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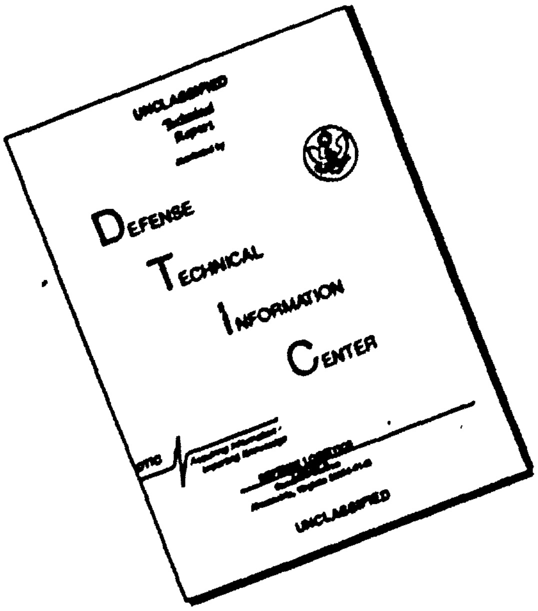

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INTERNAL REINFORCEMENT OF SOLID PROPELLANT ROCKET GRAINS (U)

FINAL REPORT

May 15, 1961 to May 15, 1962

Structural Mechanics Branch
Mathematical Sciences Division
Office of Naval Research
Washington 25, D. C.

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Solid Propellant Division
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FOREWORD

A study to devise, fabricate, and evaluate methods of internally reinforcing solid propellant grains to improve their mechanical effectiveness was conducted. This work was sponsored by the Structural Mechanics Branch of the Office of Naval Research under contract number Nonr - 3500(00).

Work under this contract began on May 15, 1961 and was completed May 15, 1962. Messrs M. G. DeFries, F. C. Moore, and A. V. Rice are cited as major technical contributors to this project.

ABSTRACT

The results of an experimental program to study the effect of organic reinforcements embedded in solid propellant rocket grains are presented. Criteria for materials selection is defined. A comparison of the mechanical behavior of reinforced and unreinforced propellant beams in simple flexure is presented, and ballistic compatibility of reinforcing materials embedded in the propellant is demonstrated.

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INTRODUCTION

Solid propellants as currently known may be classed among the poorest materials which engineers must utilize as structural members. Composite propellants may be described as nonhomogeneous gels. Low internal adhesion between phases gives rise to poor cohesivity within the mass. The matrix, or binder phase, is generally a weak rubber subject to viscous flow and to marked changes in properties over the operations temperature range. The resultant low stress levels to which designs of solid propellant grains must be restricted are often the limiting factors of motor performance. In practice, failures of grains all too frequently are caused by the problems related to the inherent physical limitations of solid propellants as structural materials. These problems are manifest in the form of distortion and displacement of the perforation or of the entire grain due to viscous flow over long periods of time, separations at liner and propellant interfaces, and to development of cracks or dewetted regions under tensile or shear forces.

An obvious method to improve the structural integrity of solid propellant grains is by the internal reinforcement approach. Prior attempts[1] have been concentrated on the incorporation of high modulus reinforcement materials with dissimilar coefficients of thermal expansion related to the propellant, thereby limiting the thermal cyclibility of the unit. This study has been oriented toward the use of reinforcement materials having generally the same coefficient of thermal expansion as the propellant.

1. DeFries, M. G. and Rice, A. V., Internal Reinforcement of Solid Propellant Rocket Grains, American Rocket Society reprint #2751-63.

SUMMARY

Three factors contributing to solid propellant rocket motor malfunctions and approaches towards minimizing them by reinforcement of propellant with organic rod, plate, and mesh embeddments are described.

Thirteen candidate reinforcement materials were screened for:

(1) tensile strength and modulus

(2) coefficient of thermal expansion

(3) compatibility with propellant

(4) adhesion to propellant

Nylon and polystyrene were chosen as materials for rod embeddment. A nylon scrim was selected for embedded meshes. A reinforcing composition consisting of an epoxy resin filled with ammonium perchlorate and copper chromite, which can be controlled to burn at the same rate as the propellant, was developed.

Bonds between propellant and nylon, and propellant and polystyrene are greater than the strength of propellant at 80°F and 120°F. Neither rod geometry nor embedded depth affect this value appreciably.

Bearing tests indicate that propellant movement 1/8" diameter rods or larger is insignificant when stressed with forces predicted in large grains.

Tear tests showed that dewetting and crack development is retarded by approximately the force required to break the embedded meshes. The crack propagates along the mesh reinforcement rather than penetrating into the propellant. Fabric placement was shown to be critical in that best results were obtained when the fabric was embedded as close to the propellant surface as possible.

Reinforced beams in simple flexure were used to demonstrate the extent to which the rate of slump or creep may be retarded by embedded reinforcements. As predicted, reinforcement materials having

the highest modulus of elasticity were the most effective. Apparent moduli of both propellant and reinforcement were calculated using the conventional elastic beam formulae. Reinforcement materials exhibit decreases in apparent moduli with time at a rate consistent with reported values for the material themselves. Initial moduli of reinforcements calculated on the basis of behavior in the beam compared fairly closely with measured values of tensile moduli. Rods of energetic material composed of epoxy resin and oxidizer were not effective as reinforcements due to bond failure.

End burning motors simulating the web thickness of large motors were fired statically with longitudinal and transverse embedded reinforcements to show ballistic compatability of the embeddments with the propellant. Nylon rods 1/8" and 1/4" in diameter were consumed within three seconds of exposure to the flame temperature without affecting the performance of the motor.

An internal burning grain containing four types of reinforcing materials[1] was fired in a windowed motor. Burning in the vicinity of the reinforcements was pictorially recorded with a Fastex camera of 3,500 frames per second on Ektachrome color film. Progressions of the flame around these reinforcements was normal. Polystyrene was the only material which was not completely consumed during the operation of the motor. The presence of these embedded reinforcements did not affect the performance of the grain to an appreciable extent as determined by comparison of the pressure-time trace with that of an unreinforced control grain.

A model reinforcing system for a solid propellant grain of the first stage A-1 Polaris type was designed on the basis of simplified assumptions. It was predicted that eighteen 1/2" diameter nylon rods

1. Zyten 101 Nylon, Q200.5 Polystyrene, and EP-12-53C energetic reinforcement in rod and plate form and B-9809 rayon fiber in an open weave fabric.

anchored to the head of the motor case would support 75 per cent of the weight of the grain, reducing the load carried by the bond between propellant and motor case wall to 25 per cent of the grain weight. Six 1/8" thick nylon spacer plates attached between each pair of adjacent rods, and separated by twenty inches, would be expected to reduce deflection of the star points on horizontal storage by a factor of 50 per cent. This reinforcing system would constitute only .06 per cent of the total grain volume and would probably burn as fuel during the action time of the motor without detracting from the impulse of the system.

2. Liner Separation

Liner separation may occur between the liner and motor case or propellant. The separation is due to shear and tensile forces generated by the propellant weight or thermal history. Occurrence of these separations is aggravated by the apparent decrease in propellant strength due to viscoelastic effects over increasing time spans, or due to chemical changes during aging. Volumetric shrinkage of propellant during polymerization or cooling after cure may cause separations.

These separations are most pronounced in bonded dome areas and at the nozzle-end of the grain.

The purpose of the reinforcement in this case is to reduce stress levels at critical areas by providing additional support to the grain, or to reduce shear to tensile stress at the liner interface by transmitting loads directly from the propellant to the rigid motor case. This may be accomplished by anchoring rods to the motor case and extending them radially into the grain. The liner would be applied after the rods have been attached to the motor case. This type reinforcement system is illustrated in Figure 2.

3. Propellant Failure

When forces exerted on the propellant grain are sufficiently great, a crack or tear may be developed. In some instances a high strain area without gross separation may occur. In the case of an internal burning grain, the stresses are magnified in the region of the fillets, causing this region to be the one in which cracks are most likely to develop. The forces causing the localized stresses are generally due to:

a. Thermal Gradients

During heating or cooling of a motor, the difference in volumetric changes between the propellant and case induces shear and tensile stresses at the peripheral interface, and places circumferential and longitudinal tension on the propellant at the surface of the fillets. Constraint of the propellant movement by the case is complicated by stresses generated by different moduli existing within the grains due to the temperature gradient. Separation may occur within the propellant or at the fillets under these conditions.

b. Ignition

High transitory stresses during ignition can increase stress levels excessively at the fillets. Pressurization of the chamber imposes additional circumferential and longitudinal strains on the propellant due to expansion of the motor case.

c. Acceleration

Inertial forces generated during acceleration magnify stresses on the grain fillets and the bonded areas stabilizing the grain to the motor case.

The purpose of the reinforcement designed to prevent propellant failures is (1) to reduce the general stress levels in the grain by transmitting loads directly to the case, thus reducing the strain imposed on the propellant in critical regions (2) to distribute stresses internally so that the radial strain at the fillet is reduced or (3) to provide an effective increase in modulus at critical strain areas so that local stresses will not strain the propellant excessively.

In order to distribute stresses internally, fabric materials were incorporated in the propellant adjacent to the critical areas. The fabric may be in the form of a cylinder of approximately the diameter of the fillets or it may be in the form of longitudinal bands placed near each fillet. Such placement of mesh is illustrated in Figure 3.

B. Selection of Reinforcing Materials

The ideal reinforcing material has been postulated to have the following attributes: (1) a coefficient of thermal expansion identical to that of the propellant; (2) a relatively high modulus of elasticity; (3) adhesion of the propellant to the reinforcing material would be stronger than the propellant; (4) it would be chemically compatible with the propellant and; (5) it would be consumed during the action time of the motor.

Selection of the reinforcing materials for further evaluation was based on the combined merits of each candidate material in respect to these requirements.

1. Conventional Plastics in the Form of Rods

Fourteen commercially available conventional plastics were evaluated in order to select two materials for further study. The following data were collected to aid in this selection.

a. Coefficient of Thermal Expansion

A quartz tube dilatometer was used to measure the linear coefficient of thermal expansion of the materials in the following table.

Material	LINEAR COEFFICIENT OF THERMAL EXPANSION x 10^{-5} in/in/°F -65°F to Amb	Amb to 160°F
ANP-2865	3.2	6.4
ABS Resin	2.0	5.2
Cellulose Acetate Butyrate	-	5.7
Delrin	2.4	5.0
Epoxy - Polyamid	4.5	7.0
Lexan	-	3.6
Lucite	4.7	6.5
Nylon, Zyten 101	3.4	6.7

Material	LINEAR COEFFICIENT OF THERMAL EXPANSION x 10^{-5} in/in/°F -65°F to Amb	Amb to 160°F
Penton	3.9	5.8
Phenolic - linen filled	-	1.4
Polyester - glass filled	-	.7
Polypropylene	3.6	6.8
Polystyrene, crosslinked	2.8	3.8
Poly Vinyl Chloride	3.1	4.2
Teflon	5.8	6.2

Nylon and Polypropylene apparently have linear coefficients of thermal expansion more similar to that of the propellant than any of the other materials evaluated.

b. Propellant Bond to Candidate Reinforcements

Rods of candidate materials 3/16" in diameter were embedded to a 1 1/2" depth in uncured propellant. The propellant was cured 7 days at 135°F and the rods were extracted axially from the propellant at ambient temperature. The force required to extract the rods was measured with a Tinius-Olsen eletomatic universal testing machine. The reported results are the average of two samples of each material tested.

