patent No. 3, 143, 321) which consists of a metal tube which is forced endwise onto a mandrel which expands it and causes it to split and curl.[1, 2, 3] Originally this bumper was designed to protect an auto from damage in a 5 mph impact with a rigid surface. A prototype of the bumper was built and dynamic tests were in progress when the U.S. Department of Transportation issued its new car bumper standards. These standards require that a bumper be capable of withstanding repeated impacts, in other words that the bumper be self restoring. This unfortunate standard made it useless to continue with the 5 mph bumper.[3] Work was later begun on a 15 mph version of this bumper since it is believed that eventually the Federal Standards will require bumpers to protect autos at higher impact velocities. At these higher velocities devices such as the tube and mandrel energy absorber which are compact, light weight, and low in cost will seem very attractive in comparison to the heavier, bulkier, and more expensive repeatable energy absorbing devices. The work on the 15 mph bumper will continue after the end of this project under University of Denver support.

2. Introduction

In response to pending Federal requirements and a growing body of state legislation, automobile manufacturers and their original equipment suppliers began to work seriously on the development of practical energy absorbing bumpers. The McCord Corporation, Detroit, Michigan, an original equipment manufacturer, was already in the field; previously the company had been manufacturing the polyurethane covered bumper used on some Pontiac models; this bumper is designed to protect the vehicle in impacts up to 2 mph. McCord decided to develop a low cost energy absorbing system to use in conjunction with the polyurethane covered bumper to extend the impact capability of the bumper to 5 mph. This company became aware of the work done at the University of Denver on the NASA patent development program and asked the university to furnish technical support in the development of the energy absorbing bumper. The NASA tube and mandrel energy absorber was recommended as the energy absorber element for the bumper, and McCord, with the help of Battelle Memorial Institute, designed a bumper utilizing tube and mandrel energy absorber elements. The University of Denver developed an energy absorber having the desired characteristics and also built and tested the prototype bumper.

Unfortunately the multiple impact thinking has been written into the Department of Transportation Standards for Passenger Cars (Standard No. 215, Exterior Protection). This standard requires the bumpers to be capable of resisting repeated impacts. Since the bumper developed on this project needs to have its energy absorber tubes replaced after impact, it cannot meet this standard. When this standard was in the proposal stage the University engaged in educational activities aimed at having the standard rewritten to allow bumpers such as ours, having replaceable energy absorbing elements. After the standard was written the University voiced its objection to the standard with the Department of Transportation, major insurance companies, and with members of the United States Senate and House of Representatives. At present the repeated impact provision stands.

In spite of this unfortunate and unexpected Federal Standard the tube and mandrel energy absorber may still find its way onto new automobiles. It is anticipated that future Federal Standards will require bumpers to protect autos from impacts at higher velocities. Since the kinetic energy increases as the square of the velocity the energy which must be absorbed in a 10 mph impact is four times that in a 5 mph impact and the energy in a 15 mph impact is nine times that in a 5 mph impact. When it comes to absorbing these high levels of energy, devices such as the tube and mandrel which are highly efficient but small in size, light in weight, and low in cost will seem very attractive in comparison to repeatable energy absorbers which are heavier, bulkier, and more expensive.

In anticipation of these future standards, the tube and mandrel energy absorbing bumper has been scaled up from 5 mph to 15 mph, and prototype testing has begun.

This section summarizes the work done previously on the 5 mph bumper[3] and describes the recent work on the 15 mph bumper.

3. Previous Work[3]

a. Requirements

If damage to automobiles, impacting rigid barriers at speeds up to 5 mph, is to be prevented, it seems there are two alternatives:

1. Bumpers can be made capable of dissipating the kinetic energy or

2. The vehicle and bumper can be made so strong that it is unaffected by such impacts, i.e., the energy is absorbed in elastic deformation of the vehicle structure.

However, the storage of energy by very stiff vehicle structures creates an additional hazard in impacts between vehicles.

It can be shown mathematically that an elastic impact results in the impacted vehicle being projected into the intersection at twice the velocity which it would be in the inelastic collision.[3] Therefore, the best solution to the problem is to equip automobiles with energy absorbing bumpers.

The function of an energy absorbing bumper is to dissipate the kinetic energy of a moving automobile allowing it to be brought to rest without damage and without storing energy. In order to stop the vehicle a resistive force must be applied. Under the influence of this force the automobile will be brought to rest while traveling some distance. Hence, in moving against the resistive force the vehicle will do work. If the vehicle is brought to rest by an energy absorbing device, it is obvious that for a given maximum resistive force the most efficient use is made of the available stroke by a device which provides a constant resistive force.[1, 2, 3] Therefore, an energy absorber is desired which will give a nearly constant resistive force over its stroke.

For an energy absorbing bumper with a constant resisting force, the relationship between the stroke S of the bumper, the vehicle impact velocity V, the vehicle mass M, and the resisting force F of the bumper can be expressed mathematically as

$$S = V^2M/2F \tag{6.1}$$

Hence, for a given vehicle mass and impact velocity the stroke is inversely proportional to the resistive force of the bumper. While it is desirable, from the viewpoint of the automobile stylists, to have a very small stroke, this must be balanced against the ability of the vehicle frame to resist the bumper force. An additional consideration is the decelerations which would be imposed on the passengers in an impacting vehicle. A very small stroke would be undesirable in this regard.

In addition to the capacity for protecting the vehicle from damage in a 5 mph head-on impact with a rigid barrier, the bumper requirements include the ability to resist a centered 5 mph impact with a pole and the ability to withstand some angled and some non-centered pole impacts. The bumper must be quite rigid to perform all of these functions. Naturally the bumper would also need to have sufficient strength to resist the loads imposed on it by jacking and towing as well as those imposed by mismatched impacts with bumpers on other vehicles.

McCord concluded after discussions with automobile manufacturers that the bumper should be designed to have a stroke of 3 inches and an average resistive force of 17,000 lbs. Such a bumper would absorb 4,250 ft-lb of energy and would therefore stop a 5,400 lb vehicle from a speed of 5 mph. This 17,000 lb resistive force would be divided equally between two energy absorbing elements mounted between the bumper and the front extensions of the vehicle frame.

b. Bumper Design

The bumper designed in a cooperative effort between the University of Denver, McCord, and the Battelle Memorial Institute is illustrated in Figure 6.1. This bumper is covered with a layer of polyurethane to cushion small impacts and reinforced with a rigid beam to distribute the load in concentrated impacts. The energy absorbers are based on the NASA tube and mandrel concept (McGehee Patent No. 3, 143, 321), and consist of a tube which is deformed by forcing it endwise onto a mandrel causing it to split and curl.[1,2] The deformation of the tube and the friction between the tube and the mandrel absorb energy. This device can be designed to provide a nearly constant force deflection curve.

For use in this bumper, the mandrel pilot was designed especially long so that it would extend through the hole in the back of the rectangular tubing used as the reinforcing beam. The energy absorber

