NASA-CR-65095

JULY 24, 1965

REPORT NO. SPP-65-107

ADDENDUM NO. II

FINAL ENGINEERING REPORT

ENERGY ABSORBING CHARACTERISTICS OF CRUSHABLE ALUMINUM STRUCTURES IN A SPACE ENVIRONMENT

Containing

Hexel Products Inc. Final Report
covering
Development and Fabrication of Bendix Energy Absorption Capsules

Prepared for

NASA Manned Spacecraft Center
General Research Procurement Office
Huston, Texas
under
Contract Number NAS 9-2074

Advanced Structures Group
~~Bendix Products~~ Aerospace Division
The Bendix Corporation
South Bend, Indiana 46620

Addendum No. 2

Hexcel Products Incorporated

Final Materials Report
June 1, 1965

Covering
"Development and Fabrication of Bendix
Energy Absorption Capsules"

for
Study of
Energy Absorbing Characteristics
of
Crushable Aluminum Structures
in a
Space Environment

NASA Contract NAS 9-2074

The Bendix Corporation
Bendix Products Aerospace Division
South Bend, Indiana

INTRODUCTION

This report (prepared by the test specimen supplier - Hexcel Products Inc., Berkeley, California) is presented in compliance with our commitment to submit a Final Materials Report outlining those experiments, developments, studies and other efforts related to materials and their processing toward fulfillment of the technological requirements of Contract No. NAS 9-2074. (Ref: The final engineering report submitted by Bendix Products Aerospace Division in compliance with the above contract is No. SPP-65-107 "Energy Absorbing Characteristics of Crushable Aluminum Structures in a Space Environment" dated July 24, 1965)

HEXCEL PRODUCTS INC.
Research and Development
Berkeley, California

DEVELOPMENT AND FABRICATION OF BENDIX ENERGY ABSORPTION CAPSULES

FINAL REPORT

June 1, 1965

Bendix P.O. Nos.	422026H
	422027H
	422028H
	422030H

Hexcel Job Nos.	2567
	2568
	2569
	2570

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2.1 INTRODUCTION

On October 7, 1963, four Purchase Orders were received from the Bendix Corporation, South Bend, Indiana, for the development and manufacture of energy absorption capsules for their evaluation and test program of the LEM vehicle landing gear. Under NASA sponsorship, Bendix was to initiate a study of the energy absorption characteristics of several aluminum honeycomb configurations under different environmental conditions. This program is discussed in the Bendix Aluminum Honeycomb Specification dated September 12, 1963. Hexcel Products Inc. was awarded the contract to develop and manufacture the honeycomb capsules which were then to be tested by Bendix. A description and discussion of the several configuration sizes, core types, and loading characteristics is presented in Section 3.1 of this report. Hexcel's development efforts are discussed in Section 4.1.

1.1 ABSTRACT

This report presents an outline and detailed discussion of the development effort, and fabrication techniques used for nine different configurations of a cylindrical honeycomb energy absorption capsule. These capsules were fabricated for the Bendix Corporation, who was to conduct a test program of the capsules under NASA sponsorship. Because of adverse crush characteristics experienced during the development phase, several configurations were modified in size without necessarily deviating from the original concept of each configuration. This program has led to a better understanding of the energy absorption characteristics of various honeycomb core types and has resulted in establishing some critical factors to be considered in the design of slender, crushable honeycomb columns.

3.1.0 PROGRAM OUTLINE AND OBJECTIVES

In accordance with Bendix' requirements, this program was divided into four phases each with a separate Purchase Order number.

3.1.1 The first phase (P.O. 422026H) involved making samples for each of the nine configurations requested. Based on a limited amount of background information, the design and fabrication methods were established for each type. Table I presents the original Bendix requirements and Hexcel's suggested design and fabrication methods. After Bendix' approval, these were the designs selected and a six-inch long sample of each type was made of available material and shipped for Bendix' visual inspection.

3.1.2 The second phase (P.O. 422027H) required fabrication of six-inch long parts of each type which were made of materials such that they would meet the required crush characteristics. All types had to crush at a static load between 5100 and 5900 lbs.; for each configuration, the average load was not to vary more than $\pm$ 5%. After Hexcel's static testing, four of these "preproduction" samples were to be delived to Bendix. It was at this point that considerable difficulties were encountered; this is discussed more fully in Section 4.1.

3.1.0 PROGRAM OUTLINE AND OBJECTIVES CONT'D.

3.1.3 Upon release by Bendix, based on their tests of the six-inch long capsules, the fabrication of full-length capsules would start as phase three (P.O. 422023H). Ten parts of each configuration were to be made for this phase. End cuts were to be taken, tested at Hexcel, and the "peak" load and static crush curves to be supplied for each part to Bendix. The requirement for full-length capsules was that they were to have a stroke of 40 $^{+.5}_{-.00}$ inches, which would mean that the total length would depend upon the percent stroke for each core type. This, in fact, varies between 75 and 80% as was experienced and shown in Section 4.1.

3.1.4 The final phase consisted of fabricating 33 parts of two configurations, and two parts of two other configurations to be selected by Bendix after their testing and evaluation of the 90 capsules supplied in phase three. The release of this phase (P.O. 422020H, Amendment No. 3) was given by Bendix on April 2, 1965. The parts requested were as follows:

33	Parts	SPX	166C	Issue	C
33	"		167C	"	D
2	"		168B	"	C
2	"		168C	"	C

4.1.0 DEVELOPMENT EFFORT

The following sections present a detailed discussion of the development efforts by Hexcel in order to obtain capsules as originally requested, the difficulties encountered, methods and attempts made to overcome the problems, changes suggested and made in configuration details, and data obtained on the various core types fabricated.

The sections are broken down by configuration as outlined in Table I. Figures I-A through I-F show photographs of typical modes of failures experienced in the development phase. Each type is discussed in the text.

TABLE I CONFIGURATION SUMMARY

CONFIG. No.	PART No.	CORE TYPE	ORIGINAL		MODIFIED (FINAL)				
			OD	ID	OD	ID	LENGTH IN.	AVG. CRUSH STR. PSI.	CELL SIZE
1A	SPX-168A	15-0-15 CROSS-CORE	3.0	2.0	3.0	2.0	52.5	1400	1/16 HEX.
1B	SPX-168B	30-0-30 CROSS-CORE	3.0	2.0	3.0	2.0	52.5	1400	1/16 HEX.
1C	SPX-168C	TUBE-CORE	3.0	2.0	3.0	2.0	56	1400	3/32 SINE
2A	SPX-167A	15-0-15 CROSS CORE	6.8	6.0	6.9	5.5	51	405	3/32 HEX.
2B	SPX-167B	30-0-30 CROSS CORE	6.8	6.0	7.0	5.5	51	370	3/32 HEX.
2C	SPX-167C	TUBE-CORE	6.8	6.0	7 3/16	5.5	50.5	330	3/32 SINE
3A	SPX-166A	15-0-15 CROSS-CORE	6 1/4	-	5.5	-	50	230	1/8 HEX.
3B	SPX-166B	30-0-30 CROSS-CORE	6 1/4	-	5.9	-	50	200	1/8 HEX
3C	SPX-166C	EXPAND. H.C.	6 1/4	-	6 1/4	-	52	180	1/8 HEX

Fig. 1-A Failure of 3"O.D. - 2"I.D. cylinder made from 15-0-15 CROSS-CORE wrapped with glass reinforced tape.

Fig. 1-B Failure of 6.8"O.D. - 6.0"I.D. cylinder 30-0-30 CROSS-CORE wrapped with glass reinforced tape.

Fig. 1-C Failure of helically wrapped cylinder. 1/8" corrugated strips 2" wide wound into 6.8"O.D. - 6.0"I.D. cylinder.

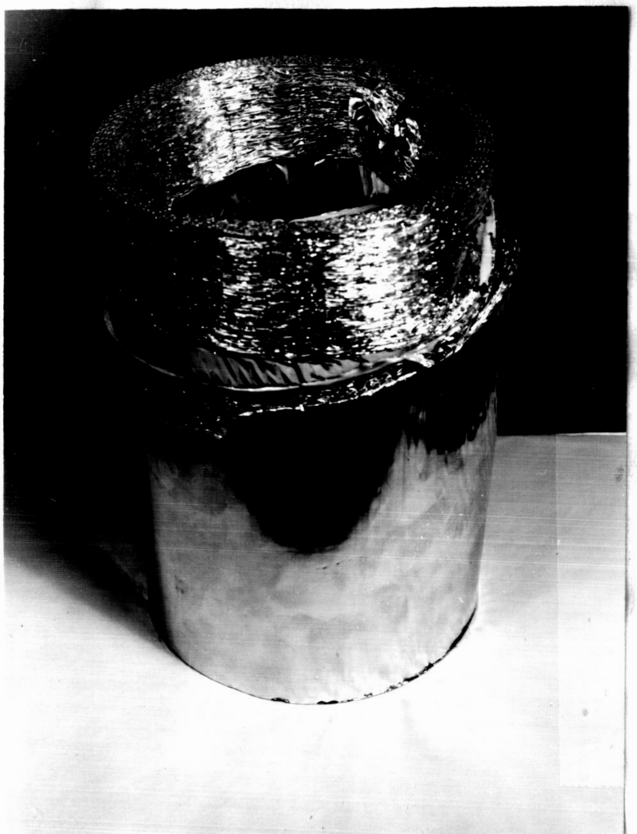
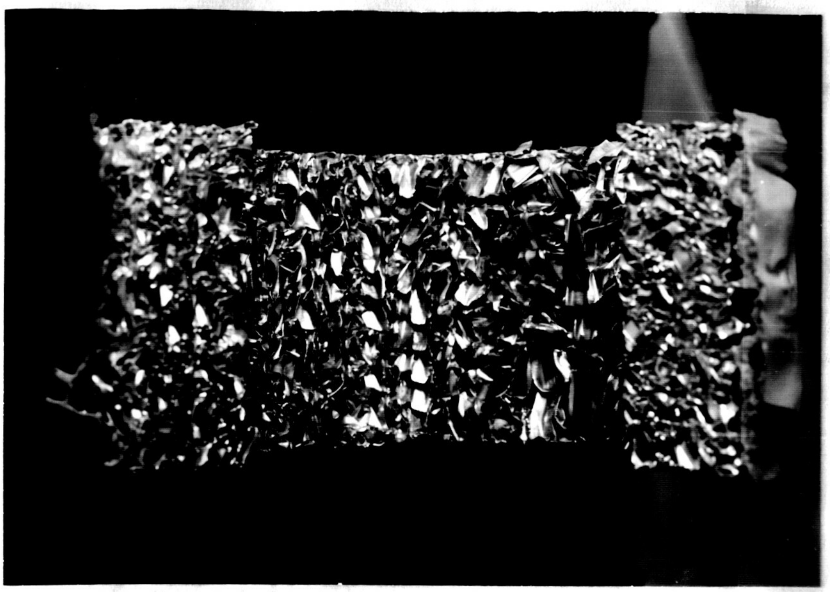


Fig. 1-D Buckling of 6.8"O.D. - 6.0"I.D. spliced cylinders.