MATERIAL	BOND STRENGTH
Cellulose Acetate Butynate	26.6 ± 5 psi
Delrin	13.6 ± 2 psi
Lexan	49.6 ± 2 psi
Lucite	35.0 ± 10 psi
Nylon, Zyten 101	57.7 ± 1 psi
Penton	22.1 ± 1 psi
Phenolic - linen filled	35.0 ± 1 psi
Polyester - glass filled	41.3 ± 7 psi

MATERIAL	BOND STRENGTH
Polypropylene	13.5 ± 8 psi
Polystyrene, crosslinked	62.7 ± 5 psi
Polyvinyl Chloride	46.5 ± 7 psi
Teflon	5.3 ± 5 psi

Polystyrene, Nylon and Lexan were the outstanding performers in terms of propellant bond strength.

c. Compatibility of Candidate Materials with Propellant

The effect of candidate materials in contact with propellant on the autoignition temperatures of the propellant is a measure of their compatibility. The test sample consists of a .1 gram of dust sanded from the candidate material embedded in .2 grams of propellant. It is wrapped in aluminum foil and placed in a copper autoignition block. The temperature is raised at a constant rate until the sample ignites. The following results were obtained.

	Auto Ignition	
Sample	Time	Temperature
ANP-2865 (Control)	17 min 20 sec	482°F
ANP-2865 + ABS	18 min 45 sec	500°F
ANP-2865 + Delrin	19 min 45 sec	489°F
ANP-2865 + Epoxy Polyamid	20 min 42 sec	500°F
ANP-2865 + Lexan	19 min 00 sec	486°F
ANP-2865 + Lucite	18 min 20 sec	484°F
ANP-2865 + Nylon	22 min 38 sec	496°F
ANP-2865 + Penton	22 min 00 sec	544°F
ANP-2865 + Polypropylene	19 min 35 sec	486°F
ANP-2865 + Polystyrene, crosslinked	18 min 28 sec	494°F
ANP-2865 + Polyvinyl Chloride	23 min 22 sec	500°F
ANP-2865 + Teflon	24 min 10 sec	512°F

These results indicate that none of the materials tested would present a safety or ballistics problem by lowering the autoignition temperature of the propellant appreciably.

Nylon was selected as the most promising reinforcing material to be used in the form of embedded rods because of its similar coefficient of thermal expansion with the propellant, the relatively good propellant to nylon bond, its reasonably high modulus of elasticity (200,000 psi), and its availability.

Crosslinked polystyrene was selected as the second material to be used because of its excellent propellant bond and high modulus of elasticity (300,000 psi). Its lower coefficient of thermal expansion will allow evaluation of mismatch between matrix and reinforcement in this parameter.

2. Fibrous Materials

Burlington Industrial Fabric's style 9809 rayon scrim and style 9560 nylon scrin were selected to be used as embedded mesh reinforcing materials. These fabrics have the following characteristics:

Fabric	Weave	Slip Set	Strands per inch	Thickness	Tensile lbs/in	Yarns
B-9809	Leno	Vultex	4	.010	15	Rayon W-300
B-9560	Plain	Green 576	16	.008	70	Nylon 210T330

Flow of uncured propellant through these meshes was observed in the following manner. The bottom of a casting carton was removed and a piece of the fabric being evaluated was stretched over the opening and taped into place. The cup was filled with two inches of propellant and the flow through the fabric was observed.

All of the propellant flowed through the B-9809 indicating that it would be possible to cast a grain by filling on only one side of this fabric. The B-9560 restrained the flow of propellant to the extent that only 1/16" thick layer of propellant was formed on the opposite side of the fabric when the propellant was fully cured. This indicates that propellant may require casting on both sides of this fabric.

3. Combustible Materials

A combustible material was developed to provide a reinforcement that would be consumed during motor firing at the same rate as propellant, and would contribute to the impulse of the motor.

The material is an epoxy polyamid resin system loaded with a ground[1] ammonium perchlorate oxidizer and a copper chromite burning rate catalyst. The formulation selected as the combustible reinforcing material for further evaluation is designated EP-12-5 3C. Curves showing the effect of copper chromite and ammonium perchlorate on the burning rate of the material are shown in Figure 4. Each data point represents the average of four strands burned at 80°F and 1000 psi in an ARC strand burner.

C. Behavior of Embedded Reinforcements in Polyurethane Propellant

Mechanical

Four types of tests were conducted to evaluate the mechanical performance of nylon and polystyrene rods, plates, and meshes embedded in a typical polyurethane propellant (ANP-2865 HG Mod I).

1. Bond Test

The bond test specimen designed to determine the bond strength between the propellant and reinforcement quantitatively is shown in Figure 5. Test samples were prepared by casting propellant around a reinforcing rod extending a prescribed distance into an acrylic mold. The embedded ends of the rods were domed to form a hemisphere with a radius equal to that of the rod in order to minimize stress concentrations at the end of the rod. The propellant was bonded to the internal walls of the mold to provide an infinite boundry condition.

The force required to extract the rods was measured with a Tinius-Olsen 12,000 pound Electromatic Universal Testing Machine at a

1 Average particle size 21.4 microns

crosshead separation rate of 1"/min. Results showed that the only true bond failure occurred between the energetic reinforcing material and propellant. In the other cases, a full coat of propellant remained with the extracted rod, demonstrating that the bond strength is greater than the strength of the propellant at 80°F and 120°F. Neither the rod geometry nor embedded depth affect this value appreciably.

2. Bearing Test Models

The bearing test model shown in Figure 6a was designed to determine the extent of viscoelastic propellant flow around embedded nylon reinforcement rods under loadings normal to the rod. This type of sample was prepared by casting ANP-2865HG polyurethane propellant around the reinforcing in a two piece mold. The mold was removed and the surface of the propellant was coated with silicone oil to reduce friction. The propellant was replaced in the acrylic mold, and ends of the reinforcing rods were secured to provide the sole support of the sample. A load distributing plug was placed in the top of the sample and dead weights were applied. Deflection of the top surface was measured with a Federal Model C815 dial gage.

Top surface displacement as a function of time was assumed to be a function of propellant flow past the rod. An unreinforced control was tested concurrently to establish the extent of propellant compression and distortion in the propellant column. The displacement of the control subtracted from the displacement in the specimens supported solely by the reinforcement should be equal to propellant flow past the reinforcement.

Results from samples tested at 120°F under various loading conditions are shown in Figure 7. These results indicate propellant movement around the 1/8" or 1/4" diameter rods is very low when stressed with forces less than 16 psi. The maximum bearing stress predicted for 1/2" diameter rods in a Polaris grain or horizontal storage is 5.4 psi[1]. By extreme extrapolation of the 8 psi curve containing a 1/4" diameter rod, we might

1. Bearing stress was assumed to be that generated by the total weight of the star point resting on a longitudinal rod at its center of gravity.

predict less than five thousandths of an inch total deflection of the star point in the vicinity of the embedded rod after two years storage at 120°F.

These values are of such low magnitude that propellant movements past embedded reinforcement rods due to loads normal to their axis are not expected to be a problem in grains with properly designed reinforcement structures.

3. Tear Test Models

The model for demonstration of the effectiveness of embedded meshes to reduce dewetting and crack formation at the fillets is shown in Figure 6b. Test samples were prepared by casting the propellant in a mold containing a strip of fabric held in the desired position. The notch in the model is designed to simulate the fillet in a grain with a star perforation. The distance between the mesh and the base of the fillet was varied from 0" to 1/4". Two candidate reinforcing meshes were evaluated.

The force required to initiate dewetting and crack development[1] and to cause ultimate failure of the test samples was determined with a Tinius-Olsen Electromatic Universal Testing Machine at a crosshead separation rate of .05"/min. Tests were conducted at 80°F.

Results indicate that the effectiveness of the reinforcing mesh for retarding dewetting and crack development decays rapidly as the fabric is removed from the base of the fillet, but that the placement of the mesh does not change the enhancement of ultimate strength of the sample. The increment in force required to induce high local strains at the fillet, as indicated by dewetting, or to cause complete failure, is roughly equal to the strength of the fabric, when the fabric is placed directly at the fillet.

No cracks developed in the samples in which mesh was located at the base of the fillet until sufficient force was generated to break the fabric. In those cases in which the reinforcement was buried within

1. Dewetting and crack development was determined visually.

the propellant, a crack developed and propagated to the fabric, at which point it was diverted along the fabric until a force sufficiently strong to break the fabric was developed.

The use of high-strength fabric for this application is therefore indicated. Relative effectiveness of the fabric will be greatest for low strength propellants, or at elevated temperatures. It may be postulated that this type of reinforcement becomes relatively less effective at low temperatures at which propellant modulus and strength increase markedly. Propagation of a crack, if it forms, may be diverted to a circumferential direction rather than a radial one in the latter instance. Experiments to determine propellant behavior at other temperatures are recommended.

From these tests it is concluded that reinforcement in the form of embedded meshes is effective in preventing the development of cracks by restricting localized strain at points where stress concentrations are likely to occur.

4. Flexure Test

Beams in simple flexure generate shear and bearing forces between the reinforcement and the elastic analysis of this configuration is well known. For these reasons, considerable emphasis was placed on experiments with rectangular reinforced propellant beams in simple flexure.

a. Beams Stressed to Failure at Constant Deflection Rate, and Relaxation at Constant Deflection

An unreinforced control beam, and beams reinforced with eight 1/8" diameter Zyten 101 nylon and crosslinked polystyrene rods cast from the same batch of propellant were stressed to failure as center loaded beams with a Tinius-Olsen Testing Machine. The testing speed or deflection rate in all cases was .1"/min. Tests were conducted at 80°F. Propellant hardness was the same in the three beams as determined by initial and one minute readings of a Shore A Durometer. Stress versus deflection curves for the three beams are shown in Figure 8; the discontinuities are due to the relaxation of load at the points where travel of the crosshead was halted.

At 19, 37, and 82 pound loads (corresponding to 1/2", 1", and 2 - 1/2" deflections of the control beam) the crosshead movement was stopped for ten minutes, and relaxation of the beam, as reflected in reduction of load in the top crosshead, was recorded. The magnitude of relaxation was approximately the same in both the unreinforced and reinforced cases. However, the deflection of the reinforced beams was about one-eighth that of the unreinforced beam at the 19 and 37 pound load level.

Results of these tests provide two interesting empirical conclusions regarding relaxation of loads in unreinforced and reinforced beams maintained at constant deflection. These results may be stated:

1. The rate of relaxation of load in reinforced and unreinforced viscoelastic beams is equal when the beams are subjected to deflection under equal loading, and subsequently maintained at this deflection.

2. The relative rate of relaxation of load in reinforced beams is lower than that in unreinforced beams maintained at the same deflection.

Data at selected time points supporting these statements are presented in Table I. It may be seen that relaxation of all beams subjected to 19 and 36 pounds (nominal) loading were substantially equal. However, when beams subjected to center deflections of 0.5" and 1.0" are compared, the force on the deflecting crosshead decays relatively more rapidly in the case of the unreinforced beam.

Notwithstanding the numerous assumptions at variance with actual test conditions, the results of the above experiments were analyzed using the conventional elastic beam formula, assuming that a fictitious modulus, E^t, describes the propellant properties at any time t.