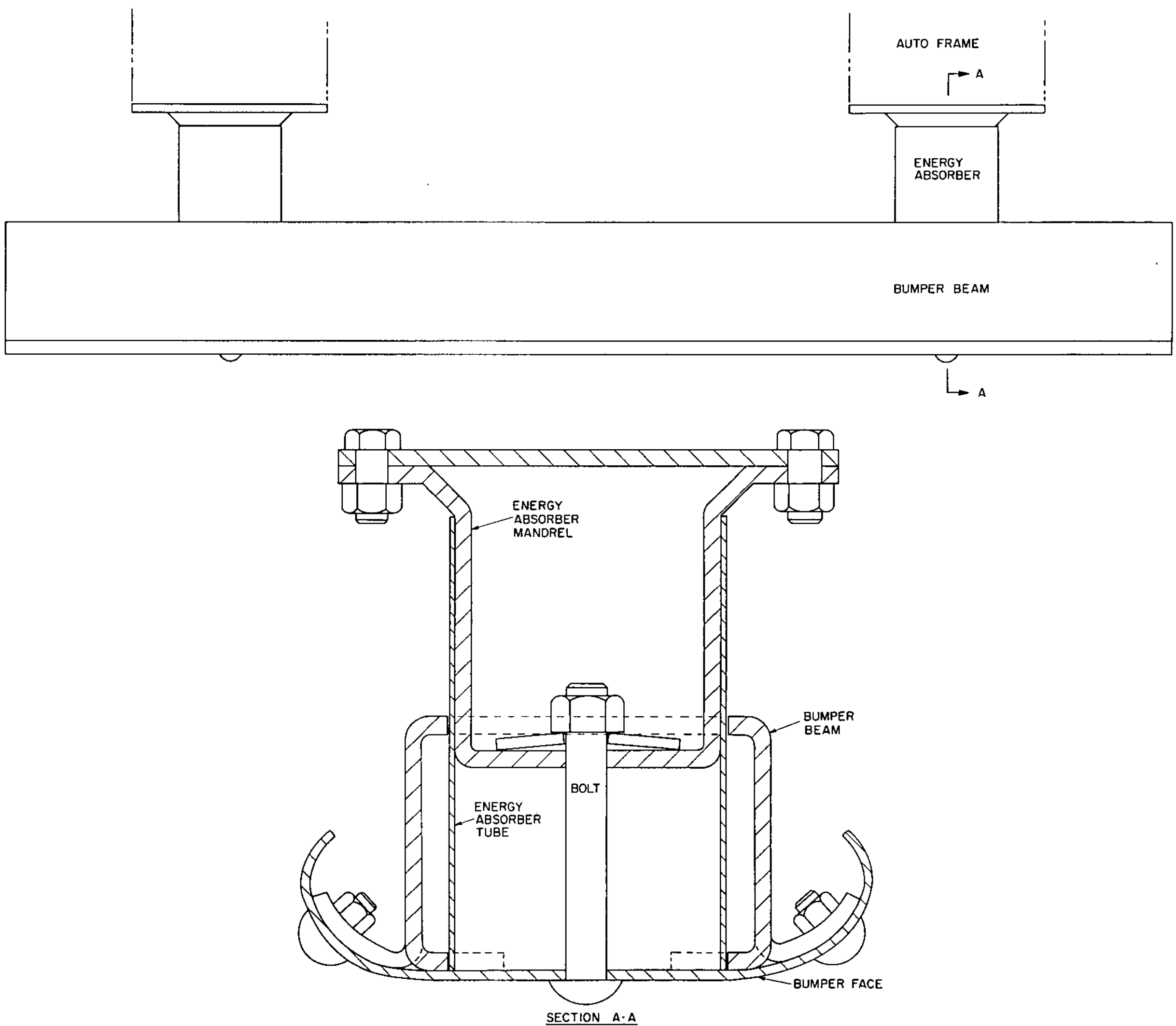

Figure 6.1. Energy Absorbing Bumper

tube was designed to extend on through the beam to the back side of the bumper. This configuration makes it possible for the energy absorber to resist the off axis loading by developing bending and shear stresses in the tube and mandrel. The bumper and reinforcing beam are attached to the mandrel by a long bolt which extends through the tube and the top of the mandrel and is retained by a nut and spring washer on the back side of the mandrel top. This attachment is designed to remain firm even after slight deflections of the energy absorber tube and also to prevent loss of the bumper after an impact. However, the bumper will rattle after a hard impact indicating to the driver that the energy absorber tubes should be replaced. In the initial thinking it was considered advantageous to use as large a diameter tube in the energy absorber as could be allowed, perhaps 5 to 6''. However, this was found to create styling problems so the tube diameter was reduced to 3'' I. D. More recently it has been suggested that the diameter could be increased to 4'' I. D. in later prototypes.

As stated earlier, the total resistive force of the bumper was to be 17, 000 lbs. This was to be divided equally between the two energy absorbers. Each energy absorber was therefore designed for a resisting force of 8, 500 lbs. However, the bumper force is only divided equally in head-on impacts with flat surfaces or in concentrated impacts which are centered. Otherwise the load is unequally divided between them. Since these devices operate as load limiters, the one receiving the highest load will be deflected preferentially. In the case of the concentrated impact centered over one of the energy absorbers, or outboard of it, only one of the energy absorbers will be deflected. One possible means of minimizing this effect is to design energy absorbers which have an increasing force deflection curve; then the deflections of the two elements would be a function of the way the force is divided between them. Of course this would have no effect on the case where the impact is concentrated over one of the elements or outboard of one. This problem arises from the basic geometry and is therefore to be encountered in any bumper system. One possible way to overcome this is by making the energy absorbers velocity sensitive, i. e., the resistive force a function of the rate of deflection of the device. Then the device nearest the load will be the stiffest, thereby encouraging deflection of the other device.

c. Energy Absorber and Bumper Development and Testing

The tube and mandrel energy absorber used in the bumper design differs from those normally used in that it has a very long pilot on the mandrel. This energy absorber is illustrated in Figure 6.1 as it would appear if the mandrel were manufactured by a deep drawing process from one flat piece of steel. However, prototype mandrels were made from a mild steel plate and a piece of mild steel tubing joined together by a large fillet weld which was later finished for use as the tapered surface of the mandrel.

Individual energy absorbers were subjected to dynamic tests in a drop testing device which consists of a weighted table or ram which can be raised and dropped from a predetermined height and dropped onto a flat concrete pad. This ram is equipped with a steel beam on the underside onto which energy absorbing devices may be mounted. It has a weight which can be varied from a minimum of approximately 2,300 lbs to a maximum of approximately 7,500 lbs by adding steel plates.

It was found that the dynamic test produced a resistive force which has somewhat higher than obtained in the static tests. This difference is attributed to mandrel surface damage which was found to be significantly greater for the dynamic test. In order to adjust the resistive force produced in dynamic operation, the mandrel angle was adjusted.

A full scale prototype of the bumper was built and subjected to dynamic testing on the drop tester described earlier. This prototype differed to some extent from the proposed production model in that it did not have the decorative bumper face with the polyurethane covering. Also, the bumper tie bolts were not equipped with spring washers and the bolts were somewhat smaller than would be required in the production bumper to resist the tensile loads associated with impacts on the ends of the bumper. The assembled prototype bumper is seen from the rear in Figure 6.2 and is seen disassembled in Figure 6.3. In this photograph the mandrel, energy absorber tube, bumper beam, and tie bolt are seen separated. For testing, the bumper was attached to a beam on the underside of the drop tester ram. The desired impact velocity was achieved in free fall from a predetermined height.