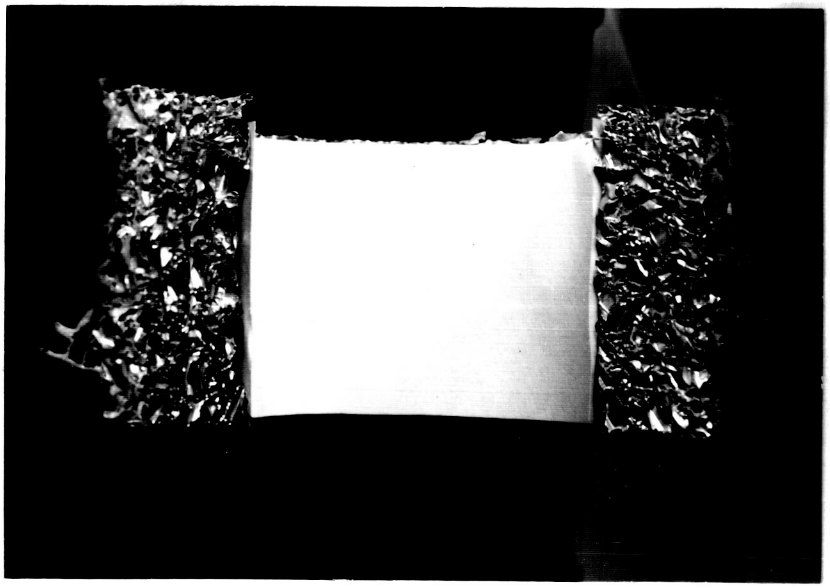


Fig. 1-E Close up of crushed cylinder 3.0"O.D. 2.0"I.D. 30-0-30 CROSS-CORE with 1/4 section cut out to show detail of crushed material.

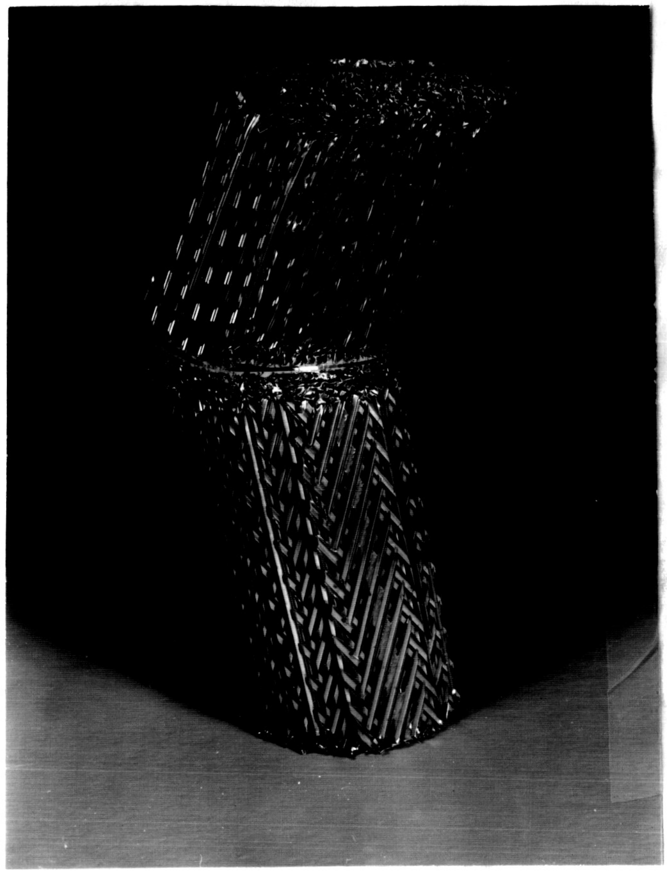


Fig. 1-F Buckling failure of a 30-0-30 CROSS-CORE cylinder spliced with .032" skin interface 3.10"O.D. - 2.00"I.D. -- 11"T.

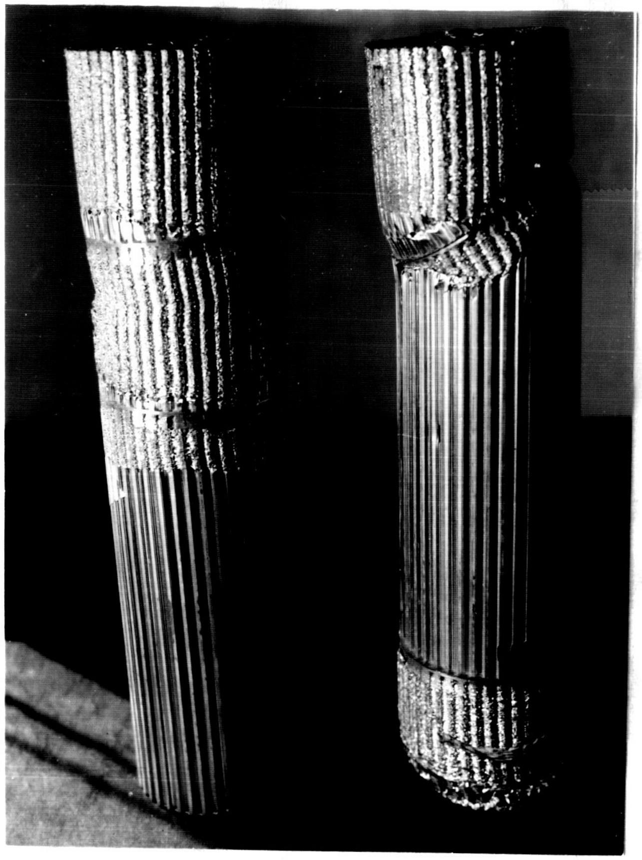


Fig. 1-G Two specimens SPX168-C tested inside a 3"I.D. support sleeve.

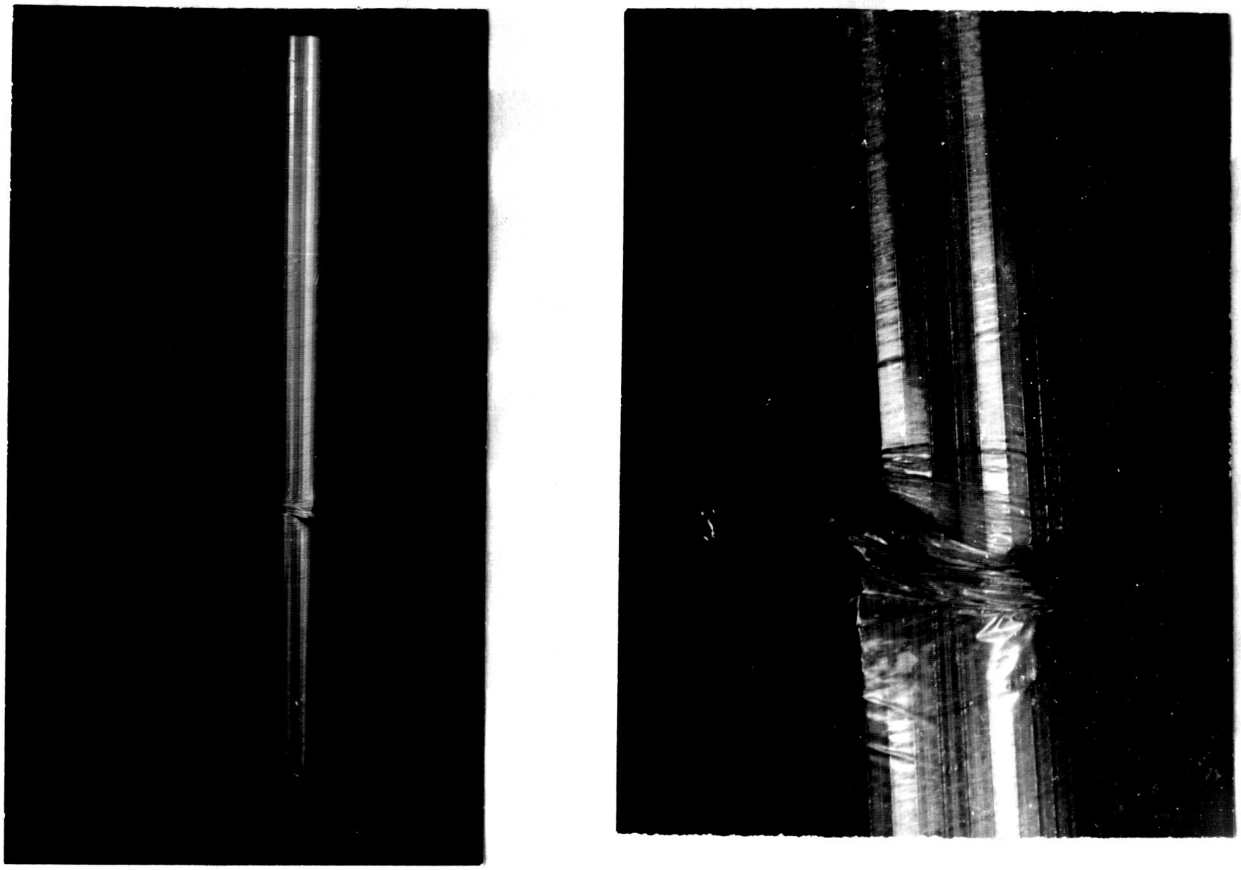


Fig. 1-H Buckling of a 47"T specimen SPX168-C made of sinusoidally corrugated AL-5052 foil.