Moduli of propellant was calculated from the control beam data shown in Figure 8 according to the formula:

$$E^t = \frac{Wl^3}{48fI} + \frac{5W'l^3}{348fI}$$

where W = center load
W' = wt of beam (5.2 lbs)
l = span (17")
f = center deflection
I = moment of inertia = 1/12 x 2-1/4 x 1-3/4^3 = 3.03 in^4
E^t = modulus at time t

Using calculated moduli of propellant at an equivalent center load and time, and assuming equal effectiveness of compression and tension reinforcement members, moduli of reinforcements were then determined by the operation:

$$E_r^t = \frac{l^3}{fI_r} = \left(\frac{W}{48} + \frac{5W'}{384}\right) - \frac{E_p I_p}{I_r}$$

where subscripts p and r refer to propellant and reinforcement.

Results of these calculations are shown in Table II. It may be seen that calculated moduli of reinforcement in the beam are somewhat lower than the range of measured values. Using this method of calculation, both propellant and reinforcements display a decrease in moduli with time. It would be desirable to repeat these experiments under more controlled conditions, and to perform creep tests in both tension and compression with the reinforcement itself to correlate with calculated values. An analysis based on viscoelastic rather than elastic behavior would be of great value for understanding the behavior of reinforced propellant beams under relaxation conditions.

The fact that low values of reinforcement moduli were obtained in these tests suggests that either the reinforcement in compression is ineffective or the propellant-reinforcement bond creeps. Tests to determine behavior of reinforcement in beams with selected rod placement (i.e., either tension or compression members), could easily be devised to shed further light on the performance of such systems.

b. Beams Stressed by Constant Load (Creep)

One of the most significant factors determining feasibility of reinforcing solid propellant grains by embedded members is the extent of decay of forces transferred to the reinforcement as a function of time, and the extent to which propellant flow is prevented thereby.

1. Loading Conditions

Beams of reinforced and unreinforced propellant were placed in two point suspension and center deflection due to their own weight was determined as a function of time. After fifteen days at 120°F under these conditions, a center-load of four pounds was applied. The recovery rate of test beams, subjected to a four pound center load for fourteen days, was measured for an eighteen hour period when 73 per cent of the original four pound load was removed. This measurement was conducted immediately prior to loading the beams with the eight pound weights. Outer fiber stresses for these conditions were:

Const. load due to weight of beam	5.00 psi
Const. load due to weight of beam plus 4 lb. center load	12.68 psi
Const. load due to weight of beam plus 8 lb. center load	20.36 psi

2. Test Environment

The tests were conducted in a surveillance facility capable of storing fifty pounds of propellant under controlled temperature and humidity. A 10 x 10 foot cinder block room was insulated with an aluminum foil fiberglass barrier, and a l room interior surfaces were coated with an epoxy paint to reduce moisture transmission. An explosion-proof forced air heater was installed and set to maintain a room temperature of 12 ± .75°F. A Dryomatic Model 50 dehumidifier maintained a 10 ± 5 per cent relative humidity throughout the test area.

3. Beam Design

A total of eight propellant beams 1-3/4" x 2-3/4" x 18" were tested. Distance between supports was 17". A 1" wide strip of metal was positioned between the beam and all external load points. Beams are described below:

See table next page.

Beam No	Batch No	Propellant Hardness[1]	Type Reinforcement	Reinforcement % by Volume	Reinforcement Position A[2]	Reinforcement Position B[3]
1	13	71	None	0%	-	-
2	13	71	8-Zyten 101 nylon rods, 1/8" dia.	2%	1-1/8"	1/2"
3	14	70	2-Zytel 101 nylon rods, 1/4" dia.	2%	1-1/8"	-
4	13	71	8-Q200.5 Polystyrene rods, 1/8" dia.	2%	1-1/8"	1/2"
5	17	64	None	0%	-	-
6	17	65	8-Energetic rods,[4] 1/8" dia.	2%	1-1/8"	1/2"
7	17	63	60 strands, Zytel 101 nylon, mono-filament, 1/32" dia.	1%	15/16" 1-1/8" 1-5/16"	5/32"
8	18	71	8-Zytel 101 nylon rods, 1/8" dia.[5]	2%	1-1/8"	1/2"

1. Shore A durometer; 1 min. reading at 120°F.
2. Distance between center line of row of reinforcement and neutral axis.
3. Distance between centers of reinforcement in one row.
4. EP-12-55C.
5. Heated 24 hours at 215°F to reduce moisture.

4. Test Results

Deflection of test beams as a function of time and load at 120°F are shown in Figures 9 and 10. These results substantiate the preliminary results presented in the previous report that initial deflection and rate of creep is retarded significantly by embedded reinforcements. Nylon monofilament and crosslinked polystyrene were most effective, as would be predicted from their relatively high modulus of elasticity and capability of effecting a strong propellant bond. There is no apparent difference in the 1/8" and 1/4" diameter nylon reinforcement when placed in an equivalent moment of inertia in the beams. Drying the nylon rods prior to embeddment improves their performance slightly. The reinforcement derived from the energetic reinforcement decayed rapidly after ten minutes, indicating a probable bond failure.

One objective of the study of reinforced beams is to be able to predict increased service life for motors which fail by a slump mechanism. For instance, deflection after twenty days in the reinforced beam is only 50 per cent of the initial deflection of the unreinforced beam under an eight pound center load as shown in Figure 9. Projected at this creep rate and stress level, it is predicted that deflection after three years of the nylon rod reinforced beam would be only 60 per cent of the immediate deflection of the unreinforced beam. All reinforced beams, however, did continue to creep, although the creep rate was slower than in the case of the unreinforced control beams.

From the deflection versus time curves in Figures 9 and 10, the change in apparent modulus versus time has been computed for the propellant in the two unreinforced controls, and for the reinforcing materials positioned in beams subjected to the uniformly loaded beam by its own weight plus an eight pound center load at 120°F. Equations used for these calculations are:

$$E_p = \frac{Wl^3}{48fI} + \frac{5W'l^3}{384fI}$$

$$E_r = \frac{l^3}{I_r}\left[\left(\frac{1}{f} - \frac{1}{f_c}\right)\left(\frac{W}{48} + \frac{5W}{384}\right)\right]$$

E_p = propellant modulus — l = span length

E_r = reinforcement modulus — f = deflection

W = load — I = moment of inertia

These results are shown in Figure 11. The change in apparent modulus versus time may be a result of bond degradation or creep in the reinforcement itself. The energetic reinforcing material is believed to fail by the bond degradation mechanism whereas this is not believed to be a significant factor in the nylon and polystyrene reinforcements. The change in apparent modulus versus time of these materials is interpreted to be a result of creep in the material itself, and for the nylon, approximates reported values for creep rates.

Modulus of elasticity was determined at 80°F for nylon in the form of rods as 278,000 psi, for nylon in the form of monofilament as 396,000 psi, and for polystyrene in the form of rods as 530,000 psi. Modulus of the monofilament is 41 per cent greater than the nylon rod, and polystyrene is 90 per cent greater than the nylon rod. The apparent modulus of both polystyrene and nylon monofilament was of the order of 80 per cent greater than the nylon rod, as shown in Figure 11. The predicted and observed values in this case are believed to be in reasonably good agreement considering the many approximations and assumptions inherent in the elastic beam analysis that are invalid for the materials at hand.

5. Significance of Flexure Tests

In these experiments flexure tests have been conducted under the following conditions:

a. constant rate of deflection
b. relaxation at constant deflection
c. creep under uniform loading
d. creep under center loading
e. recovery after creep under center loading

It is possible to relate the time dependency of the beams under different loading conditions by the equations:[1]

Constant rate and stress relaxation

$$dS/de = (\partial S/\partial e)_t + (\partial S/\partial t)_e \; (dt/de)$$

S = Stress t = Time
e = Strain L = Load

and

Creep

$$de/dt = (\partial e/\partial L)_t \; (dL/dt) + (\partial e/\partial t)_L$$

1. Wiegand, J. H.; Recent Advances in Mechanical Properties Evaluation of Solid Propellants. ARS Journal, 1962, Vol. 32, pp. 525.

Correlation of the data by these equations would do much to aid the ability to predict performance of reinforced propellant under other conditions.

The behavior of viscoelastic, unreinforced beams could be analyzed according to the solution of Kempner[1] who predicts that a beam in flexure will exhibit time dependency proportional to the time dependency of the material in tension, or according to the solution of Baltrukonis for beam-columns.

Correlation of the data according to conventional elastic formulae on the basis of an apparent modulus of both propellant and reinforcement seems to give values in reasonable agreement with those reported elsewhere.[2, 3, 4] One case of failure of a reinforcement to perform satisfactorily was observed, and was attributed to failure of the bond between the reinforcement and the propellant. Results of the tests in which beams were subjected to loads for sixty days were extrapolated to predict performance after serveral years, assuming that the bonds would remain intact. This assumption may or may not prove to be valid, considering the experience with liner to propellant and to motor case bonds, which fail under circumstances not necessarily predicted by relatively short-term tests. Establishment of the stress versus time-to-failure relation of the bond between reinforcement and propellant would be required. Were bonds to fail in actual motors, however, the possibility of ballistic failures is apparent. Firing test motors in which such bond failures are built in is required to determine this factor.

c. Ballistic

1. Test Motor Firings

A vital requirement for any embedded reinforcement is that it be compatible from a ballistics point of view with the propellant in actual motor firings. Two types of grains were designed and fabricated

1. Kempner, J; Creep, Bending and Buckling of Linearly Viscoelastic Columns. NACA TN3136, January 1954, pp. 7.
2. For rates of relaxation and creep of polyurethane propellant see "Solid Propellant Aging Studies", Stanford Research Institute, 4th QPR, Aug. 9, 1961, pp 12.
3. Nylon monofilament see "Stress Relaxation," H. Morgan, pp 83, Vol I, "High Speed Testing," Interscience Publishers, Inc., New York, 1960.
4. Private communication - E. I. DuPont and Company.

to demonstrate the effect of various embedded reinforcing materials on ballistic performance as compared to unreinforced control grains.

2. End Burning Motors

Two end burning grains were fabricated to simulate the relatively long burning times of large grains. These were reinforced with 1/8" and 1/4" diameter nylon rods placed parallel and perpendicular to the burning face of the grain as shown in Figure 12a. The reinforcement replaced two per cent of the propellant in the grains.

These grains and an unreinforced control grain of identical dimensions were X-rayed and found suitable for firing. One control and one reinforced grain were fired at 70°F. Pressure versus time traces are shown in Figure 13a. The action times were identical (17.5 sec) indicating that nylon in the form of rods does not affect the burning rate of the grain. The pressure-time curves were virtually identical to the last three seconds of action time where the pressure in the reinforced firing dropped from 600 psi to 525 psi and returned to 600 psi in 1.5 seconds. This dip corresponds to the location of a 1/4" diameter rod parallel to the burning face. On the basis of reduced propellant burning area due to substitution of nylon for propellant in this region, an 85 psi reduction in pressure was predicted.

Remains from the reinforced grain showed that the nylon rods were entirely consumed after approximately three seconds exposure to the hot gasses in the chamber. The longitudinal rods were consumed to within 3/4 of the headplate and the rod parallel to the burning face. was 2/3 consumed after two seconds of exposure. These results indicate that nylon in the form of rods may be used as embedded reinforcements without altering the ballistic performance of the grain significantly.

3. Core Burning Motors

An internal burning grain designed as a scale-down of the Polaris first stage configuration was reinforced as shown in Figure 12b. This network included rods and plates of nylon (Zytel 101), polystyrene (Q200.5), and energetic (EP-12-53C) reinforcing materials and a two layer fabric (B-9809) sleeve wrapped around the mandrel. The reinforcement in this case replaced two per cent of the volume of the grain. Two grains of this configuration and an unreinforced control grain of identical dimensions were X-rayed and found suitable for firing.