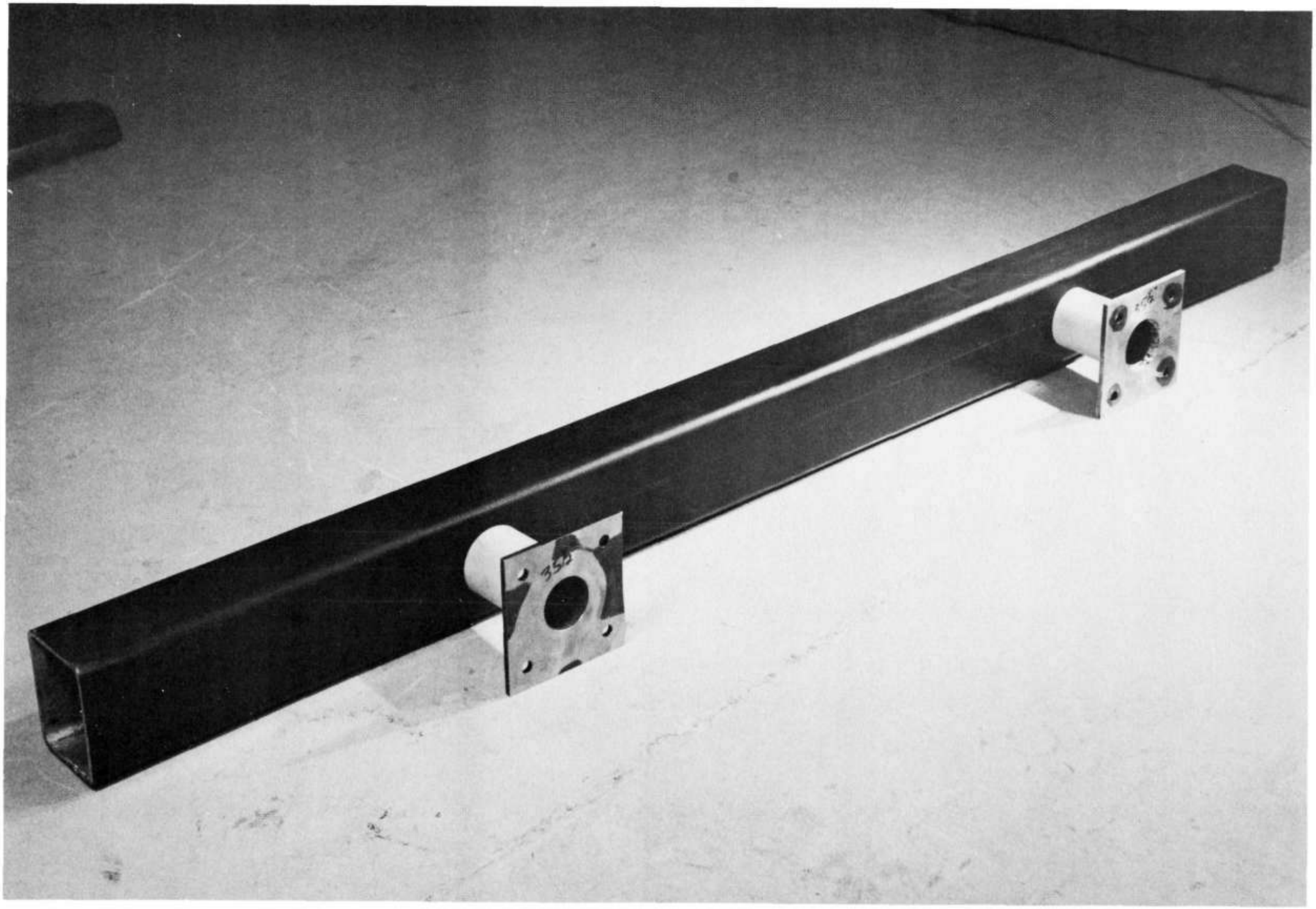

Figure 6.2. Prototype Bumper

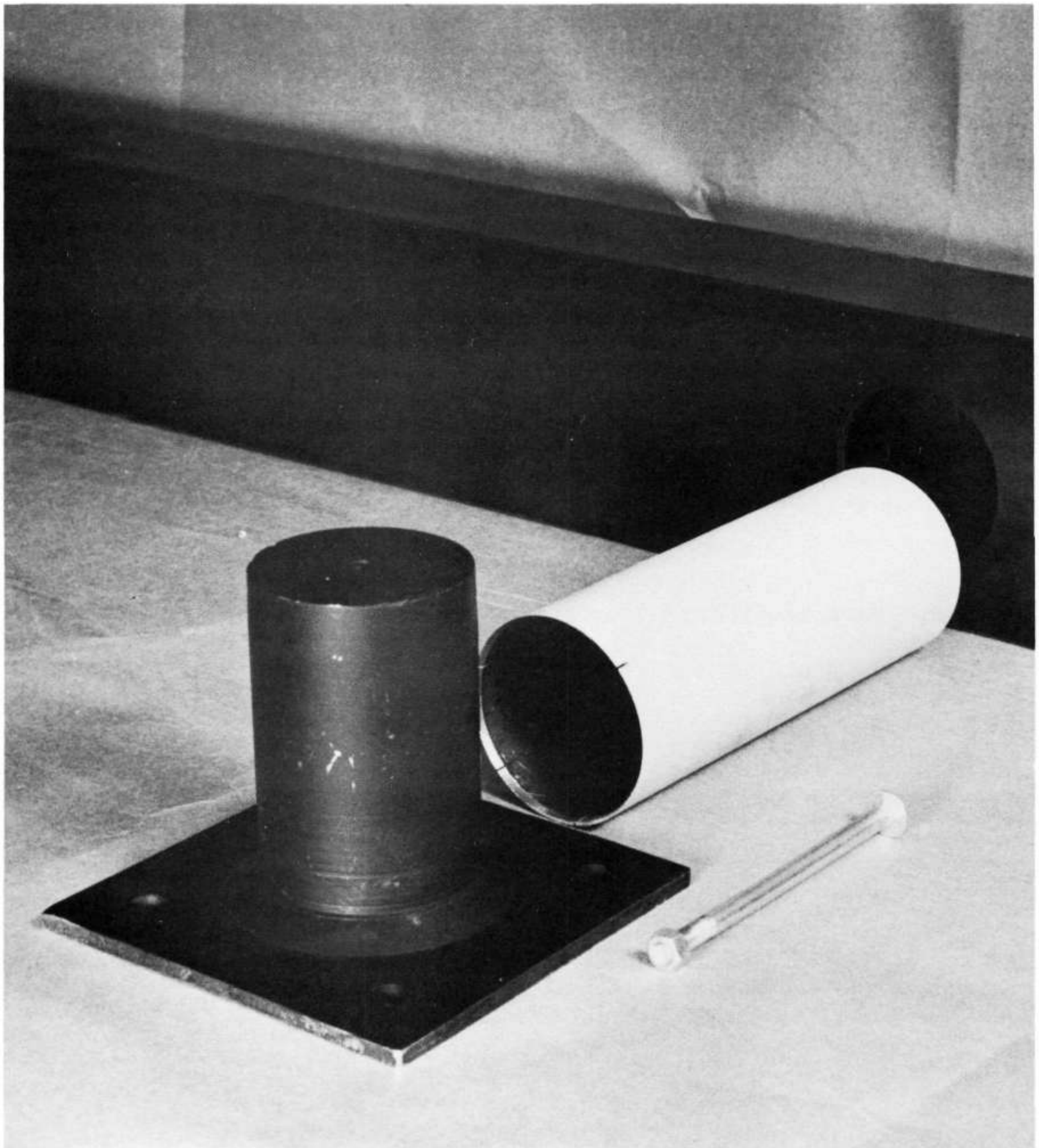

Figure 6.3. Prototype Bumper Disassembled

d. Test Results

The data for the prototype bumper tests is contained in Table 6.1. Here Tests 1-5 and 7 were normal impacts of the bumper with a flat surface. The other tests were with a segment of utility pole placed approximately midway between the two energy absorbers.

Except for the energy absorbers being a little hard in some tests, the bumper has been shown to perform successfully in 7.4 mph normal impacts with a rigid surface. Further development is required to obtain satisfactory performance in concentrated off-center impacts. The energy absorbers used in the bumper were specially designed to resist off-axis loading such as that incurred in mismatched impacts with the bumpers of other vehicles and in jacking of the vehicle. However, additional tests would be required to determine how well the bumper will perform under these conditions.

TABLE 6.1

TEST DATA FOR PROTOTYPE ENERGY ABSORBING BUMPER

No.	Tube[a]						Mandrel[b]					Average[c] Force (lbs)	Stroke (in.)			Impact Velocity (fps)	Comments
	Mt'l	O.D. (in.)	W (in.)	L (in.)	ϕ (deg)	C	Mt'l	p[e]	(deg)	D_i (in.)	D_p (in.)		No. 1	No. 2	Average		
1	MS-D[d]	3	.067	8	30	6	MS	4-1/4	35.5	2.22	2.856	19,550	2.84	2.13	2.48	7.4	Normal Test
2	MS-D	3	.067	8	30	6	MS	4-1/4	35.5	2.22	2.856	18,950	2.37	2.81	2.59	7.4	Normal Test
3	MS-D	3	.067	8	30	6	MS	4-1/4	36	2.22	2.856	15,450	3.41	3.44	3.38	7.4	Normal Test
4	MS-D	3	.067	8	30	6	MS	4-1/4	35.5	2.22	2.856	17,310	2.91	2.88	2.89	7.4	Normal Test
5	MS-D	3	.067	8	30	6	MS	4-1/4	35.5	2.22	2.856	18,200	2.87	2.87	2.87	7.4	Normal Test
6	MS-D	3	.067	8	30	6	MS	4-1/4	35.5	2.22	2.856	20,600	1.63	3.03	2.33	7.4	Central Impact on Utility Pole
7	MS-D	3	.067	8	30	6	MS	4-1/4	35.5	2.22	2.856	15,650	3.38	3.31	3.34	7.4	Normal Test
8	MS-D	3	.067	8	30	6	MS	4-1/4	35.5	2.22	2.856	24,800	0.56	3.19	1.87	7.4	Impact on Utility Pole
9	MS-D	3	.067	8	30	6	MS	4-1/4	35.5	2.22	2.856	29,000	.94	2.19	1.56	7.4	Impact on Utility Pole
10	MS-D	3	.067	8	30	6	MS	4-1/4	35.5	2.22	2.856	18,400	3.13	2.25	2.69	7.4	Normal Test

(a) See Figure 6.4 for tube nomenclature.