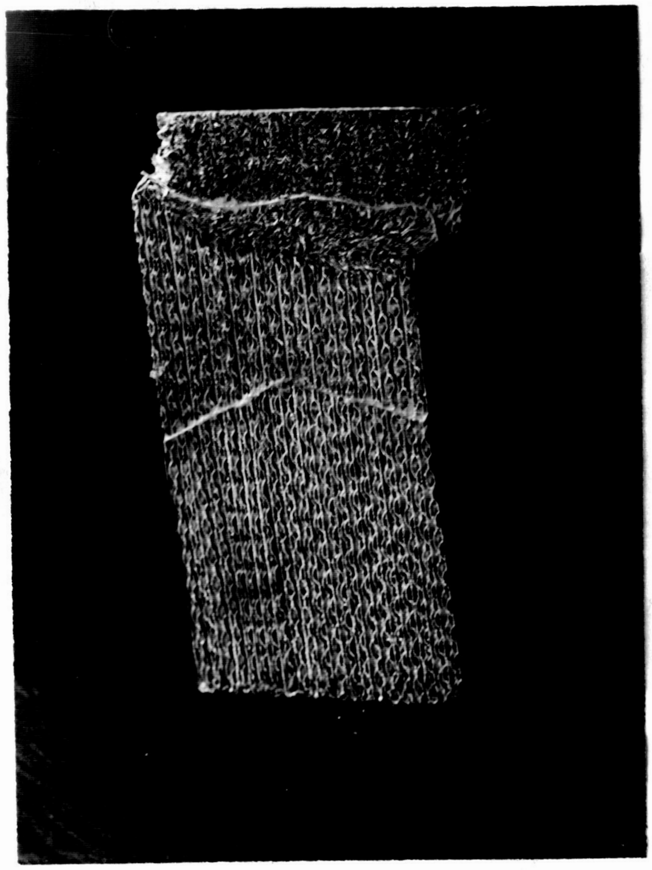
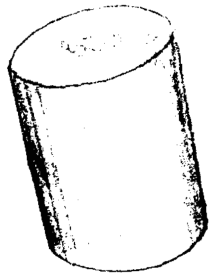


Fig. 1-J Failure of V-splice of 2 x 4" CROSS-CORE blocks
30-0-30.

4.1.1 CONFIGURATION III-C



6-1/4"O.D. - SOLID EXPANDED HONEYCOMB

This configuration was made of Hexcel's regular expanded honeycomb, AL 1/8-5056-.0009. After expansion, the core was cut into blocks which were then turned on a lathe to a diameter of 6-1/4". It was originally expected that etching or annealing of the specimens would be required to reduce the crush strength to 180 psi; however, it was found that the ± 1/8" tolerance on O.D. was sufficient to provide parts with an average crush load of 5500 lbs. In addition, it was found that slight overexpansion would reduce the strength to the required values. Figure 2 shows a typical load deflection curve for a six-inch long specimen. Note that the load fluctuations are very small and that the stroke was 78%.

Difficulties were encountered in making the 52" long capsules. Present production capabilities limit the thickness or "T" of expanded honeycomb to about 27". Hence, splicing sections would be required. To determine the effect of splicing on crush characteristics, test specimens were made of three six-inch "T" sections spliced together with a .005" aluminum skin and Shell Epon 907 adhesive. The ends of each section were precrushed prior to bonding in order to eliminate peak load during the transition from one section to the next. Figure 3 shows the crush load curve for a spliced specimen . It can be seen

4.1.1 CONFIGURATION III-C CONT'D.

that the transition at the splice is uniform with only a minor change in crush load.

Because of this finding, the long capsules were made by this method. Three sections, each being approximately 17" long, were spliced together using a .012" thick aluminum skin at the splices. The first three capsules were made using Shell Epon 907 adhesive. The remaining seven capsules were bonded with Shell Epon 931 adhesive because of the plus 300°F environmental temperature requirement.

Despite the early successes with the short six-inch "T" spliced sections, both at Hexcel and at Bendix, it was found that the long capsules would buckle during testing. For this reason, new capsules were made using only two sections about 27" long. Cylinders made this way and precrushed at the ends and not at the splice, exhibited uniform crush characteristics.

An additional Bendix requirement, which was not realized until March, 1964, is the use of a perforated plate in the splice to allow passage of gases from one section to the next. In subsequent capsule fabrication, a perforated skin was used during bonding.

For future applications, expanded honeycomb could possibly be made of the full 52" T giving a one-section capsule; however, this would require design and construction of new equipment and some degree of development work.

CONFIGURATION 3C

FIG. 2

SPECIMEN NO. 3C-4

SPECIMEN SIZE 6 1/8" OD - 6" T

FAILURE LOAD — LBS.

HEAD TRAVEL 0.5 INCH PER MIN.

TEST ANGLE 0°

R & D # — LSR # 1111 TECH. W.N.

DEPT. # — JOB # 2568

TEMP. RT TIME — DATE Jan 9 '64

MATERIAL 1/8 Al 5056 - .0003

COMPRESSION TEST

SCALE 30000 LB. 1/2 RANGE

MAG. I 1" = 1/2"

PRECRUSHED
STROKE 78%

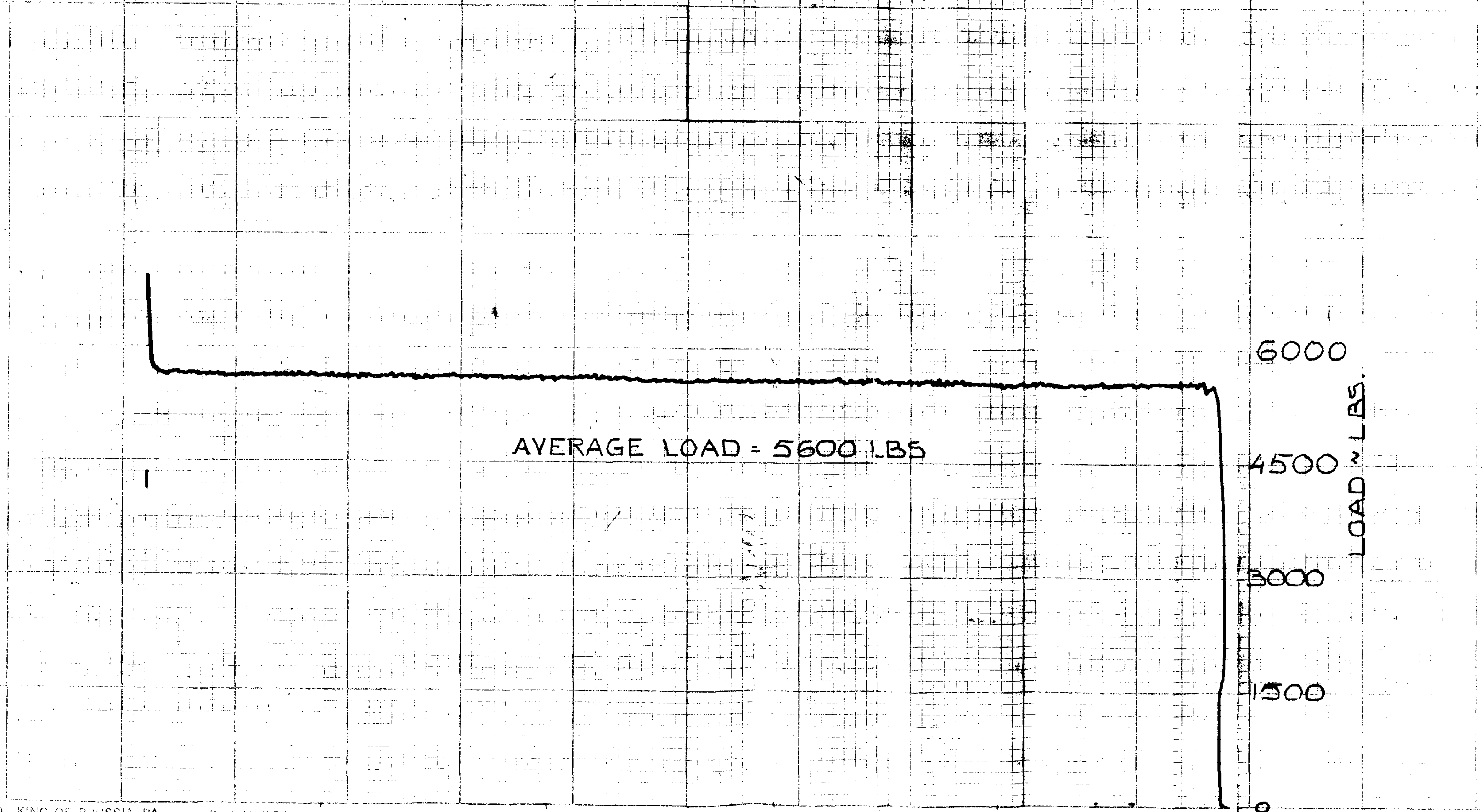


CHART NO. 1010

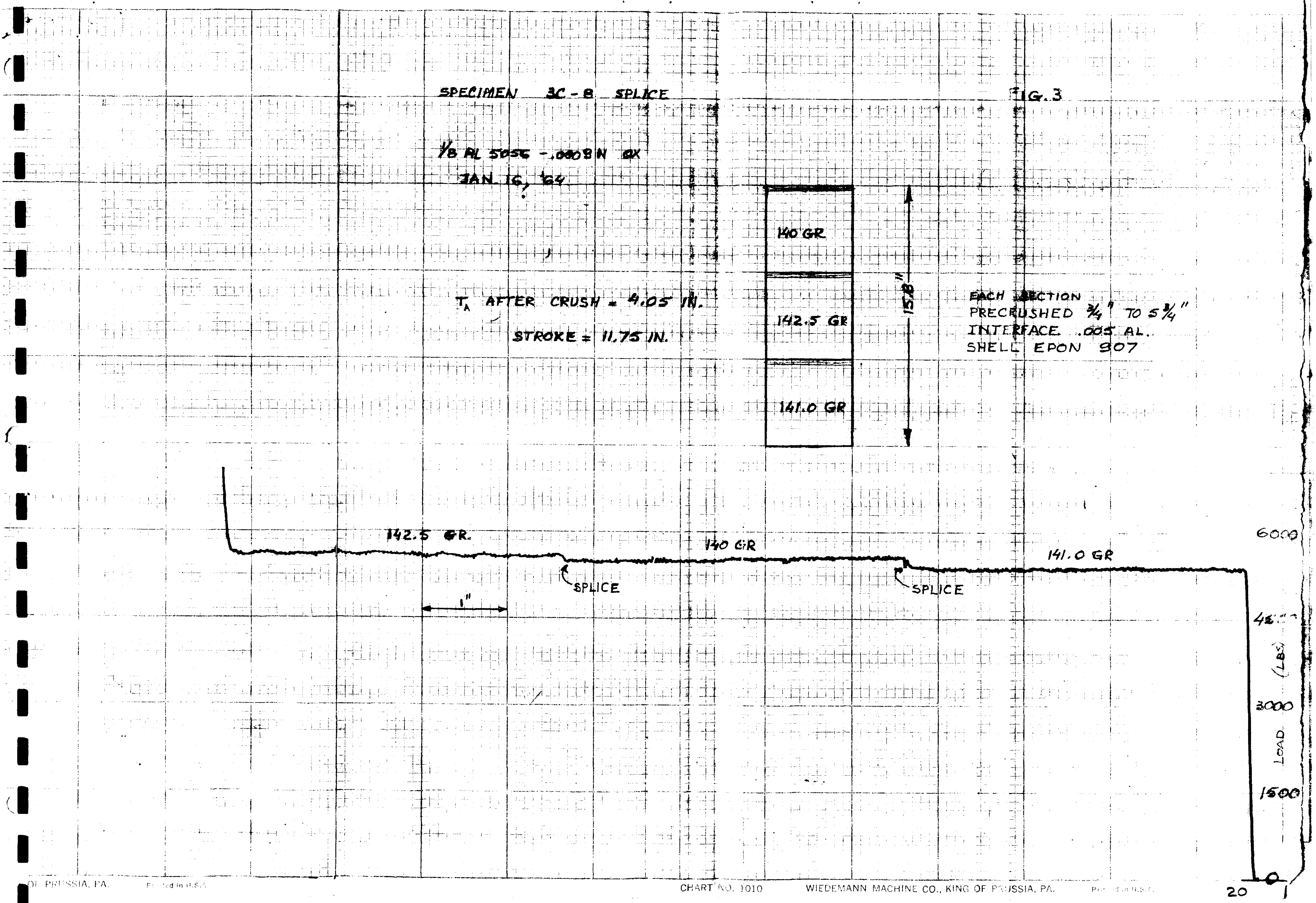
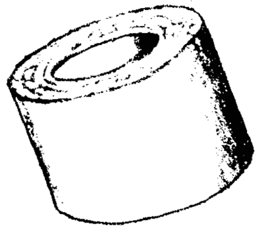