The reinforced grain was bonded to a specially designed headplate which contained a 4" diameter quartz window to allow photographic observation of the flame front in the vicinity of the embedded reinforcements. A control and a reinforced grain were fired at 70°F to supply burning rate and pressure-time data. The results are shown in Figure 13b. Burning in the vicinity of the reinforcements was pictorially recorded with a Fastex camera (3,500 frames per second) on Kodak Ektachrome ERB color film. The progression of the flame around all reinforcements in this motor was normal.

The firing curves were comparable and both traces were smooth without evidence of overpressure at any point. All of the reinforcements were completely consumed during the action time of the motor except the crosslinked polystyrene. The 1/8" diameter polystyrene rod was exposed to the flame in the chamber for 1.6 seconds and was 90 per cent consumed. The 1/8 inch thick polystyrene plate was only exposed to the flame for 1.1 seconds and it was only 20 per cent consumed. These findings have caused a greater emphasis to be placed on nylon as the optimum reinforcing material for polyurethane propellants since it is readily burned as fuel during the operation of the motor.

D. Design of Grain Reinforcement Systems

A brief analysis was made to determine a suitable method by which a solid propellant grain of first stage Polaris dimensions might be reinforced by a cage of embedded members to prevent failure by each of the postulated mechanisms.

1. Slump on Vertical Storage

Maximum allowable strain in the reinforcing material of .1 per cent was set as the design governing factor. With this consideration in mind, nylon and crosslinked polystyrene in the form of rods anchored to the head of the motor case and extending through the entire length of the grain were utilized to support columns of propellant.

It was determined that eighteen 1/2" diameter nylon rods positioned as shown in Figure 1 would satisfy the 1 per cent allowable strain condition and support the grain on vertical storage. This amount of reinforcing material constitutes only .02 per cent of the total grain volume; the rods might be tapered to reduce this further without adversely affecting their function, and to provide improved ballistic reliability as well. It is expected that these rods will be consumed as fuel during the action time of the motor, thereby eliminating any significant loss of impulse due to inclusion of inert material in these very minor amounts.

2. Slump on Horizontal Storage

To reduce slump of the star points on horizontal storage, the stresses generated by the movement of the cantilevered propellant are reduced by attaching spacers in the form of connecting plates to the longitudinal rods described above. The relationship of the reduced deflection as a function of distance between spacers is shown in Figure 14. From this curve, we can expect that six connector plates spaced at approximately 20 inch intervals would reduce the maximum deflection at the star-point to 50 per cent of the unreinforced case.

These spacers in the form shown in Figure 1 would be 1/8" thick and 1-1/4" wide and would occupy approximately .04 per cent of the total grains volume. This volume is still considered too small to affect the ballistic performance of the grain appreciably, especially as it will be burned as fuel.

3. Liner Separation During Storage

It is believed that reinforcement as shown in Figure 1 will concurrently contribute substantially to solution of the liner separation problem during long term storage. Stress concentrations at the case bond will be reduced as the propellant slump is retarded.

4. Crack Development at Fillets

It is believed that crack development in the fillets during storage, acceleration, or initial pressurization will be reduced by the reinforcement scheme shown in Figure 1. Although this mode of failure was not considered in the present analysis, mesh reinforcement at the fillet radius is proposed for use in conjunction with the reinforcing cage.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from the results of the tests and analyses performed to date:

1. The structural integrity of solid propellant rocket grains can be markedly improved by the proper selection and placement of relatively small amounts (less than 1/2 per cent by volume) of embedded reinforcements.

2. The coefficient of thermal expansion of solid propellants can be matched with commercially available plastics having greater elastic moduli and which are burned as fuel during the operation of the motor without affecting the ballistic characteristics of the grain appreciably.

3. Rate of slump or creep of solid propellant grains can be effectively retarded by the proper selection and placement of reinforcing materials in the form of embedded rods, plates, or strands.

In light of these results, it is recommended that further work be conducted to:

1. Establish the effect of long term aging on the propellant to reinforcement bond.

2. Determine the effect of amount, type, form, and placement of reinforcements on the total delivered impulse of larger grains.

3. Investigate the effect of thermal cycling and mechanical shock on the performance of reinforced grains.

4. Study the redistribution of strain in photoelastic model grains as a function of reinforcement type and location.

5. Establish analytically, in terms of linear viscoelastic theory, the effectiveness of viscoelastic propellants reinforced with materials possessing time dependent properties.

6. Select optimum reinforcing materials for propellant systems other than polyurethane.

TABLE I

Relaxation of Center Loads
at Constant Deflection
of Simple Beams

	Initial Load-lbs.	Load After 5 Min.-lbs	Load After 10 Min.-lbs	Deflection in
Unreinforced	19.0	14.1	13.5	0.50
Nylon Reinforced	19.3	14.6	14.4	0.085
Polystyrene Reinforced	19.3	14.8	14.1	0.065
Unreinforced	36.7	30.9	29.7	1.00
Nylon Reinforced	36.7	30.6	29.6	0.16
Polystyrene Reinforced	36.8	31.0	30.0	0.13
Unreinforced	79.6	69.0	Failed[1]	2.50
Nylon Reinforced	79.5	68.8	-	0.33
Polystyrene Reinforced	79.6	69.2	67.1	0.30
Unreinforced	-	-	-	-
Nylon Reinforced	110	98	96	0,50
Polystyrene Reinforced	120	107	-	0.50
Unreinforced	-	-	-	-
Nylon Reinforced	194	178	172	1.0
Polystyrene Reinforced	217	195	-	1.0
Unreinforced	-	-	-	-
Nylon Reinforced	306	262	250	2.50
Polystyrene Reinforced	Failed[2] at 285 lbs and 1.5" deflection			

1. 1/2" crack developed at bottom center of beam in tension during relaxation period of 30 minutes.

2. Failed by cracking and expulsion of one top reinforcement rod.

TABLE II

Calculated Flexural Moduli of
Propellant and Reinforcements
in Simple Beams (See Table I)

Initial Center Load-lbs	Deflection-in	Calculated Flexural Moduli (E^t) - psi: Initial	5 Min.[1]	10 Min.[1]
Propellant				
19.0	0.50	1,480	1,190	1,110
36.7	1.00	1,330	1,140	1,090
79.6	2.50	1,110	960	-
Nylon Rods				
19.3	0.085	180,000[2]	142,000[2]	142,000[2]
36.7	0.16	164,000[2]	145,000[2]	142,000[2]
110	0.50	150,600	157,100	136,000
194	1.00	130,400	122,500	118,300

Modulus of nylon (measured) - 290,000 psi
Modulus of nylon (literature) 260,000 - 400,000 psi

Initial Center Load-lbs	Deflection-in	Initial	5 Min.[1]	10 Min.[1]
Q-Polystyrene Rods				
19.3	0.065	247,000[2]	198,000[2]	190,000[2]
36.7	0.13	215,000[2]	186,000[2]	182,000[2]
120	0.50	167,000	153,100	-
217	1.00	149,900	135,000	-

Modulus of Q-Styrene (measured) - 490,000 psi
Modulus of Q-Styrene (literature) - 400,000 - 500,000 psi

1. Time of relaxation.
2. Calculated with propellant moduli of control beam deflected 0.50", all other calculated on basis of control beam under equal deflection.

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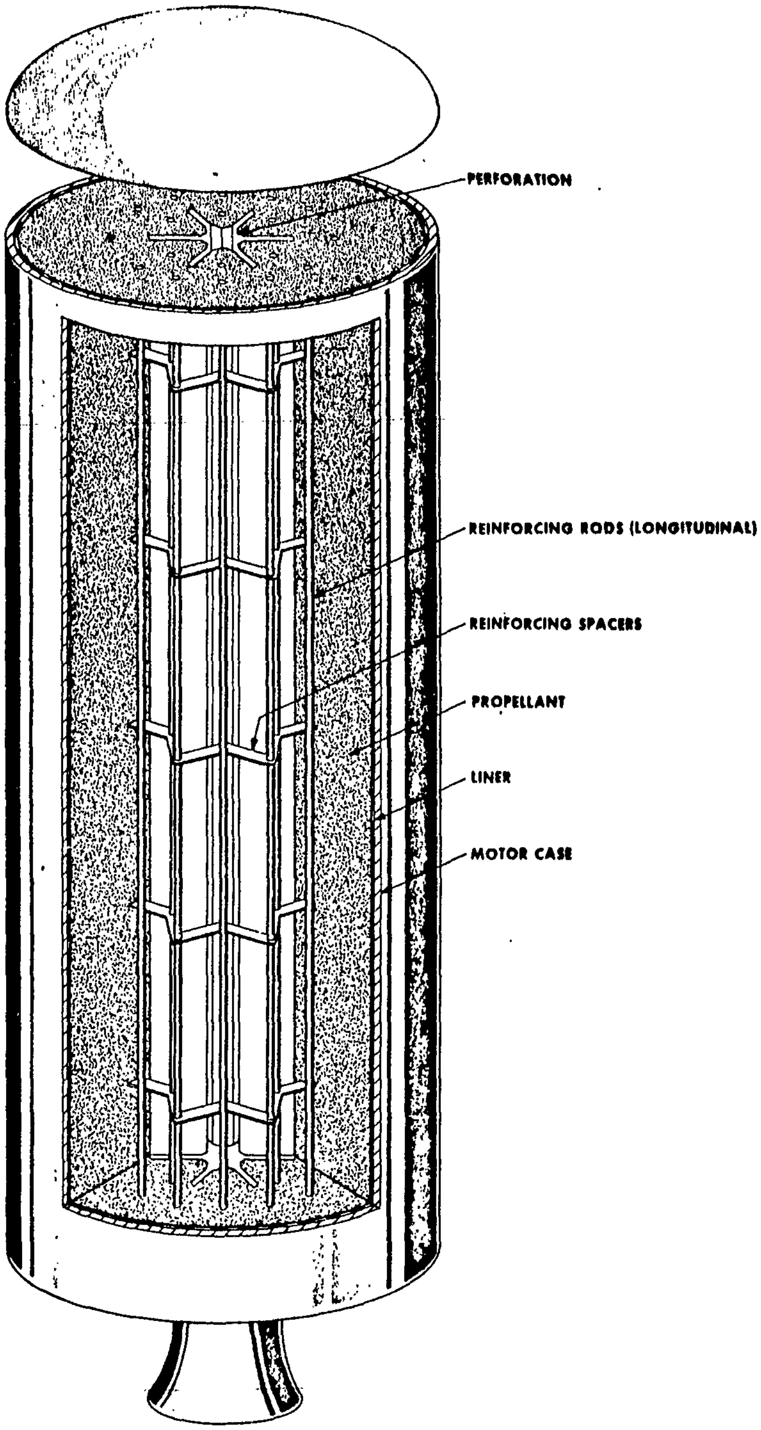

FIGURE 1 CONSUMABLE EMBEDDED REINFORCEMENT CAGE FOR GRAIN SUPPORT ON VERTICAL OR HORIZONTAL STORAGE

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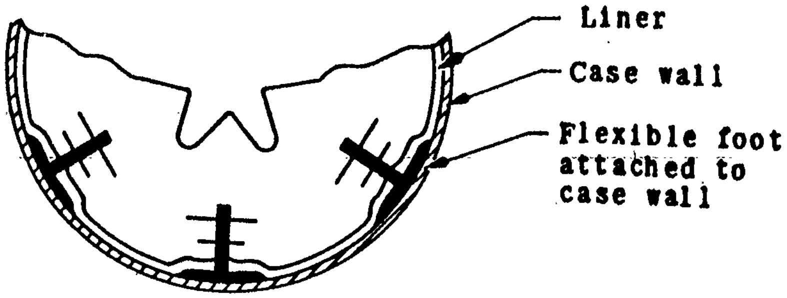


Figure 2. Reinforcement to Reduce Liner Separation.