(b) See Figure 6.4 for mandrel nomenclature.

(c) Average Force calculated from W (h + s)/s where W was the weight of the drop tester (3900 lbs), h was the drop height and s was the measured stroke.

(d) The static peak and average force were measured directly from the Tinius Olsen Compression Tester. The dynamic average force was calculated from F = W(h + s)/s where w was the weight of the drop table (2300 lbs), h was the drop height, and s was the measured stroke.

(e) Pilot length of mandrel.

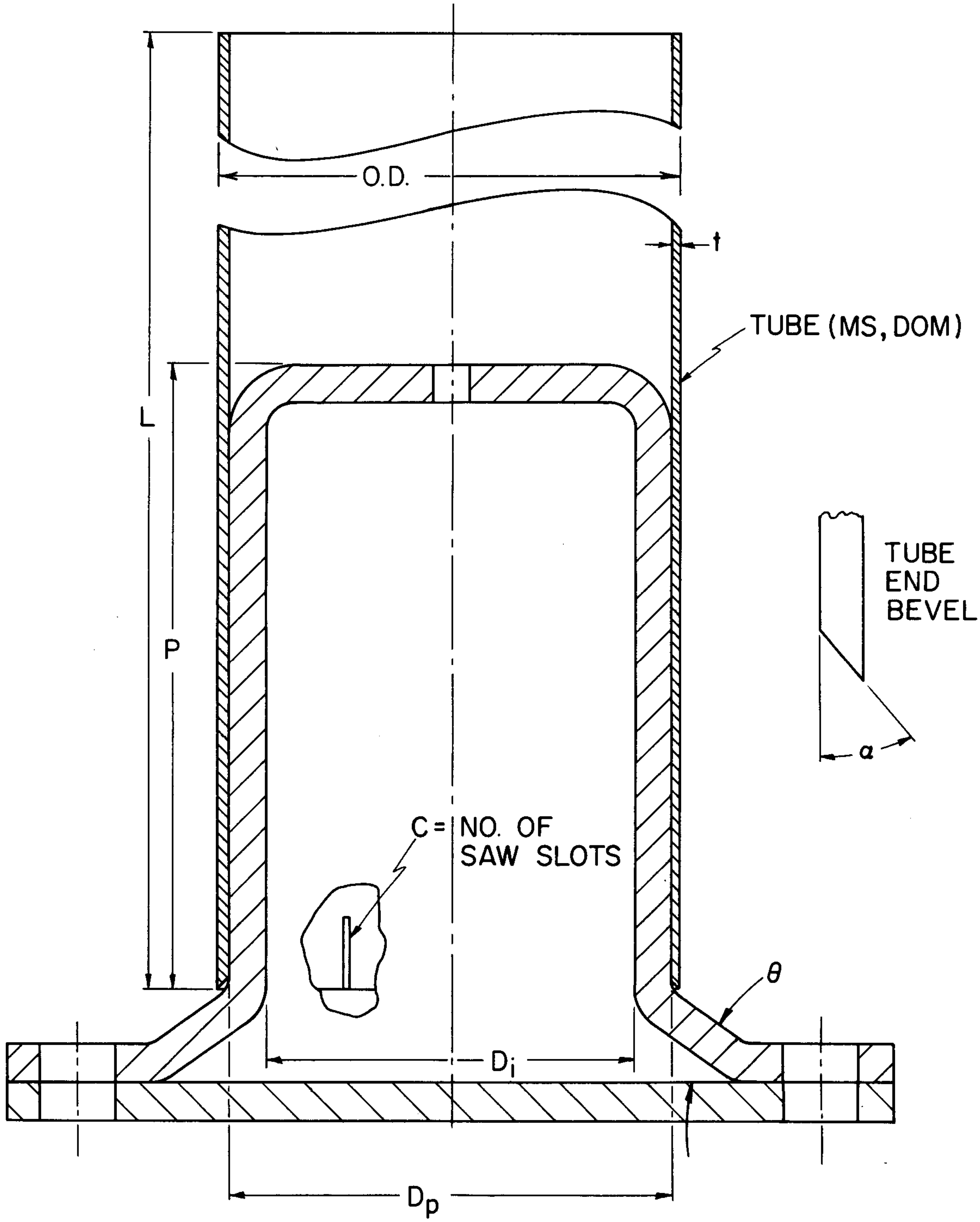

Figure 6.4. Tube and Mandrel Design for Bumper

4. 15 mph Bumper

The 15 mph bumper is, in general, a scaled up version of the previously described 5 mph bumper. It utilizes two tube and mandrel energy absorbers and a rigid beam of square steel tubing. The energy absorbers are larger in diameter than those used on the 5 mph bumper to provide a greater resistive force and longer to provide a greater stroke. At this speed the kinetic energy to be absorbed is nine times the amount at 5 mph.

a. Requirements

As discussed previously, the bumper absorbes the kinetic energy of the vehicle by having the vehicle do work against the resistive force of the energy absorbers over some stroke. A trade off exists between resistive force and stroke so that either the force or the stroke must be chosen in order for the other to be determined for a given impacting mass and velocity. It was decided arbitrarily to limit the stroke of the energy absorbers to less than one foot, if possible, and to keep the deceleration on the vehicle under 12.5 g's, the Federal Highway Administration recommended deceleration limit for energy absorbing highway structures. By an iterative process it was determined that a vehicle could be stopped with a deceleration of 11 g's and a stroke of 8-1/2". This was chosen for the design of the first prototype. While 11 g's represents more force than the average production auto can tolerate on the front frame ends, it is believed that future vehicles will be made stronger for greater impact resistance.

b. Prototype Design

The first prototype, illustrated in Figure 6.5, is basically the same as the 5 mph bumper discussed previously, with long pilots on the mandrels to provide stability in off axis loading while the rigid beam distributes the load in pole or concentrated impacts. In order to provide a safety factor for testing the bumper it has a possible stroke of 15-1/2". It differs from the 5 mph bumper in the use of external tie bolts in place of the tie bolts centered in the energy absorbers. Figure 6.6 is a photograph of the bumper mounted on the test vehicle, a 1957 GMC pickup truck. The truck with the bumper and frame strengthening structures weighed approximately 4,000 lbs. Therefore, the resistive force of the energy absorbers was to be 44,000 lbs. Two six inch O.D., 0.065" wall tubes were used with a 22-1/2" overall