SPECIMEN 3C - B SPLICE
1/8 AL 5056 - .0008 N GX
JAN 16, '64
T_A AFTER CRUSH = 4.05 IN.
STROKE = 11.75 IN.
140 GR
142.5 GR
141.0 GR
15/8"
EACH SECTION
PRECRUSHED 3/4" TO 5 3/4"
INTERFACE .005 AL.
SHELL EPON 907
142.5 GR.
140 GR
141.0 GR
SPLICE
SPLICE
1"
6000
3000
1500
0
20
LOAD (LBS)
CHART NO. 1010
WIEDEMANN MACHINE CO., KING OF PRUSSIA, PA.

FIG. 3

4.1.2 CONFIGURATION I-C

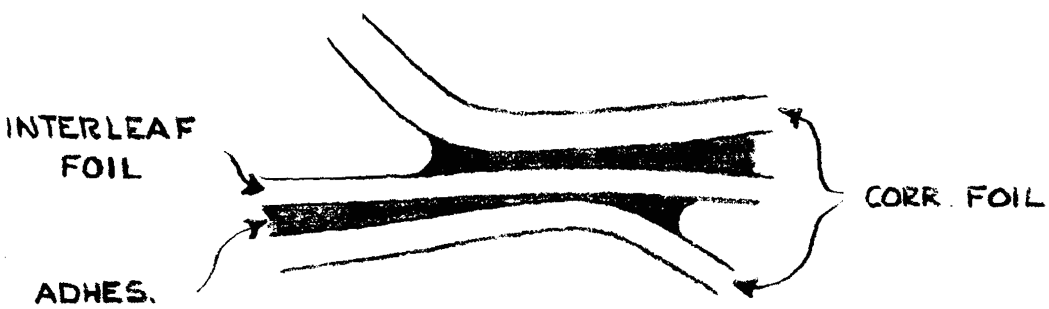


3"O.D. - 2"I.D. SPIRAL WRAPPED TUBE CORE (R)

This type is made by the spiral wrapping technique. Using a 2" mandrel, a flat foil and a corrugated foil are wrapped simultaneously around this mandrel until the desired 3" diameter is reached. The adhesive is applied to both sides of the corrugated foil before wrapping.

One of our major difficulties in producing this type to meet the desired crush strength has been the application and control of the amount of the adhesive. The original adhesive was 3M's EC-1386 diluted 1 to .67 MEK. It was applied with an electrically driven roller applicator. Because of the evaporation of MEK during this process, the viscosity variations resulted in non-uniform and non-repeatable adhesive application. Therefore, we decided to use a different adhesive which was premixed and less subject to changes in viscosity. This adhesive is Reichhold's Epotuf (Code #SF-5473-1). Even with this adhesive, the crush strength variations were noticeably large. The fluctuations are apparently caused by the amount in the node.

The sketch below is reproduced from a microphotograph of the node of two corrugated foils and the thinner flat interleaf foil. This TUBE CORE (R) was made with the low viscosity Epotuf adhesive. The sketch illustrates the non-uniform "sandwich" thickness and the fillet produced by the adhesive.

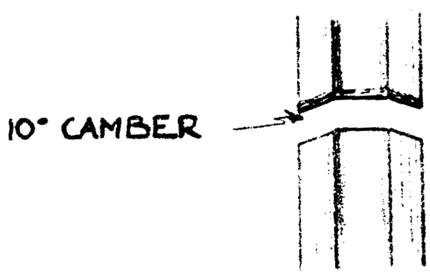


4.1.2 CONFIGURATION I-C CONT'D.

Figures 4, 5, and 6 show the variations obtained even with this Epotuf adhesive.

In addition to controlling the adhesive application, the outer skin wrap and a few nodes were removed from the cylinders to obtain an average crush strength between 5100 and 5900 lbs.

With the presently available equipment, hexagonal corrugated foil can be produced in widths up to 11" wide. Hence, in order to make the tall cylinders which have a stroke of 40", several sections have to be spliced together. Some preliminary spliced test samples were made. One set was made by cutting the ends to a 10° camber and bonding the mating ends. (See sketch below) Another splice was made with a .012" interface, and one more with a .032" foil interface to stabilize the ends. In each case, however, the specimen buckled at one of the splices. Figure 7 shows the result.



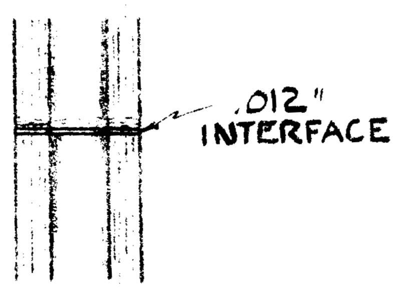
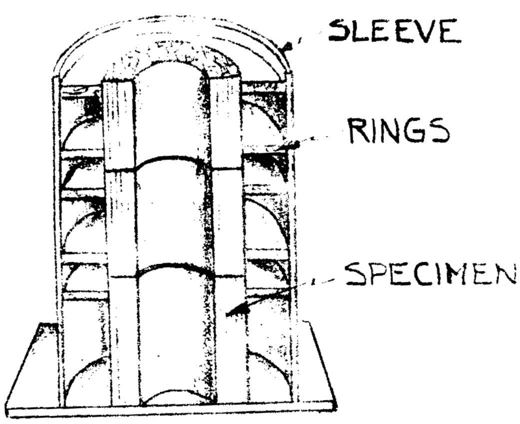


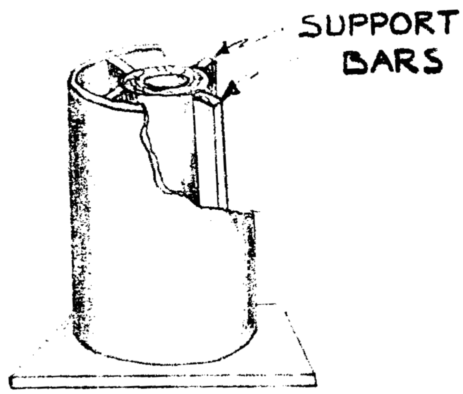
Figure 8 shows that an internal splice obtained by butting the ends of corrugated foil directly together, is also unsatisfactory. Instead of the usual folding of the foil, the butted splice split and the sections slid past each other breaking and tearing up the in and outside walls.

4.1.2 CONFIGURATION I-C CONT'D.

All of the above static crush tests were made with the specimens unsupported. Subsequently, a test sleeve support of the same inside and outside diameters as that used by Bendix was fabricated. Several spliced specimens were tested in this support. Because of the excessive clearance between the 3" O.D. annular configurations and the 4.62" I.D. of the support sleeve, however, additional means of supporting the specimens were considered.

For these room temperature tests, wooden rings were made to fit just below and above each splice as shown in the sketch below. During crushing, however, the side loads were so great that the rings actually cut into the core and buckling was still initiated. Vertical bars, supporting the specimen for the full length, were also unsuccessful





Finally, a 3" I.D. sleeve in which a spliced specimen fitted snugly was tried. Figure I-G shows two such specimens after testing. One crushed rather uniformly, but the other still buckled at a splice which resulted in a drastic drop in crush load.

4.1.2 CONFIGURATION I-C CONT'D.

During the period of this development work of splicing TUBE CORE sections, Hexcel's Engineering Department was considering modification and improvement of another type of corrugator which would be able to corrugate foil up to 70" wide. This machine, however, would only be able to corrugate a sinusoidal pattern such as used in the paper industry. The depth of corrugation is approxmately 3/32". After corrugating a few hundred feet of foil with these rollers, a few pieces of TUBE CORE were made and tested. After some deliberation and consulation with Bendix, it was decided to make this "Configuration I-C" using the sinusoidally corrugated material and make the parts in one section.

At this time, 5056 aluminum alloy was only available in storage in 1.4 mil and 2.6 mil gauges of the 61" wide web. After trying combinations of these foil gauges, it was found that the only way this configuration could be made to the desired crush strength was to use a double sheet of 2.6 mil foil as the interleaf material and a 2.6 mil foil for the corrugated material. The adhesive used, again, was Epotuf (Code SF 5473-1).

As was discussed previously, difficulties still remained in obtaining the correct crush strength. As a consequence, the TUBE CORE parts made were tested statically and as required were modified to give 5500 lb. crush load. This modification would amount to removing or adding some

4.1.2 CONFIGURATION I-C CONT'D.

of the outer wrapping. The final parts were wrapped with a glass filament tape obtained from the 3M Company, Number 870. This tape is effective in preventing peeling of the outer wrappings without effecting the crush strength. The tape is guaranteed to be good up to 300°F. Figure 9 is a load deflection curve of one of these parts provided to Bendix.