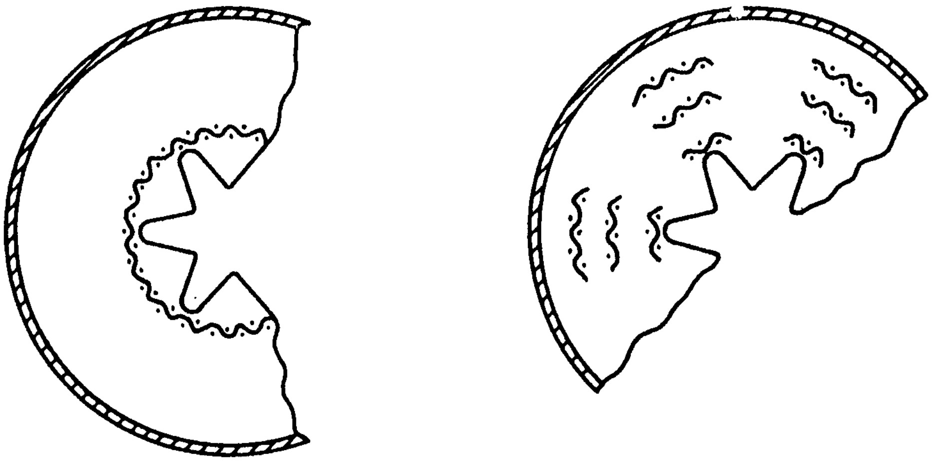


Figure 3. Reinforcement to Distribute Stress at Fillets.

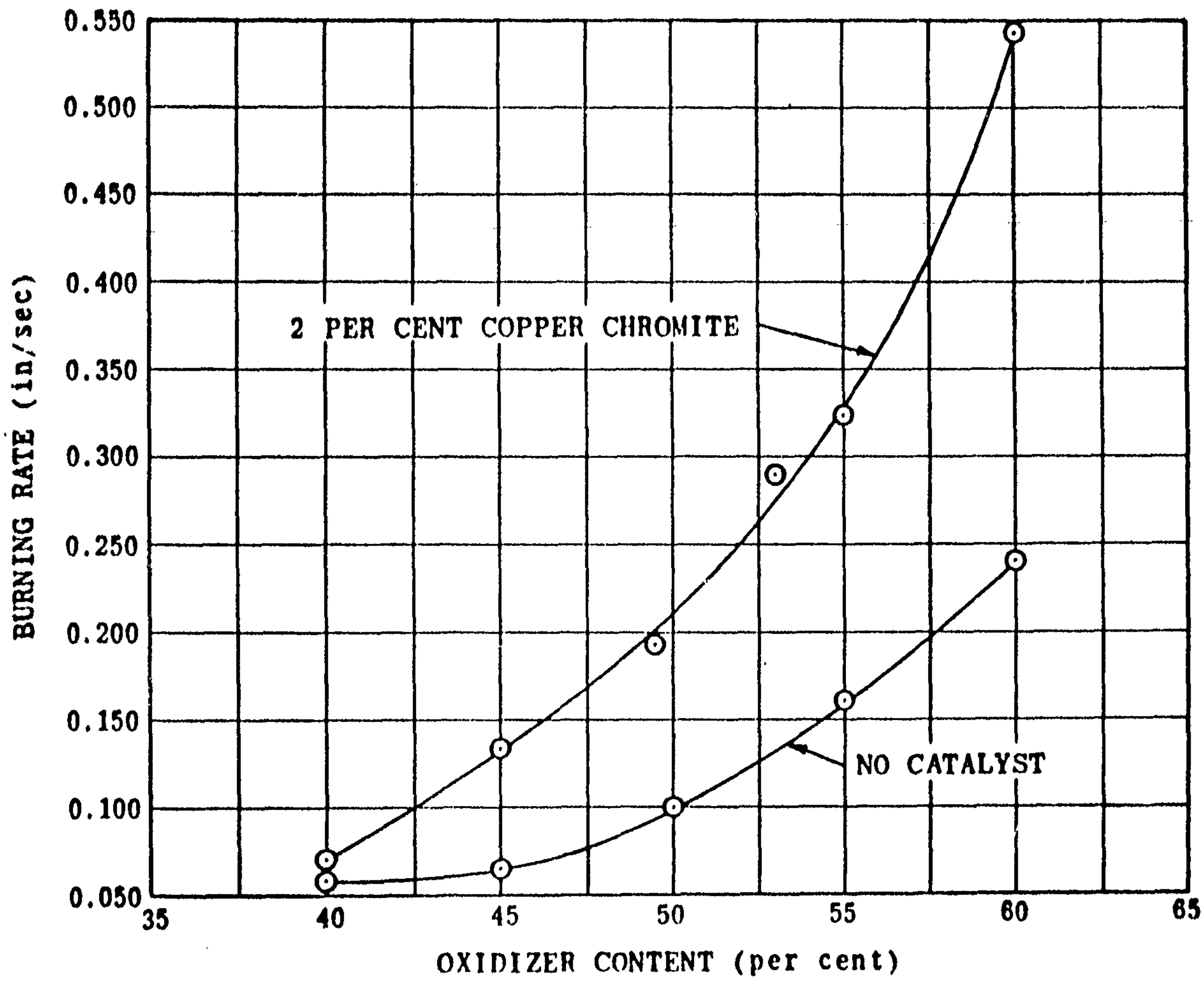


Figure 4. CURVES SHOWING EFFECT OF OXIDIZER AND CATALYST ON BURNING RATE OF COMBUSTIBLE REINFORCEMENT.

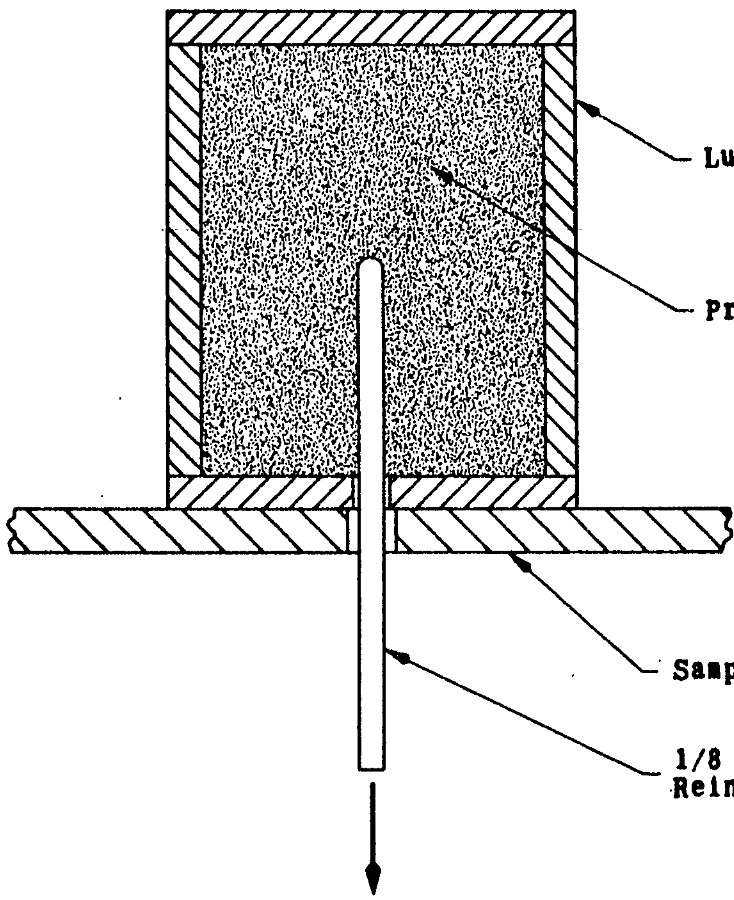


Figure 5. Bond Test Model.

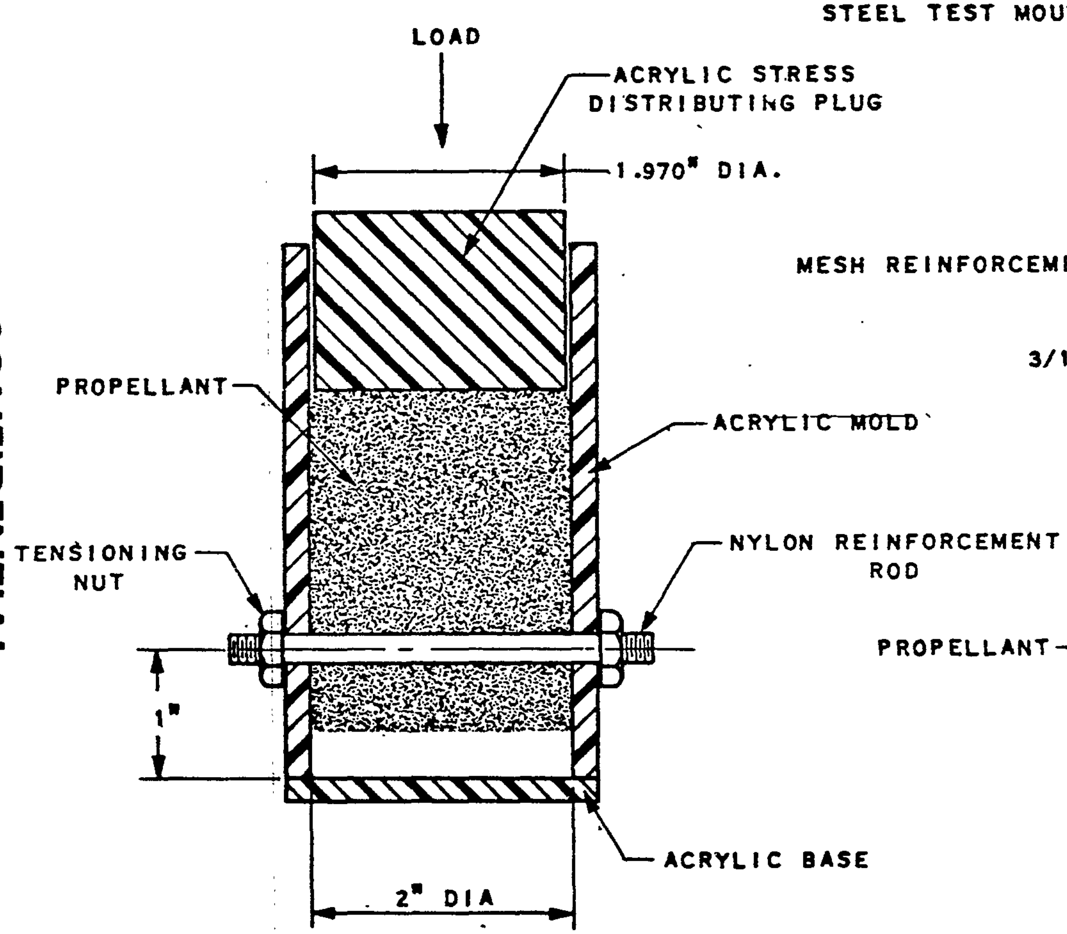


Figure 6a. Bearing Test Specimen.