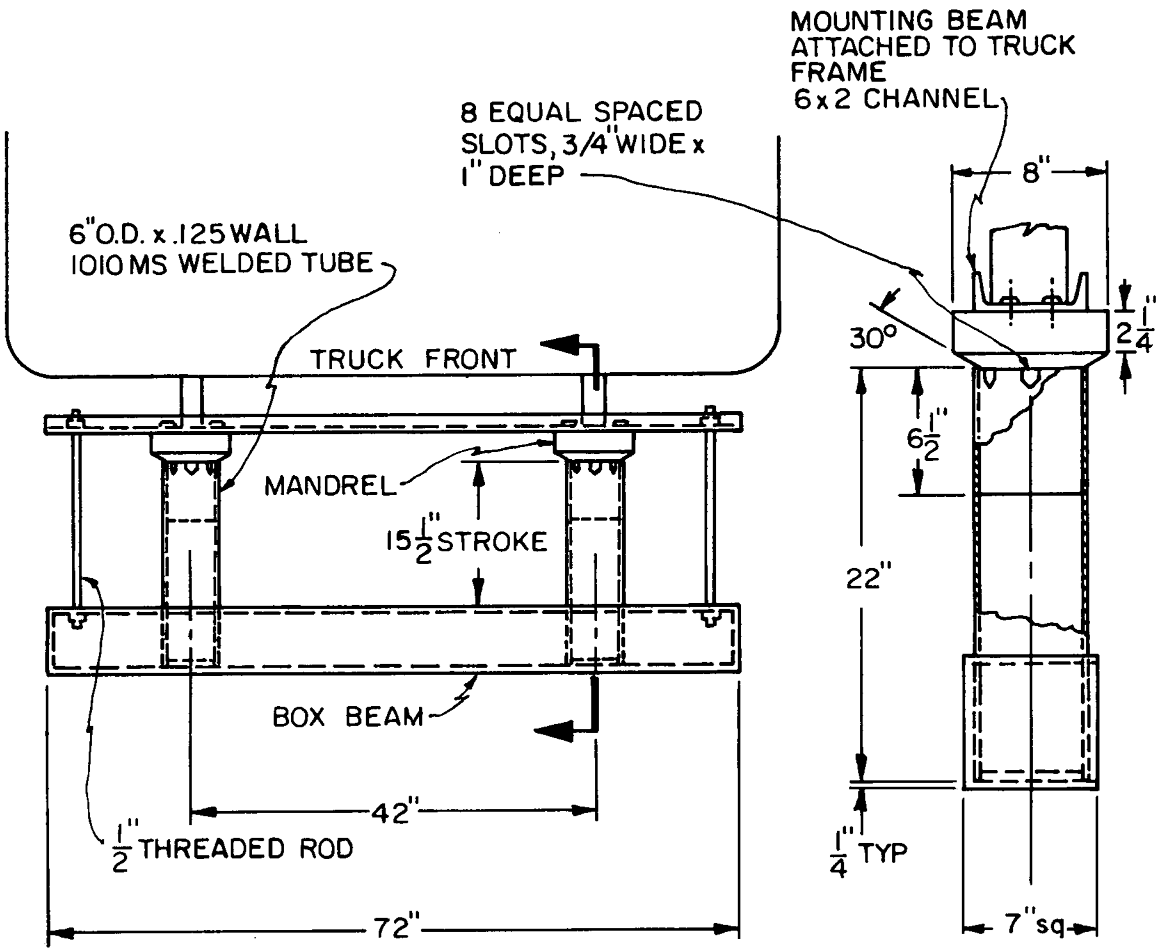

Figure 6.5. Prototype 15 mph Bumper

Figure 6.6. Bumper Mounted on Test Vehicle

length. These provide for a maximum stroke of 15-1/2", considerably more than called for in the requirements. These tubes were tested statically and found to give a force of 22,000 lb average.

c. Prototype Testing

Time on the project permitted only one prototype test which was conducted by coasting the test vehicle down an incline into a concrete barrier. The vehicle speed was predicted by trial runs and its direction was controlled by means of a cable guidance system. The vehicle, guidance cable, test track and barrier are shown in Figure 6.7. In the test the vehicle achieved a speed of 12.5 mph and impacted normal to the barrier. The energy absorbers activated and brought the vehicle to a stop as shown in Figure 6.8.

The stroke of the energy absorbers was only half of that expected, therefore, the deceleration on the vehicle was roughly twice that expected. The higher resistive force on the energy absorbers was later determined to be caused by mandrel surface damage. This can be minimized by using an adequate lubricant, painting the inside of the mandrel, or hardening the surface of the mandrel.

d. Conclusions

While only one prototype test has been concluded, the results indicate that the bumper can be made to work as designed. The test was relatively easy to conduct with the vehicle getting up to speed by coasting down an incline while under the direction of a guide cable. Additional testing will be conducted under the support of the College of Engineering, University of Denver after the NASA program is concluded.

Figure 6.7. Test Track, Barrier, and Vehicle Guidance Cable.

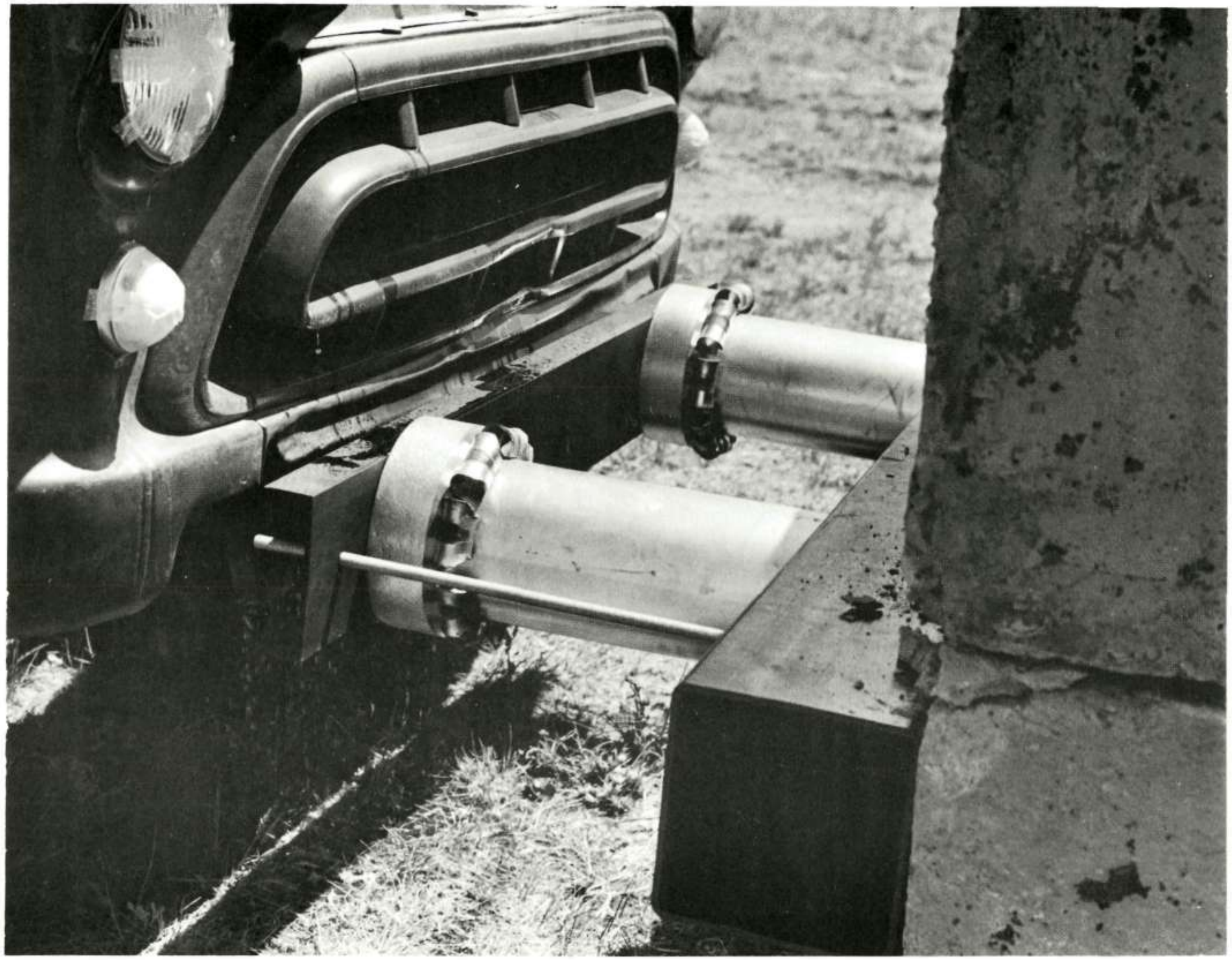

Figure 6.8. Bumper After Impact with Barrier

VII. COMMENTS ON TECHNOLOGY TRANSFER

The Government currently holds some 20,000 patents based on Federally sponsored R & D. These patents represent an enormous potential for stimulating commerce and solving pressing environmental problems. The realization of this potential requires a clear understanding of the barriers confronting such exploitation and the development of effective means for overcoming them.