FIG. 4

COMPRESSION TEST

R & D # ____ LSR # 1111 ____ W.M.

DEPT. # ____ JOB # 3568

TEMP. RT TIME — DATE 5 — '64

MATERIAL 1/8 Al 5056 - .0014 - .0026 ___

8 wraps

SPECIMEN NO. 1C-10

SPECIMEN SIZE 3" OD - 10.45" T

FAILURE LOAD — LBS.

HEAD TRAVEL 1 INCH PER MIN.

TEST ANGLE 0°

SCALE 30,000 LB. 1/2 RANGE

MAG 1 1" = 1"

T AFTER CRUSH = 2.67"

STROKE 74.5 %

T AFTER CRUSH = 2.67"

STROKE = 74.5%

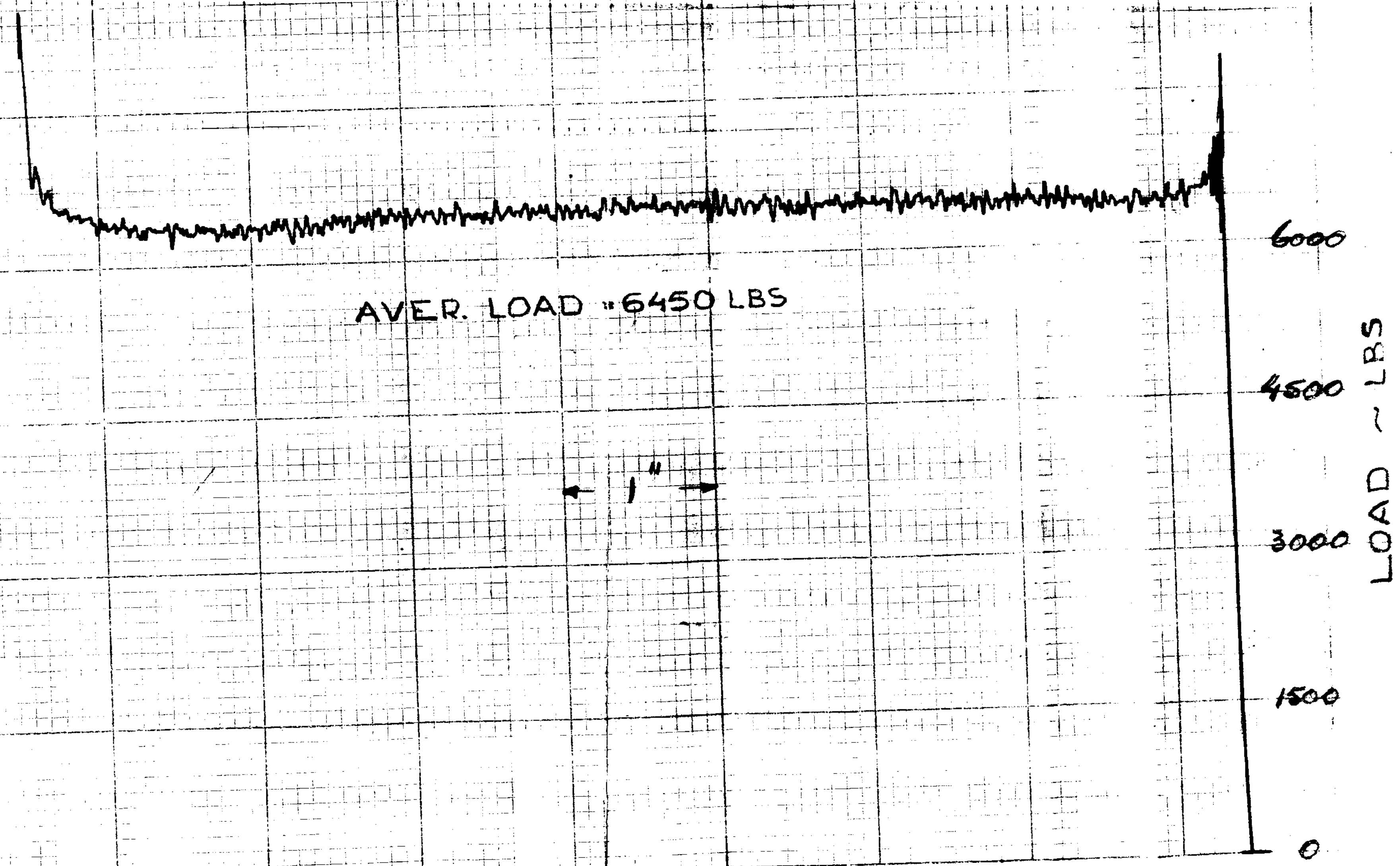


CHART NO. 1010 WIEDEMANN MACHINE CO., KING OF PRUSSIA, PA. Printed in U.S.A.

R & D # — LSR # 111 TECH WN

DEPT. # — JOB # 2568

TEMP. RT TIME — DATE Jan 14 '64

MATERIAL 1/8 Al 5056 - .0014 - .0026 # wt

8 WRAPS

SPECIMEN NO. 1C-17

SPECIMEN SIZE 3" OD = 10.42" T

FAILURE LOAD — LBS.

HEAD TRAVEL 1 INCH PER MIN.

TEST ANGLE 0

FIG. 5

COMPRESSION TEST

SCALE 30,000 LB. RANGE

MAG L 1" = 1"

T AFTER CRUSH = 2.70"

STROKE = 74.1%

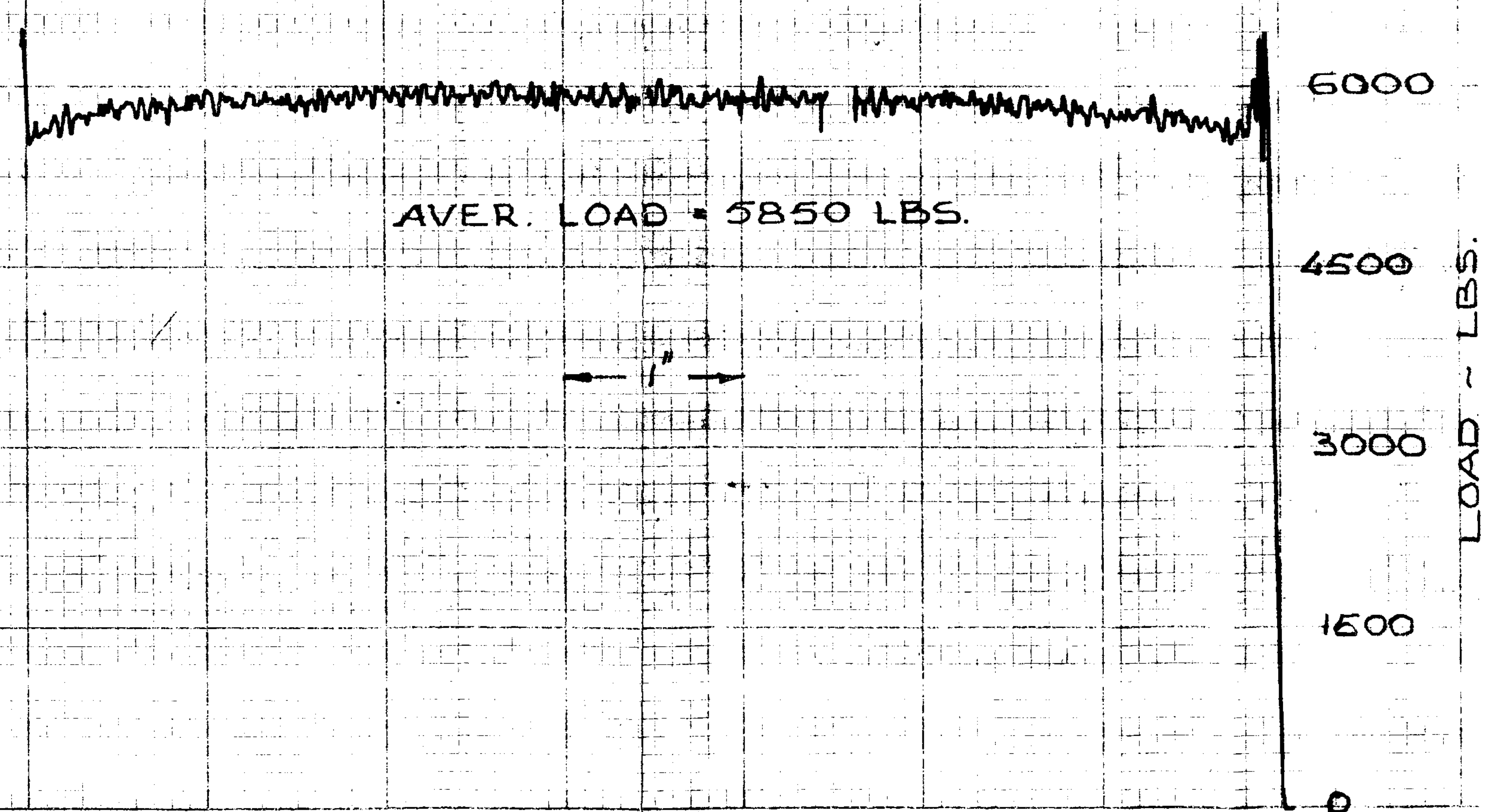


FIG. 6

R & D # — LSR # 1111 TEST WJ
DEPT. # — JOB # 2568
TEMP. RT TIME — DATE Jan 14 '64
MATERIAL 1/8 Al 5056 - .004 - .0026 sp wt
8 wraps

SPECIMEN NO. 1C-12
SPECIMEN SIZE 3" OD - 10.47"
FAILURE LOAD — LBS.
HEAD TRAVEL 1 INCH PER MIN.
TEST ANGLE 0

COMPRESSION TEST
SCALE 30,000 LB. 1/2 RANGE
MAG 4 1" = 1"