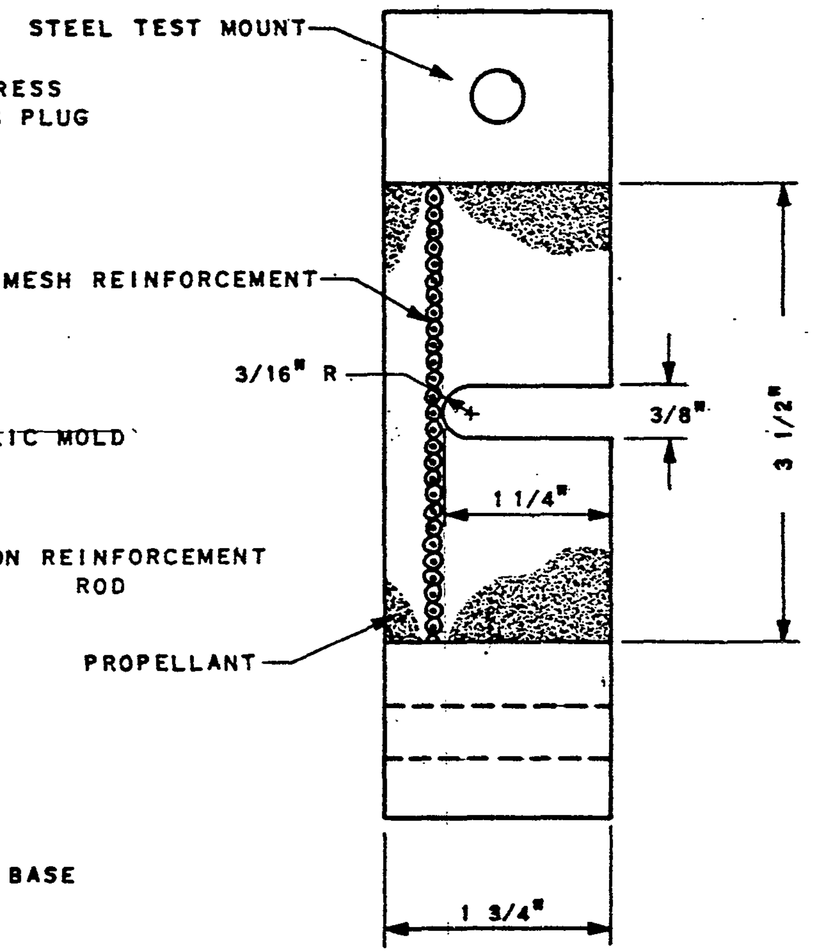
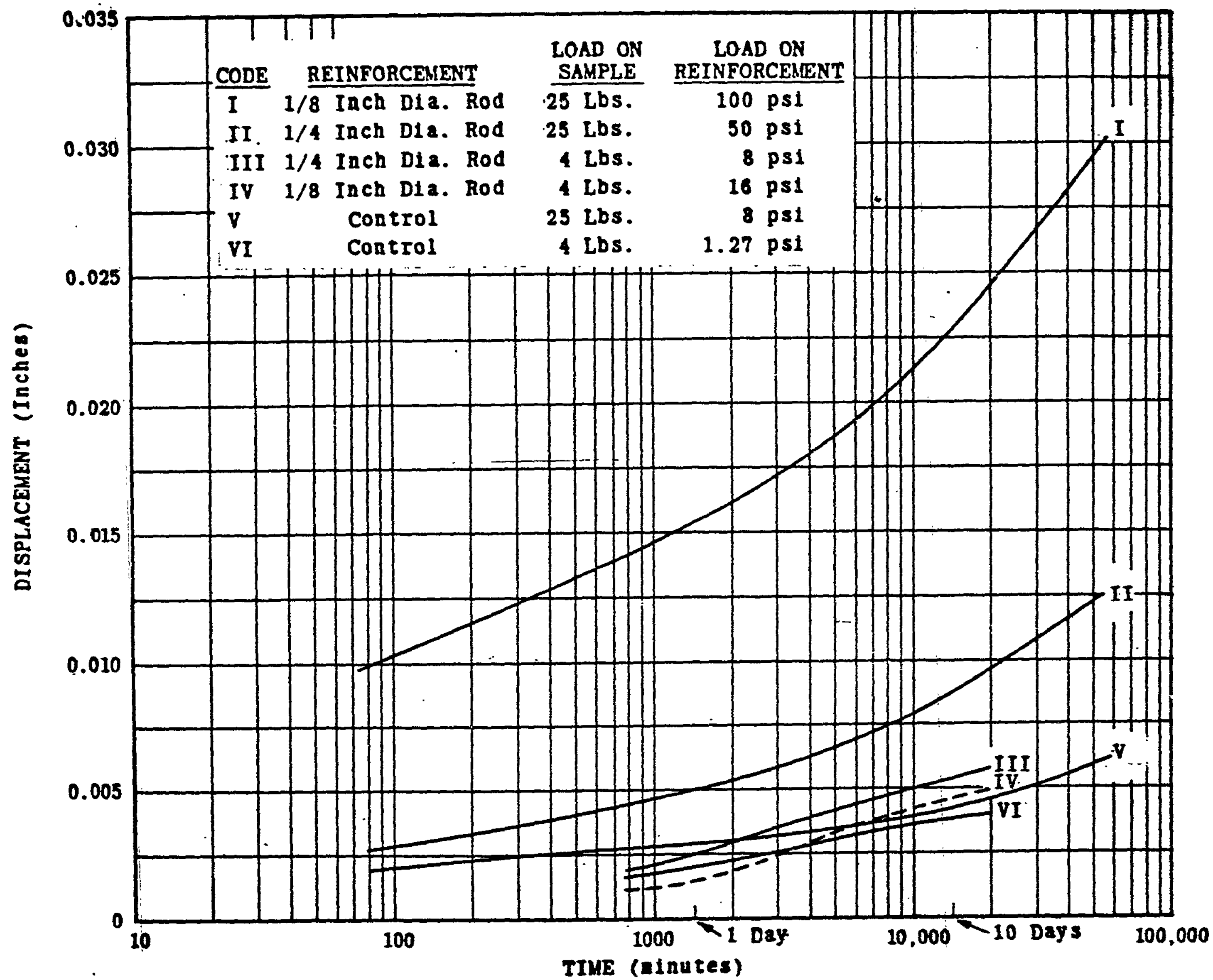


Figure 6b. Tear Test Specimen.



CODE	REINFORCEMENT	LOAD ON SAMPLE	LOAD ON REINFORCEMENT
I	1/8 Inch Dia. Rod	25 Lbs.	100 psi
II	1/4 Inch Dia. Rod	25 Lbs.	50 psi
III	1/4 Inch Dia. Rod	4 Lbs.	8 psi
IV	1/8 Inch Dia. Rod	4 Lbs.	16 psi
V	Control	25 Lbs.	8 psi
VI	Control	4 Lbs.	1.27 psi

Figure 7. DISPLACEMENT OF PROPELLANT SURFACE VERSUS TIME AS A FUNCTION OF LOAD IN BEARING TEST (TEST TEMPERATURE 120°F).

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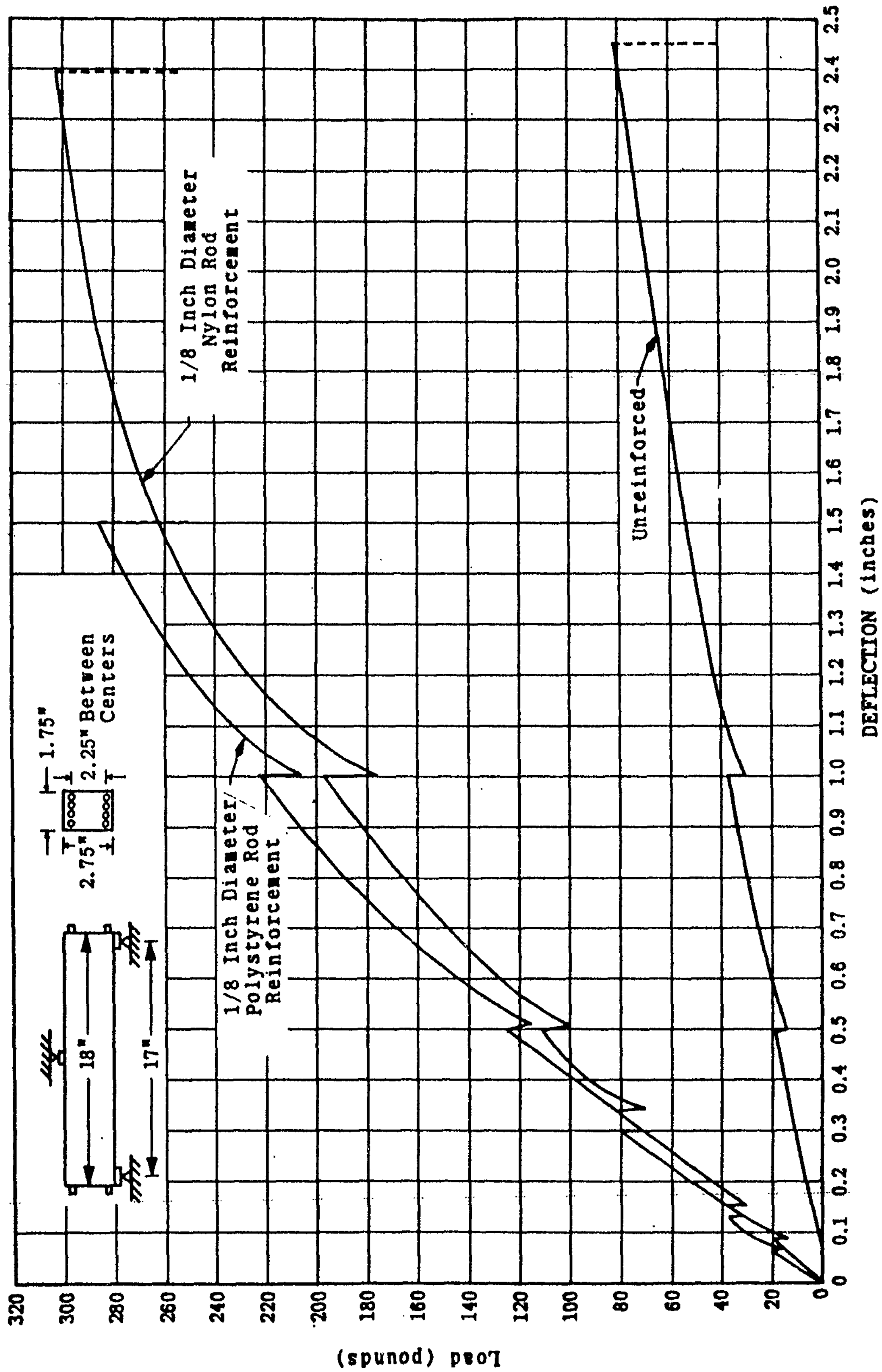

Figure 8. Deflection of Center-Loaded Beams Stressed to Failure.