Every patent has an inherent level of risk involving technical, economic, and legal factors. Every private company or venture capital source has its own acceptable level of risk which depends on factors such as the overall business climate, the availability of capital, the characteristics of the company and its management, its competitive position, and others. Before commercial exploitation can take place, the inherent level of risk must match the acceptable level of risk for the interested private company or venture capital source. This can be expressed in equation form. Let R_i equal the inherent risk and R_a equal the acceptable risk;

If $R_i > R_a$,

then in order for technology transfer to take place, either

(1) R_i must be lowered <u>or</u>

(2) R_a must be raised.

If $R_i \leq R_a$,

then technology can be transferred largely through a process of education and information dissemination.

The inherent risk in a patent exists largely due to lack of knowledge. The technology at the time the patent is filed may have been demonstrated only in the laboratory. Further examination may reveal unforeseen problems in the practical application of it. Economic risks exist in the market, the cost of development, and in the cost of production. Legal risks exist with patent coverage and level of protection. A patent may appear to offer a high level of protection but discovery, in predated literature, of similar material may weaken or destroy it. Cases are well known where patents have been set aside for this reason. In general, the inherent level of risk is lowered by reducing the level of unknowns associated with a given application of a patent on a new idea. This is accomplished by further research to develop a fund of knowledge concerning the technical areas involved, economic and marketing studies, and the investigation of competing patents.

The acceptable level of risk of a company or venture capital source involves both economic and personnel factors. Risk decisions are rarely made by an executive without regard to the probable effect of the outcome on his career. The acceptable level of economic risk may be changed considerably by government incentives such as subsidies or tax relief. Increasing the acceptable level of risk through government action is practiced in a number of countries including the United Kingdom, Japan, West Germany, and others. While this approach may strike some as alien to the American way of life, there are some historical U.S. precedents, of this nature, including land grants to railroads, agricultural subsidies, and oil depletion allowances.

Additional R & D to reduce the inherent level of risk in a new product or process is a perfectly acceptable government activity in the United States. The underlying assumption, with this approach, is that the inherent level of risk in a new product or process can be reduced enough to match the prevailing level of acceptable risk so that the technology will be exploited and new economic growth will take place. On this program the incentive tested was the reduction of risk in a Government patent to a low enough level to make it attractive to private industry for exploitation and the protection of exclusive licenses in product areas.

Our experience with this program has shown that the process of converting a patent based on a new scientific discovery of technological advancement into a marketable product through a research institute-industry partnership may follow the pattern illustrated in Figure 7.1. In opposition to the accepted text book pattern in which the product development process starts with the identification of a need and a market, this process starts with the patent on a new idea and then searches for a need and a market. In other words, the patents are viewed as answers which must match up with suitable problems. The first step is the selection of a patent for commercial exploitation. The selection of such a patent must be based on fundamental scientific, engineering, economic, and legal principles. In a given area of technology, a set of selection criteria must be developed by which competing

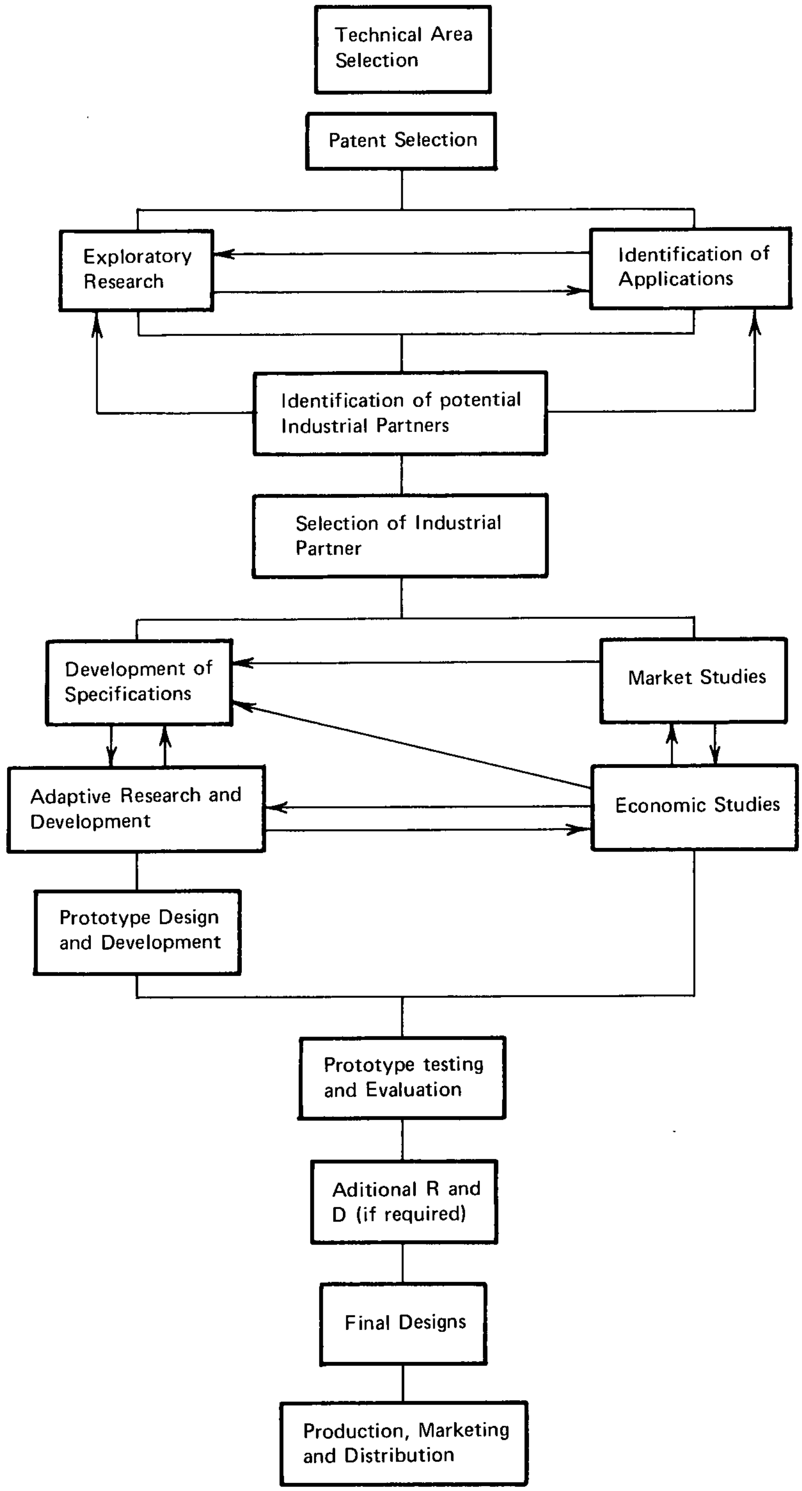

Figure 7.1. Commercial Exploitation of a Government Patent Through Research Institute-Private Industry Cooperation

patents may be judged and the best one selected. The next step is exploratory research to develop a fund of knowledge concerning the patent and related areas of technology. Also at this time the search for specific applications is extended beyond that involved in the patent selection process. This leads to the identification of possible industrial partners, which naturally influences the direction of the R & D efforts.

It is necessary to demonstrate to a potential industrial partner that the technology has something special to offer in an area he is interested in. Discussions with potential partners may lead to the discovery of other applications. Working together, the industrial partner and the research institute (or other technology transfer agent) must develop a set of specifications covering the device or process which is to be developed. This will clearly define the goals for adaptive research and development and the prototype design and development programs.

While adaptive research and development is being conducted, parallel programs involving economic and market studies should be undertaken, and the results used to influence the direction of the R & D and product development activities. The industrial partner should be encouraged to conduct a large share of this work himself. Our experience has been that companies will be quite willing to do this in-house but have difficulty finding support for work done outside. The development of prototypes is clearly the responsibility of the industrial partner. However, his testing capability may be limited and he may need the help of the research institute in this area. The results of prototype tests may indicate the need for more R & D. After this is done, the task of the research institute is largely completed.

After the successful completion of the prototype tests the remaining activities lie mostly in the realm of the industrial partner. Also at this point the inherent risk in the commercialization of the technology is only a fraction that of the raw patent and hopefully less than or equal to the acceptable level of risk of the company. During the period of development of the prototypes the companies interest in the technology may increase and this will have an effect on the acceptable level of risk.