T AFTER CRUSH = 2.66"
STROKE = 74.6%

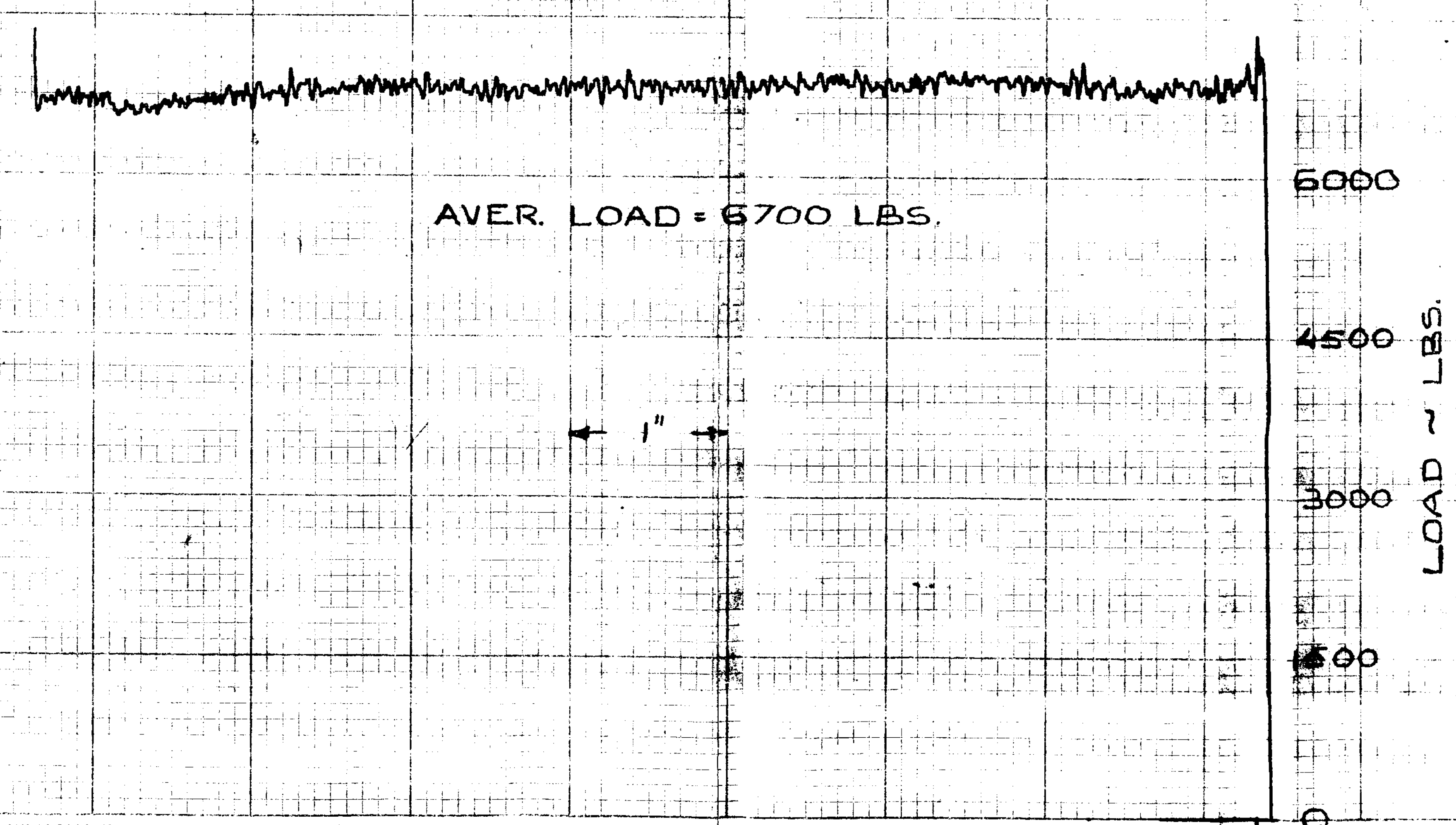


FIG. 7

CONFIG. 1C SPLICE

SPECIMEN NO. Splice, 3 SECTIONS

SPECIMEN SIZE 3" OD - 31 5/8" T

FAILURE LOAD — LBS.

HEAD TRAVEL 1.0 INCH PER MIN.

TEST ANGLE 0

R&D# — LSR# 1111 TECH. WN

DEPT. # — JOB # 2588

TEMP. RT TIME — DATE Jan 14 '64

MATERIAL 1/8 Al 5056 - .0014 - .0026 sp wt

8 wraps

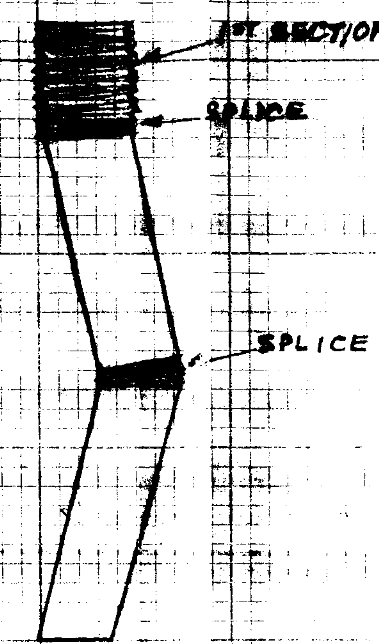
.0016 skin in splice

90% EPON

COMPRESSION TEST

SCALE 30,000 LB. 1/2 RANGE

MAG 2 1" = 1"



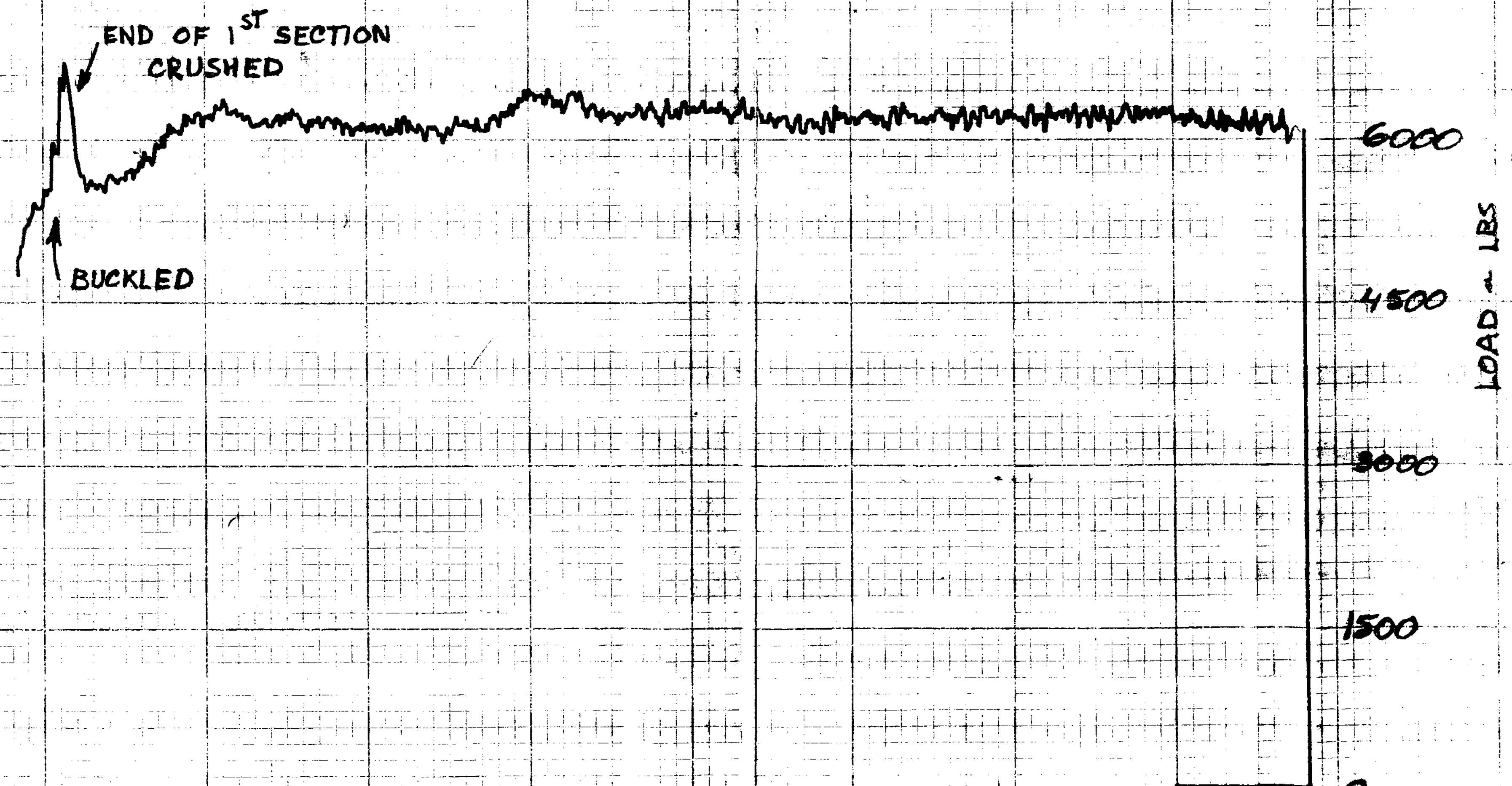


FIG. 8

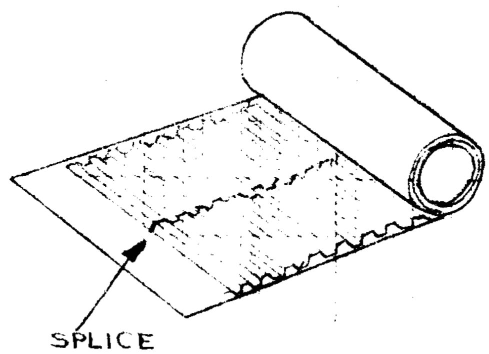
IC-19

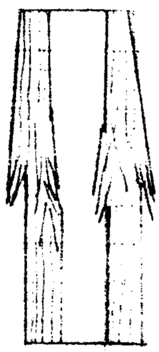
JAN 16, 64

INTERNAL SPLICE
DIRECT BUTT JOINT

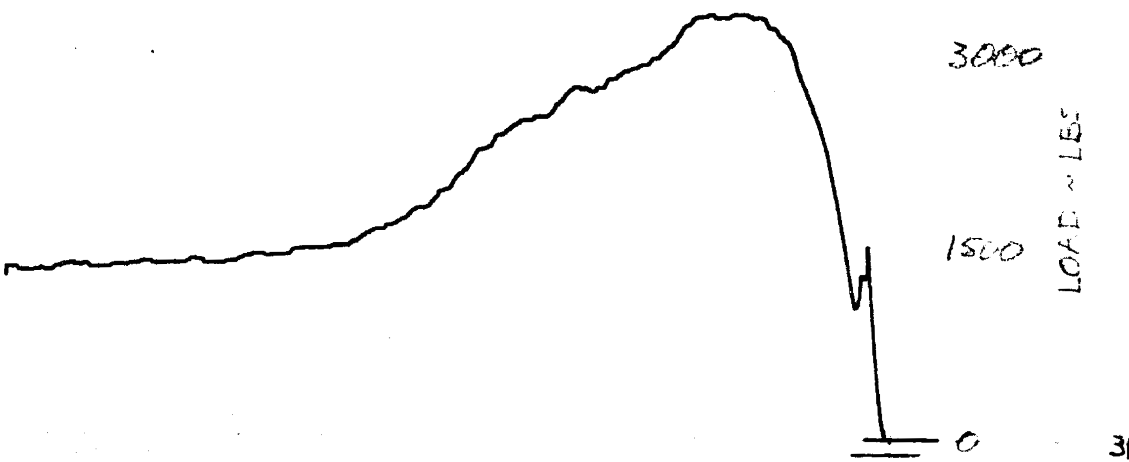
1/8 AL 5056 - .0014 - .0020
SPIRAL WRAP
8 WRAPS
HAND COATED
EPOTUF