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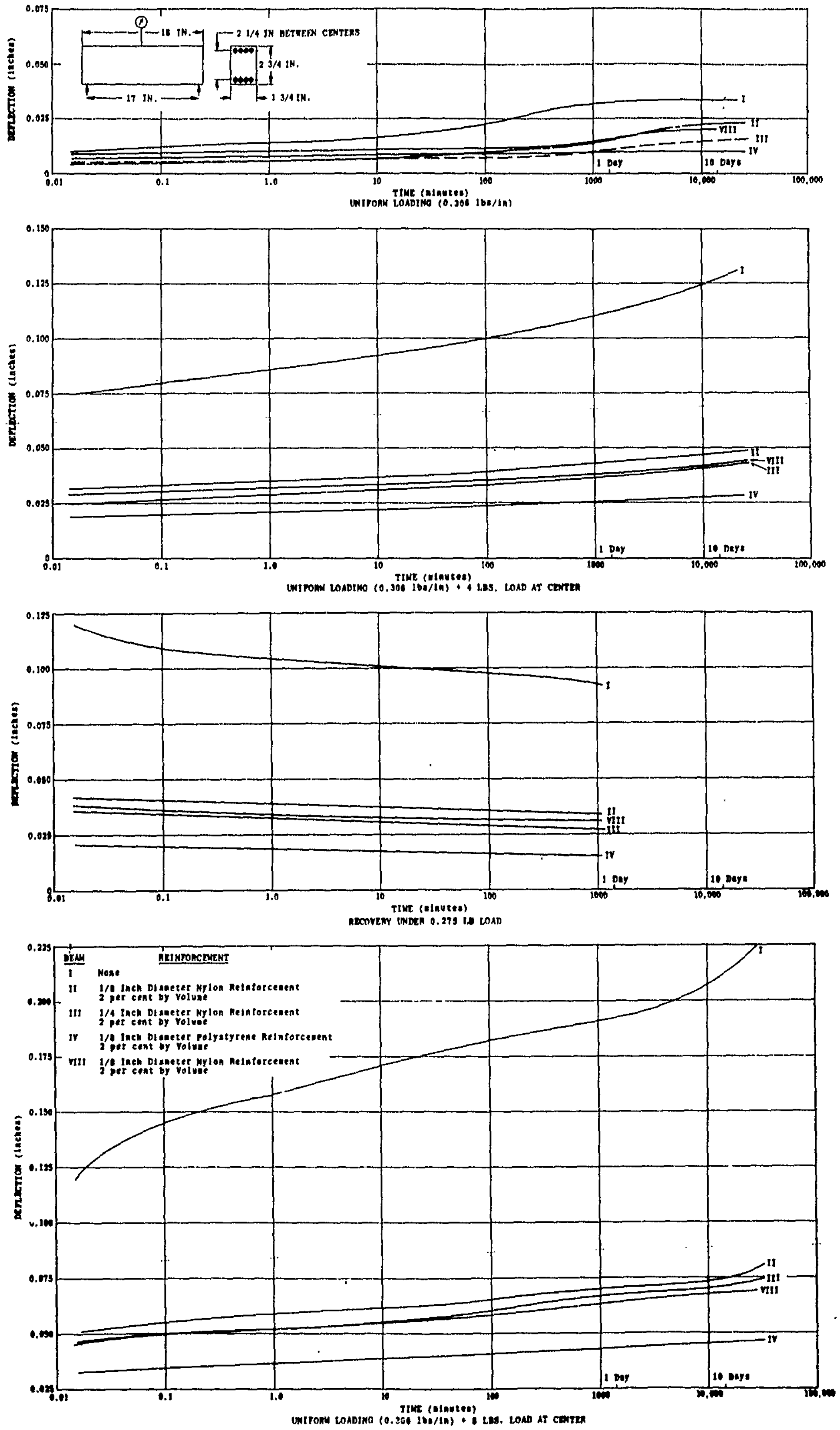

Figure 9. DEFLECTION OF BEAMS AS A FUNCTION OF TIME AT 120°F

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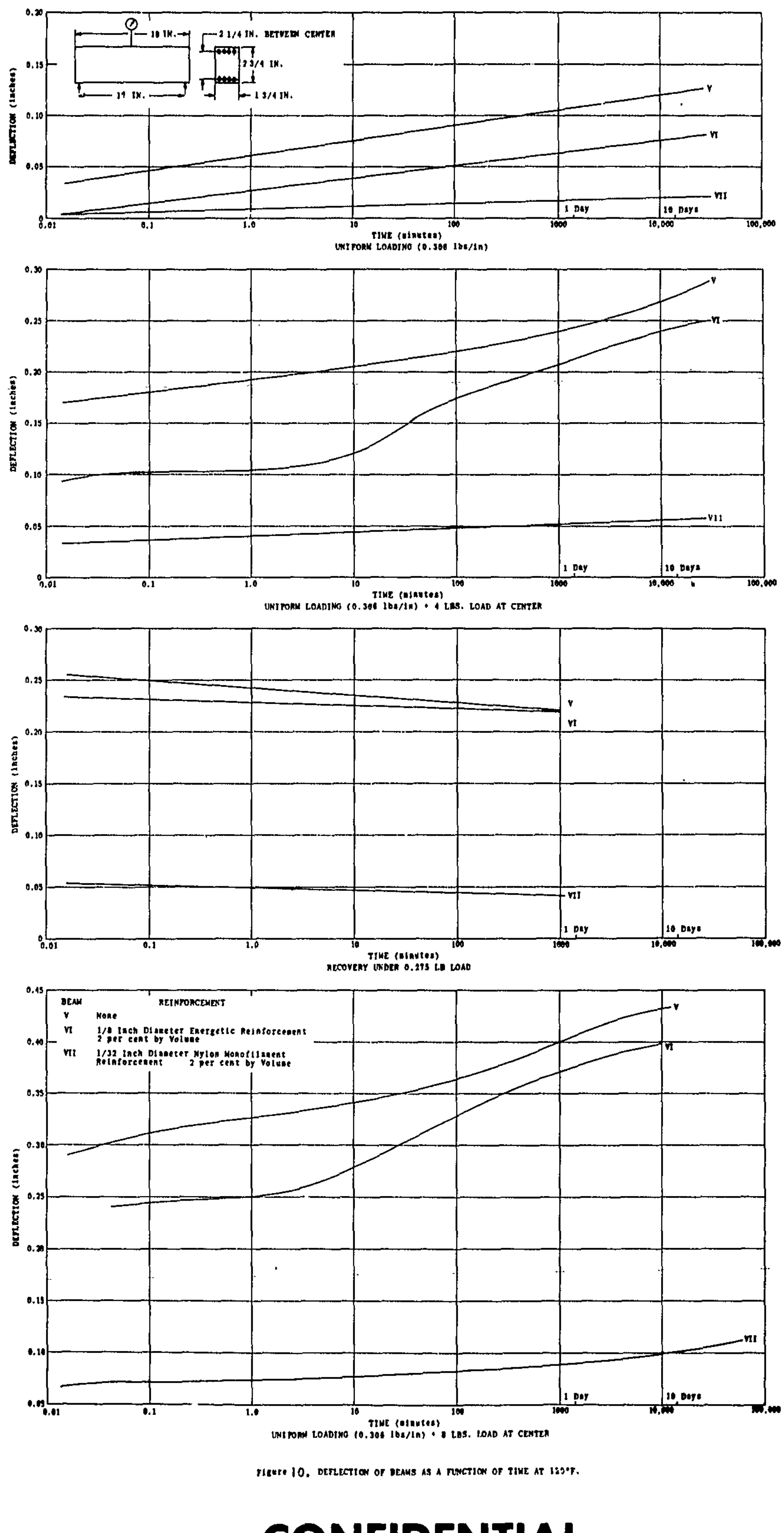

Figure 10. DEFLECTION OF BEAMS AS A FUNCTION OF TIME AT 120°F.

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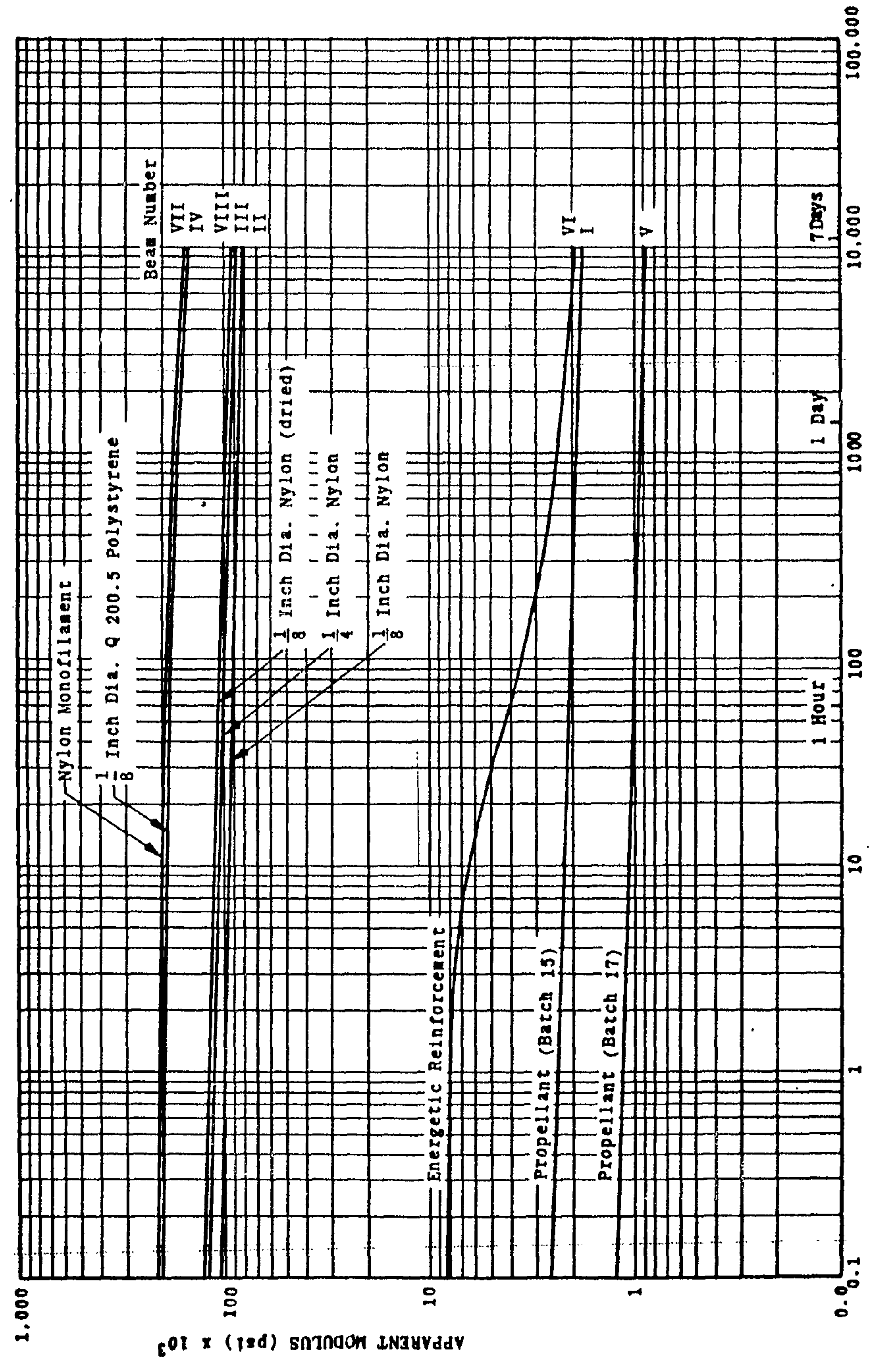

Figure 11. Change of Apparent Modulus of Propellants and Reinforcements as a Function of Time. 17 Inch Span Simple Beams Under Uniform Loading (.306 lbs/in) + 8 lb Center Load Test Temperature -120°F.