The experience gained on this program has demonstrated that companies are willing to work with an organization such as ours to develop new products based on patented new technology. They will invest a considerable amount in in-house studies, prototype development, and testing if the technology is in an area they are interested, looks good to them, and has adequate patent protection so that they can have a strong competitive position with the development product. For this protection they are willing to pay royalties.

F

VIII. COMMENTS ON THE TUBE AND MANDREL ENERGY ABSORBER

The adaptive research conducted on the program was directed toward the development of energy absorbers to fit specific applications rather than the development of a broad fund of knowledge about the tube and mandrel. However, in the process of conducting this research much was learned about the device, especially concerning the use of mild steel tubing and a conical mandrel. The drawings and photographs in the previous sections show slots on the end of the tube in contact with the mandrel; these were found to be necessary with ductile tubing to provide sites for crack initiation and to reduce the initial peak which occurs when the device is activated. It was found that in some cases the use of very wide notches would completely eliminate the initial peak by reducing the width of the strips subjected to bending as the curls started to curl. In other cases the width of the notches seemed to have little effect on the size of the initial peak.

Experience has shown that the splitting process depends heavily on the properties of the tube material. Tubing which is too soft, such as 1010 steel, fully annealed, does not split well and produces irregular curls; localized buckling also occurs. Tubing which is brittle will not work well on the conical mandrel but requires the curved mandrel such as that used by the inventor. This is because the cracks tend to run ahead of the mandrel causing the strips to contact the surface at a shallow angle and not experience much bending. Equally as important as the hardness of the tube is the orientation of the grain flow pattern since the cracks will tend to follow it. Therefore, the tubing should be made by a process which produces a well defined grain flow pattern in the longitudinal direction. Drawn tubing has the desired grain flow. In steel tubings, electric welded and DOM (welded and then drawn over a mandrel) have the desired grain flow patterns. Seamless mild steel tubing, which we have tried, has a grain flow oriented at 45° to the axis of the tube and produces spiral curls which radiate tangentially from the surface of the tube in a plane normal to the axis. The steel tubing which has worked well in our experiments includes 1010 welded in 2"-6" O. D. and 1015-18 DOM in 1"-4" O. D., 1010 in 1"-1-1/4" O. D. was too soft. Some 1018 DOM which we received had not been given its final anneal and was to brittle for use with the conical mandrel.

A short pilot section is used on the mandrel to center the tube. Ordinarily this is on the order 1/8 to 1/10th the diameter of the tube. However, in applications where off axis loading is expected, such as the auto bumper, longer pilots are required. In the auto bumper energy absorbers we have used pilots having a length equal to the diameter of the tube. More work needs to be done to define the effect of the pilot in resisting off axis loading and in determining how much off axis loading the tube and mandrel can withstand.

Analytical equations have been derived[1,2] to predict the resistive force of the tube and mandrel energy absorber. However, these have not been entirely successful in predicting the resistive force over a large range of tube sizes and types of materials. The following equation was obtained imperically from test data for a series of tests with mild steel and DOM tubes operated on conical mandrels with a half angle of 60°. The insides of the tubes and the surfaces of the mandrels were painted with aluminum paint for lubrication and protection. The mandrels were made of mild steel. The resistive force F is given by

$$F = 212\ D^{1.863}\ e^{(70.7/e^{0.456D})}\ T \qquad (8.1)$$

where D is the outside diameter of the tube and T is the wall thickness, both in inches. The agreement between equation 8.1 and the data is illustrated in Table 8.1.

While the 60° mandrel gives the best overall performance, it is possible to operate the energy absorber with other mandrel angles. The effect of varying the mandrel angle is illustrated in Figure 8.1. The effect of varying the thickness of the tube while holding the diameter and the mandrel angle constant is illustrated in Figure 8.2. As would be expected, the resistive force is a linear function of the diameter. The effect of varying the thickness while holding the diameter and the mandrel angle constant is illustrated in Figure 8.3. Here again, the curve satisfies the intuition by showing the resistive force to be approximately a function of the thickness squared.

Some of the experimental results on this program have raised the question of whether the tube and mandrel energy absorber is velocity sensitive when steel tubing is used. A recent series of experiments with a 1" O. D. DOM tube revealed that with the inside of the tube and the mandrel painted with aluminum paint no noticeable change in the resistive force could be detected at impact speeds up to 85 fps.

TABLE 8.1

All Insides of Tubes and Mandrel Surfaces Painted With Aluminum Paint

Diameter	Mandrel Half Angle Theta	Thickness	F. Calc.	F. Act.	% Dev.
1.125	60	.046	1850	2200	-15.89
1.125	60	.065	3400.8	3400	.0242
2.0	60	.064	3946	4100	- 3.76
2.625	60	.065	4385	5000	-12.29
3.0	60	.061	4922	4900	.44
3.0	60	.093	8755	7600	15.2
3.0	60	.12	14235	14000	1.678
3.005	60	.064	4675	4900	- 4.59
3.26	60	.064	4880	5350	- 8.79
4.0	60	.142	14177	17500	-18.99
4.0	60	.188	23962	22500	6.499