11.25" T





TYPE OF FAILURE



Aug 17, '64

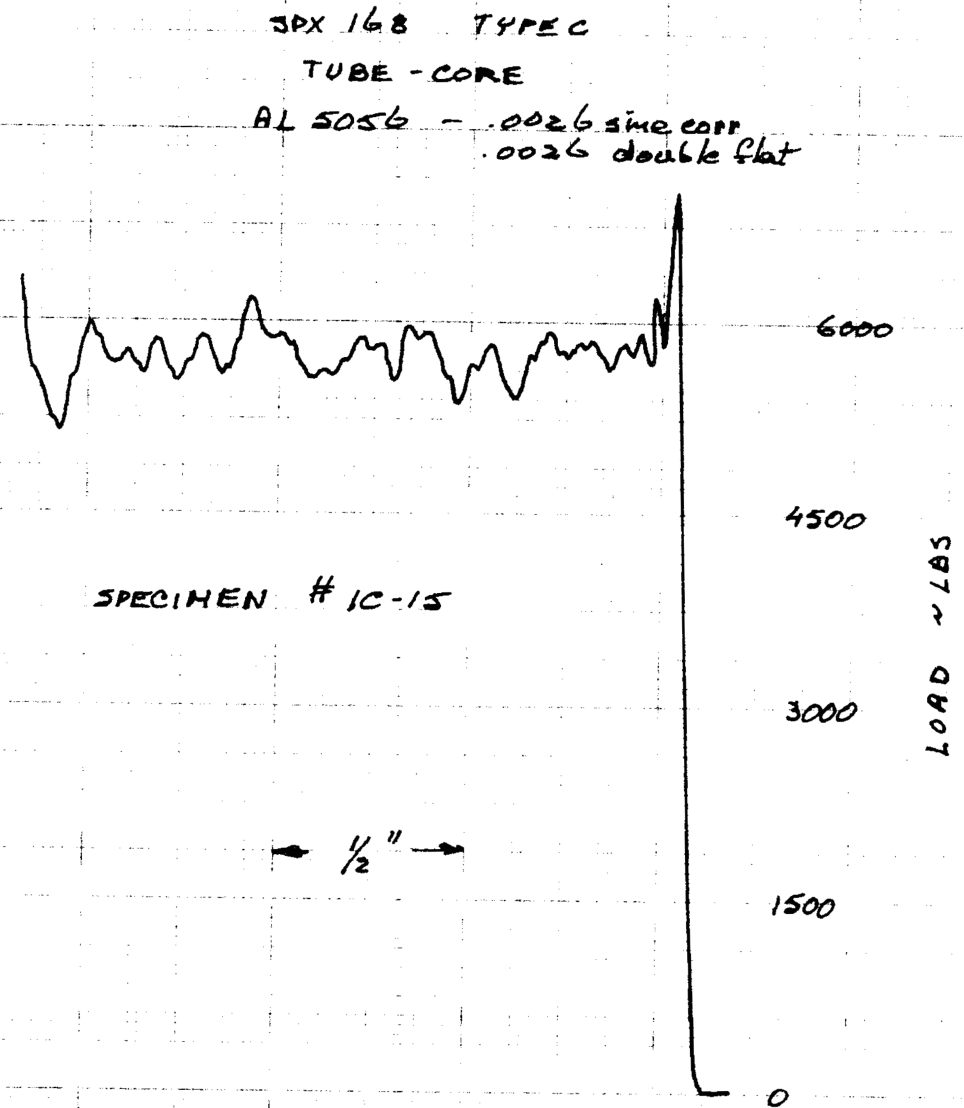
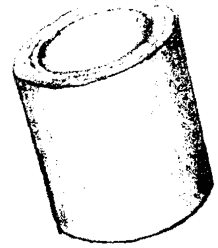


FIG. 9



6.8"O.D. - 6.0"I.D SPIRAL WRAPPED TUBE CORE (R)

4.1.3 CONFIGURATION II-C

With this configuration, similar problems have been encountered as with Configuration I-C. Figure 10 shows the test results of the spliced specimen. The unstable wall caused inward buckling as shown in the sketch. This instability was also observed in some non-spliced six-inch "T" specimens.

After some preliminary theoretical work, it was found that this instability was possibly caused by Euler buckling. As a consequence, a mutual decision with Bendix was made to develop a TUBE CORE of a cross-sectional area which would be of a stable configuration. Several dimensions were tried and after agreement with Bendix, the final dimensions were selected to be 5-1/2" I.D. and 7-1/4" O.D.

Again, this configuration was made using the sinusoidally corrugated material in order to provide full-length TUBE CORE parts. The foil combinations used were 1.4 mil, flat foil; and 1.4 mil, corrugated material. Again, the adhesive used was Epotuf. These parts were also wrapped with 3M's No. 870 filament glass tape. Figure 11 shows the typical load deflection curve for the end piece taken from one of these capsules provided to Bendix.

COMPRESSION TEST

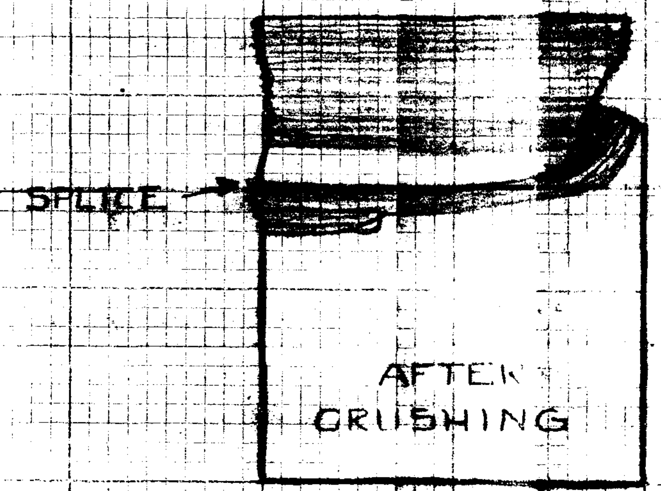
FIG. 10

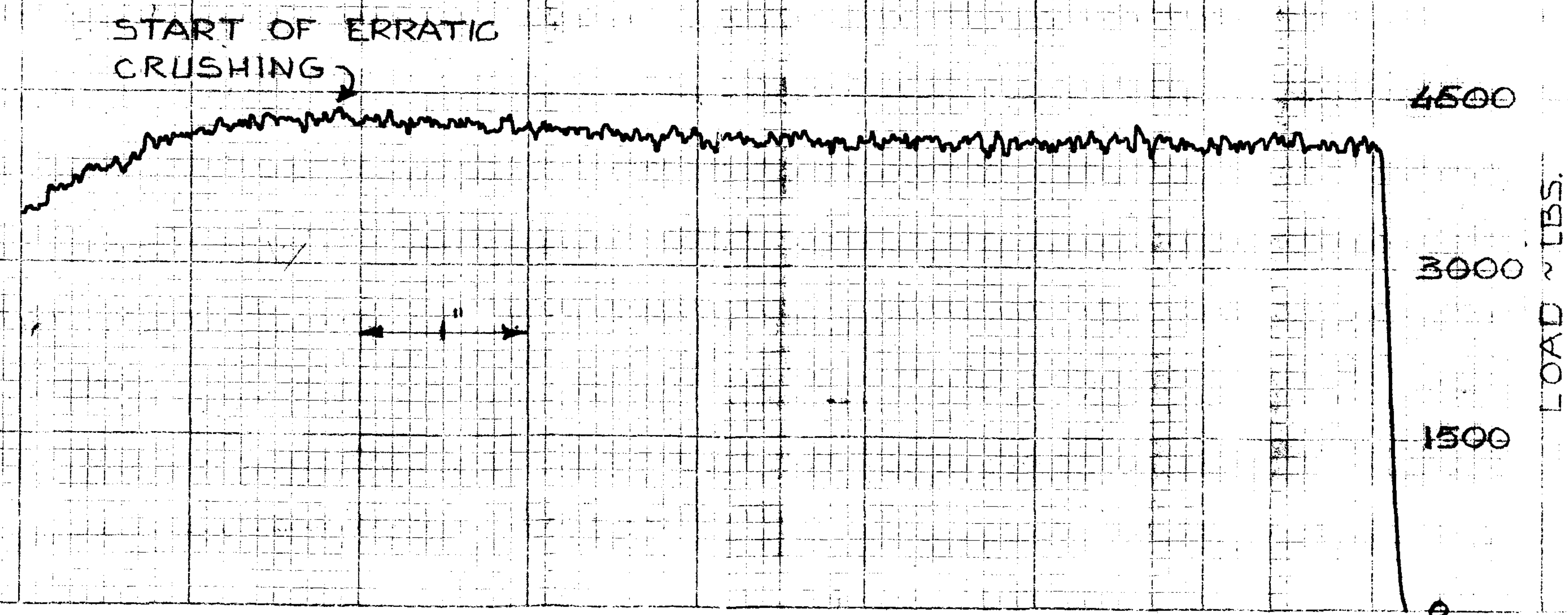
— #	—
LSR #	1111
TECH	W.N.
DEPT. #	—
JOB #	2568
TEMP.	RT
TIME	—
DATE	[illegible]
MATERIAL	1/8 Al [illegible] -.0014 -.0014 [illegible]
SPECIMEN NO.	Splice 2 sections
SPECIMEN SIZE	6.8" OD
FAILURE LOAD	— LBS.
HEAD TRAVEL	1.0 INCH PER MIN.
TEST ANGLE	0

SCALE 30,000 LB. 1/2 RANGE

[illegible] 1 = 1"