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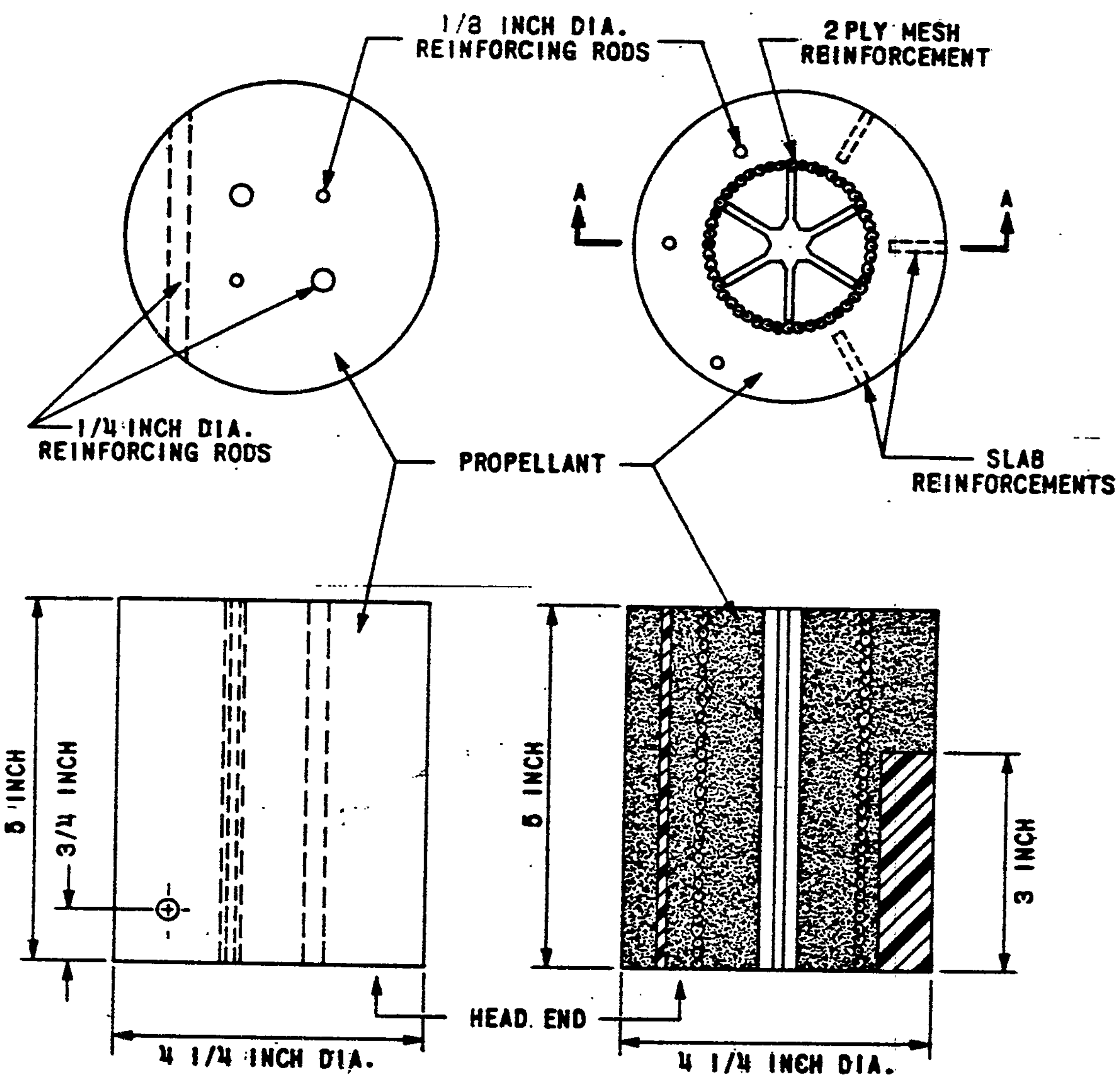

a END BURNING GRAIN

b PERFORATED GRAIN

Figure 12. Reinforced Test Grains

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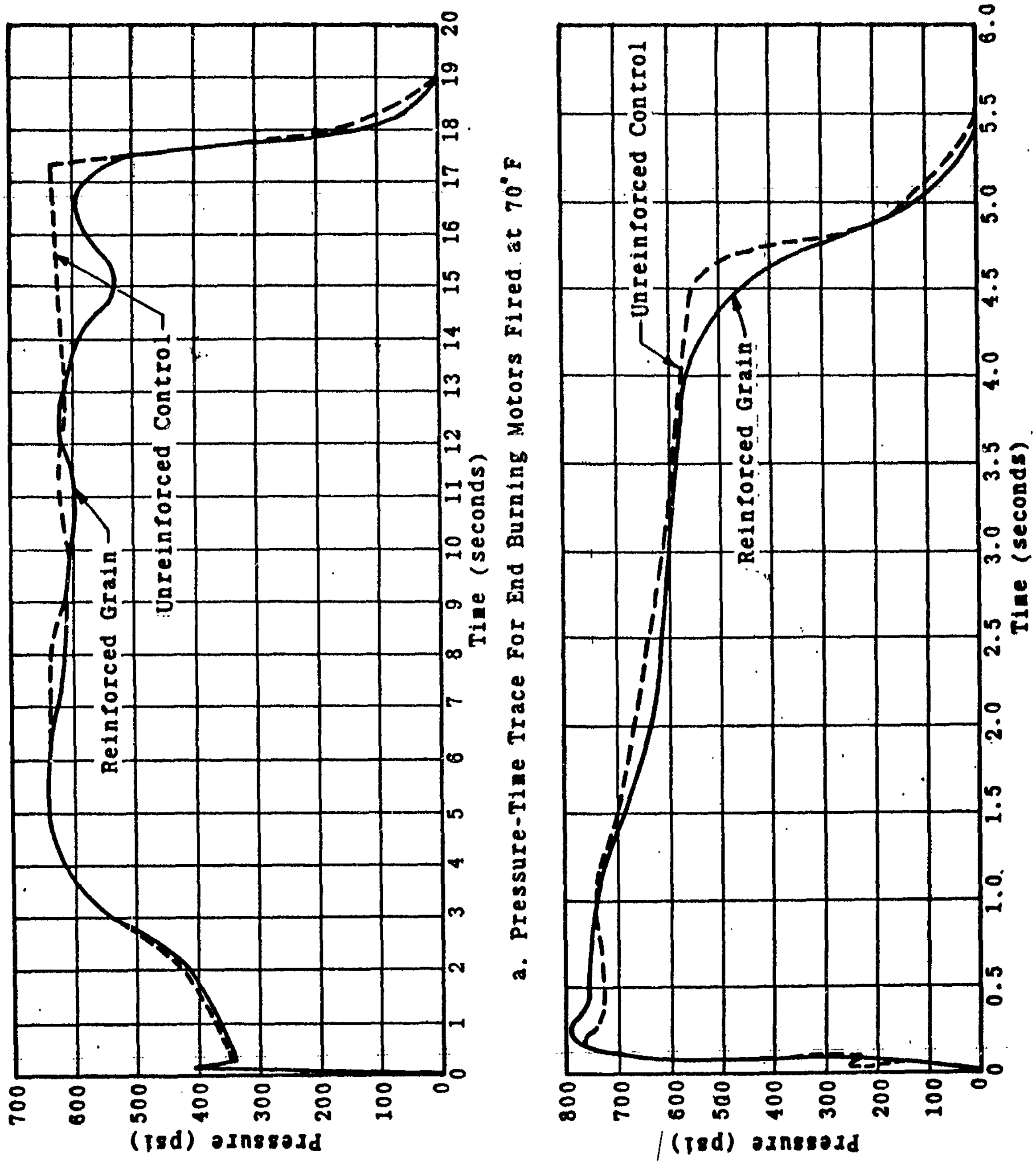

a. Pressure-Time Trace For End Burning Motors Fired at 70°F

b. Pressure-Time Trace For Core Burning Motors Fired at 70°F

Figure 13. Test Motor Firings

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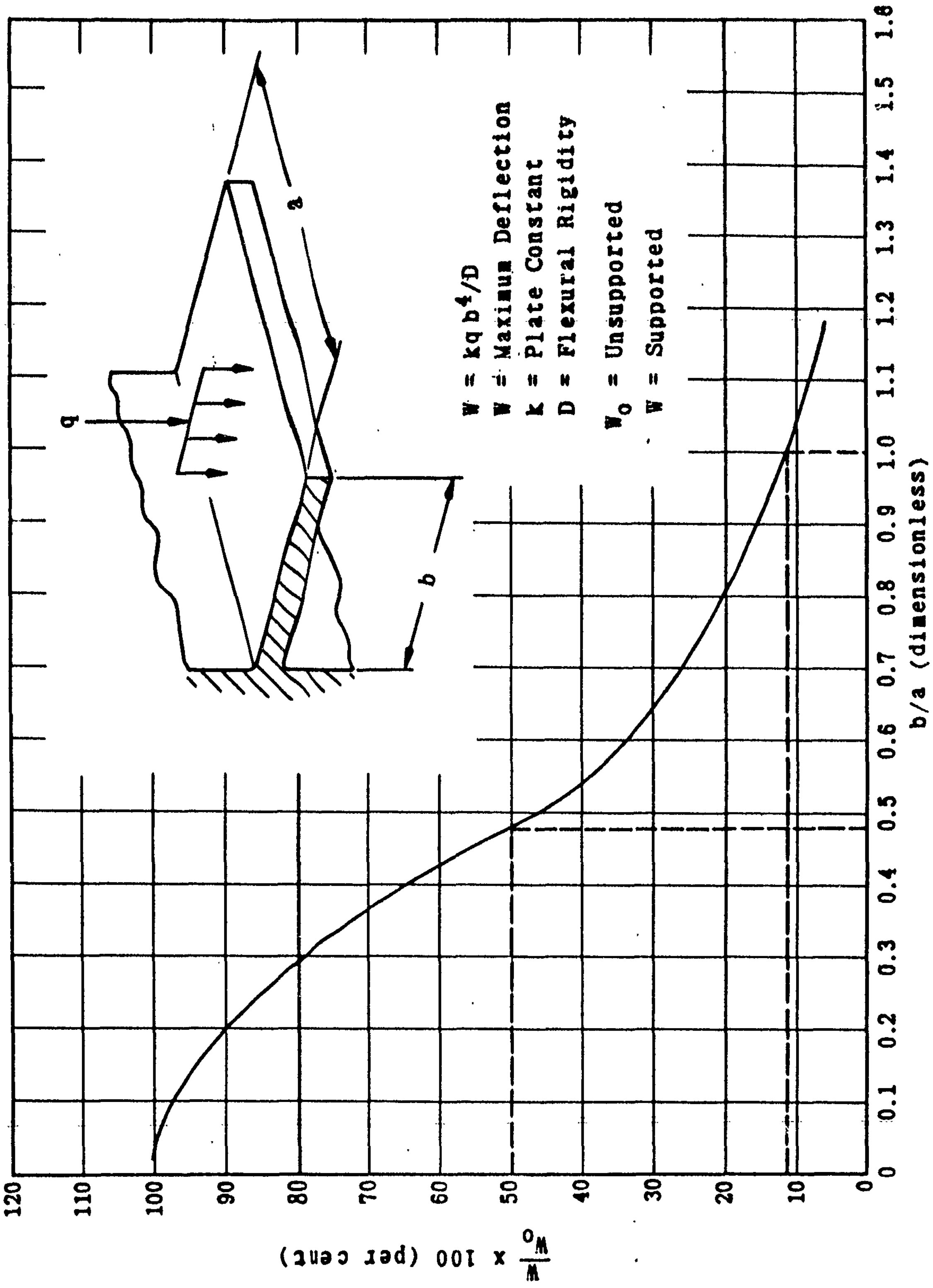

Figure 14. Ratio of Unsupported Deflection to Supported Deflection Versus Ratio of Support Spacing to Cantilever Length.

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