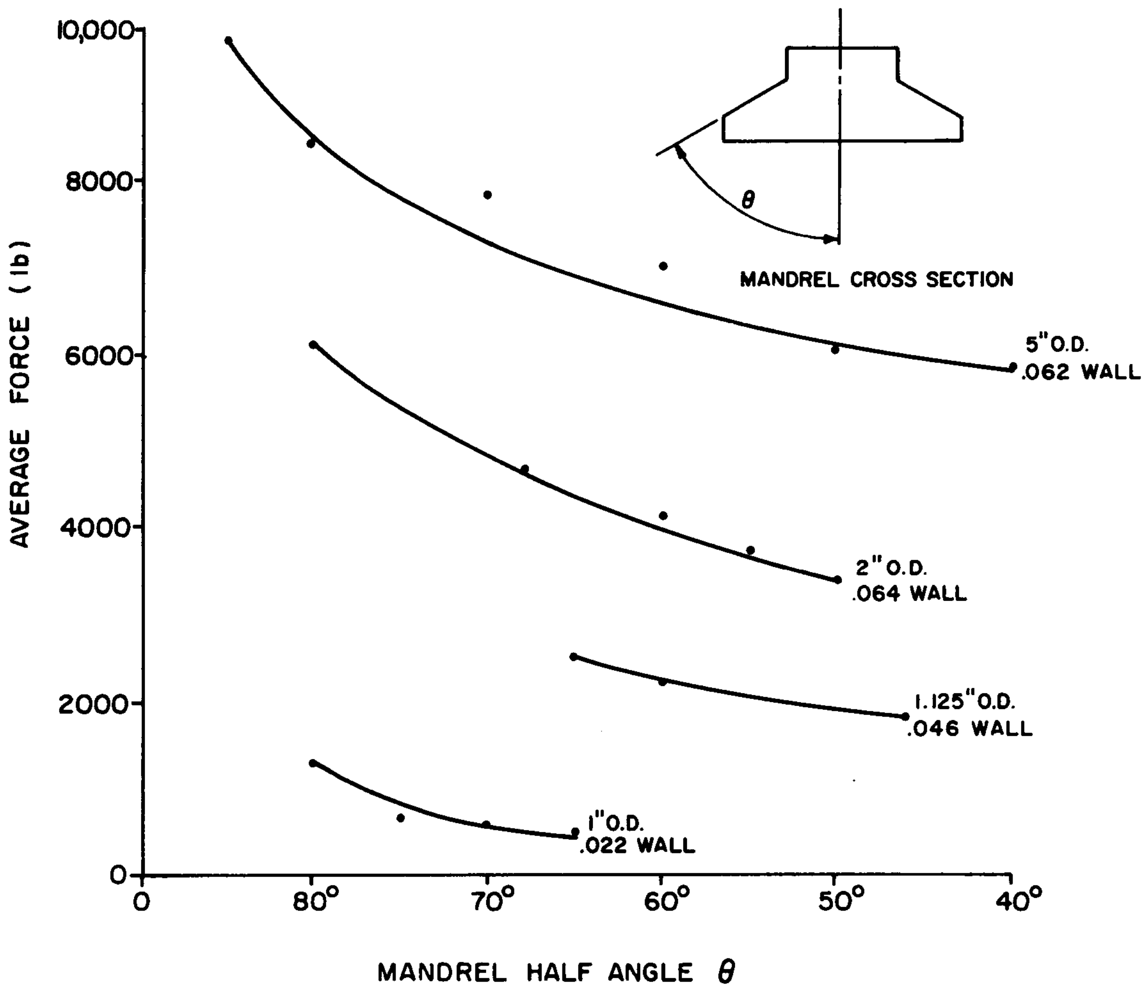

Figure 8.1. Resistive Force as a Function of Mandrel Angle

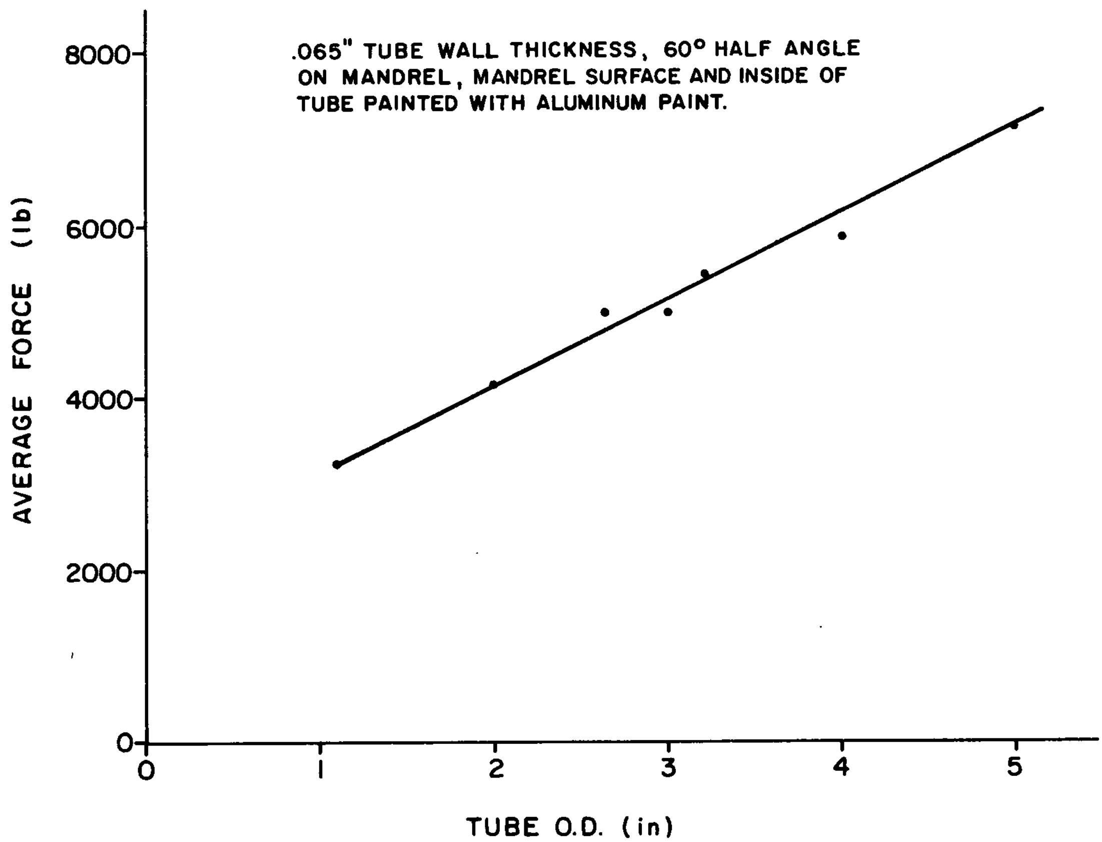

Figure 8.2. Resistive Force as a Function of Tube Diameter

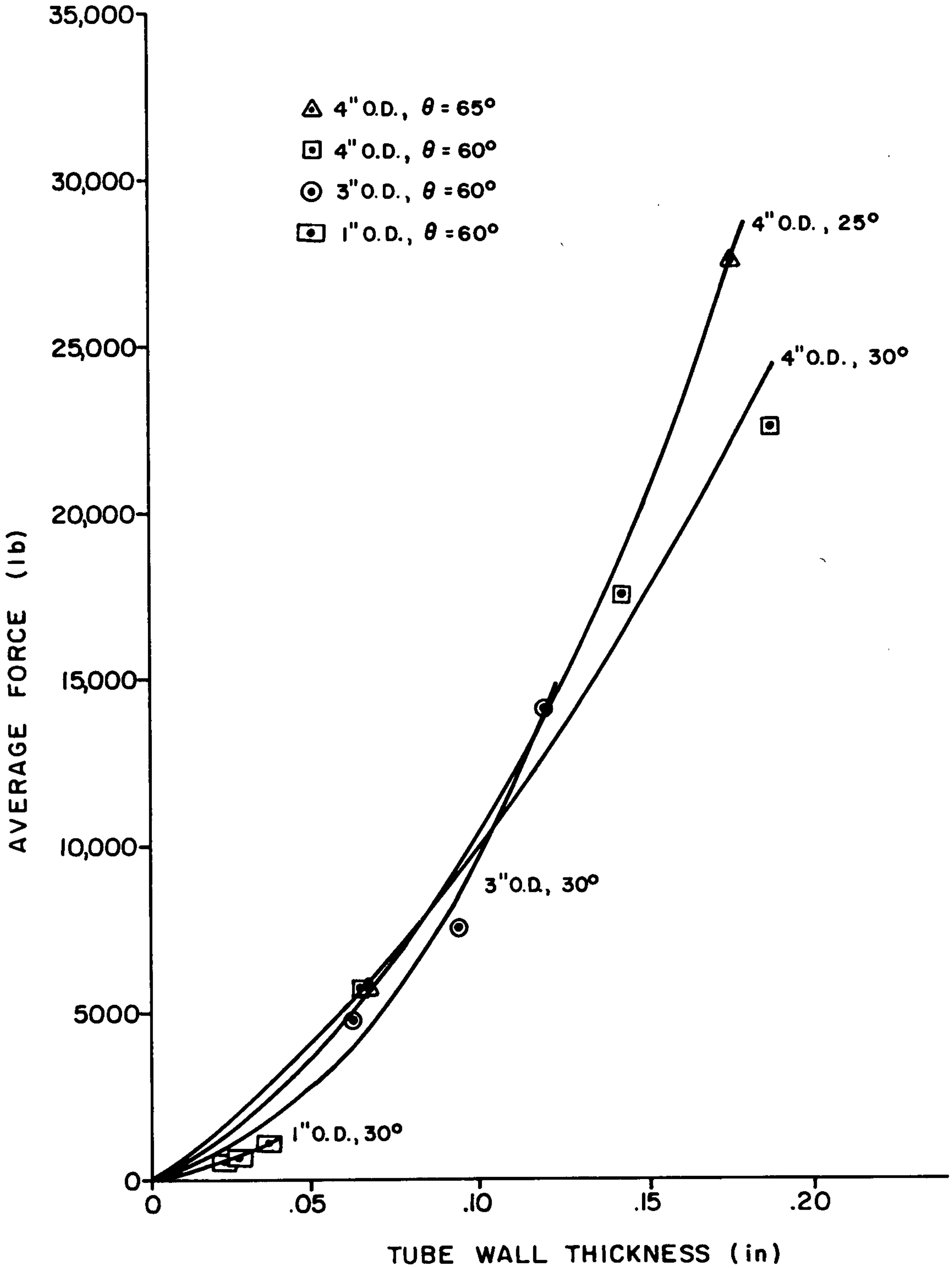

Figure 8.3. Resistive Force as a Function of Tube Wall Thickness

This program has demonstrated that the tube and mandrel energy absorber is truly a magnificant device. In aerospace applications it can be made to absorb large amounts of energy per unit weight using 2024-T3 aluminum tubing while in earthbound applications it can be made to absorb large amounts of energy per unit cost using commerically available mild steel tubing.

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