SPLICE WITH
.012" INTERFACE
SHELL EPON 907





33

Nov. 2, '64

SPX 167 TYPE C
TUBE-CORE
AL 5056 -.0014 Sine corr
.0014 flat

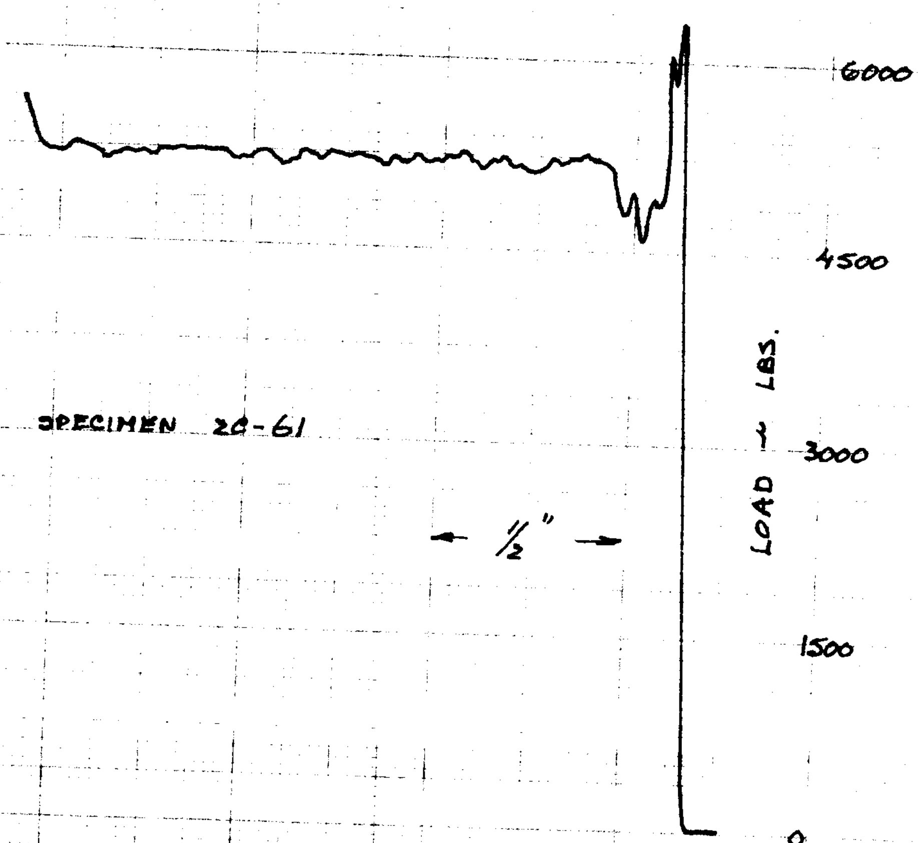


FIG. 11

4.1.4 CROSS-CORE CHARACTERISTICS

CROSS-CORE has been considered for energy absorption applications, however, our tests have shown that its crush characteristics are not as uniform as regular honeycomb or spiral wrapped core. The CROSS-CORE that exhibited this non-uniformity was made in the following manner.

Initially, a suitable jig for holding the successive corrugated foil pieces was constructed. The foil used was one with 1/8" corrugations. The placement of the foil pieces depends on the CROSS-CORE type. For example, for the type denoted as 30-0-30 CROSS-CORE, the placement was as shown in Figure 12. The first foil piece was placed with its corrugations at 0° with respect to the reference axis; the following foil piece was placed with its corrugations at an angle of +30° with the reference axis followed by a piece with corrugations at an angle of -30° with the reference axis; then this sequence was repeated starting with the 0° inclination again. Each of the corrugated foil pieces had the adhesive applied to both its faces prior to placement. After building up the core block in the manner described above to the desired size, the block was cured at 350°F under sufficient pressure. This bonded block was then trimmed and specimens of the required shape and size were cut from the core block.

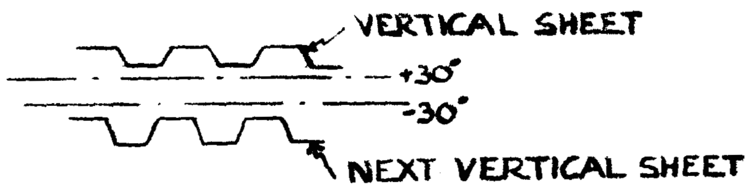
4.1.4 CROSS-CORE CHARACTERISTICS CONT'D.

This procedure was followed for the fabrication of all CROSS-CORE types, the mode of placement being dependent on the desired cell orientations. Our tests have shown large force fluctuations and significant load drops at the beginning and end of the stroke with this CROSS-CORE. Figure 13 shows the load curve of a 2" x 4" test cut of AL 1/8 -5056- .0034 CROSS CORE (30-0-30) which demonstrates this phenomenon. Figure 14 shows the periodicity of the fluctuations exhibited. The curve of Figure 14 is drawn from that of Figure 13 by eliminating the secondary fluctuations. A possible explanation for the observed phenomena may be as follows:

An examination of Figure 14 shows that the period of fluctuations corresponds closely to the theoretical vertical distance between nodes, h_2. In this distance h_2, the compressive strength is not as great as that for the bonded section and the foil would buckle more readily and under lower loads. The drop in load towards the end of the stroke is probably due to the unsupported foil ends. The distance h_1 is the maximum possible height where the corrugated foil is not bonded and this may result in buckling at a lower load.

4.1.4 CROSS-CORE CHARACTERISTICS CONT'D.

The pattern shown in the sketch of Figure 14 does not necessarly repeat itself from layer to layer. When the block is laid up, the corrugated sheets oriented in the same direction may have their nodes offset. This is best illustrated by the sketch below.



The pattern is shifted right or left as the layers are built up. This results in a random distribution of the bonded nodes, and less violent peaks during crushing. Because of the randomness, however, the load curve is not the same from specimen to specimen and the fluctuations observed are erratic.

With low-density CROSS-CORE (0 to 8 pcf), an additional problem was encountered. The stroke (distance of head travel with respect to initial specimen height) was less than the usual 70 to 80%. For example, one block of 30-0-30 core made with .0009" foil had a density of 5.60 pcf and a stroke of only 50%. The mechanics of crushing CROSS-CORE IS complicated as discussed. Apparently, what happens with the low-density core is that the unsupported foil buckles and folds over but the bonded nodes remain undisturbed in their same relative position. Thus, only the unbonded ribbons contribute to the crushing action.

To overcome this problem and make the distribution of bonded areas more uniform, the core was laid up with a flat foil interleaf between each

4.1.4 CROSS CORE CHARACTERISTICS CONT'D.

corrugated sheet. Thus, the whole ribbon of a corrugated sheet was bonded to a flat foil. This improved the crush characteristics significantly, particularly for the 15° cell-oriented core. However, the fluctuations were still excessive.

Figure 15 is a plot of percent stroke versus density for several CROSS CORE blocks with and without the flat interleaf. It can be seen that despite the improvement with the interleaf, a large amount of scatter still exists. This makes it impossible to predict with reliability, the overall specimen length required to give a specified stroke length.

Figure 16 shows the variations in crush strength with density. Again, a large amount of scatter exists making it difficult to specify the density for a required crush strength.

The fluctuations of crush load from the average have always been more than $\pm$ 5%. In fact, as Figure 17 shows, the fluctuations have been as high as 17%. These fluctuations have been very random and unpredictable. On the average, however, the fluctuations have been higher for the core with flat foil interleaf.

Because of the above mentioned difficulties, a decision was made with Bendix to eliminate the requirement that the fluctuation should be within $\pm$ 5%. As long as the average crush load would be within the initial range, the core would be passable. With respect to the difficulty in

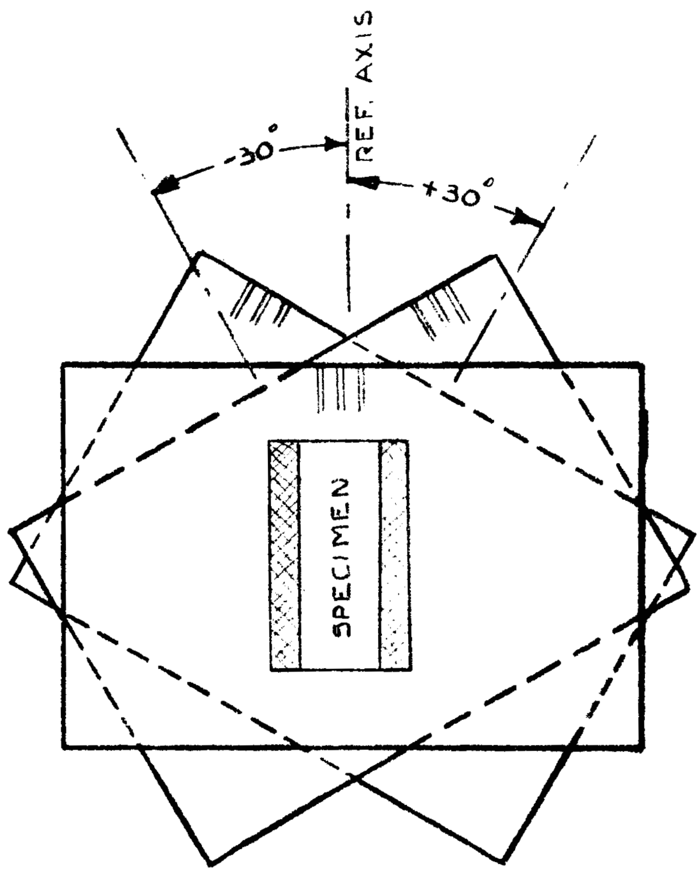
4.1.4 CROSS CORE CHARACTERISTICS CONT'D.

obtaining CROSS CORE of the exact crush strength requirement, an approval was obtained from Bendix to make the CROSS CORE configurations of such dimensions that they would meet the 5500 lb. crush load. This is discussed more fully in the following sections.

FIG. 12

METHOD OF CROSS-CORE LAY-UP

30-0-30



FOIL IS CORRUGATED 1/16" DEEP CORRESPONDING TO 1/8" CELL SIZE.

THE CROSS-CORE IS LAID-UP WITH ONE SHEET VERTICAL, THE NEXT WITH ITS CELLS +30° FROM THE VERTICAL, AND NEXT WITH -30° FROM THE VERTICAL. THEN THIS ORDER IS REPEATED.

THE SAME METHOD APPLIES TO 15-0-15

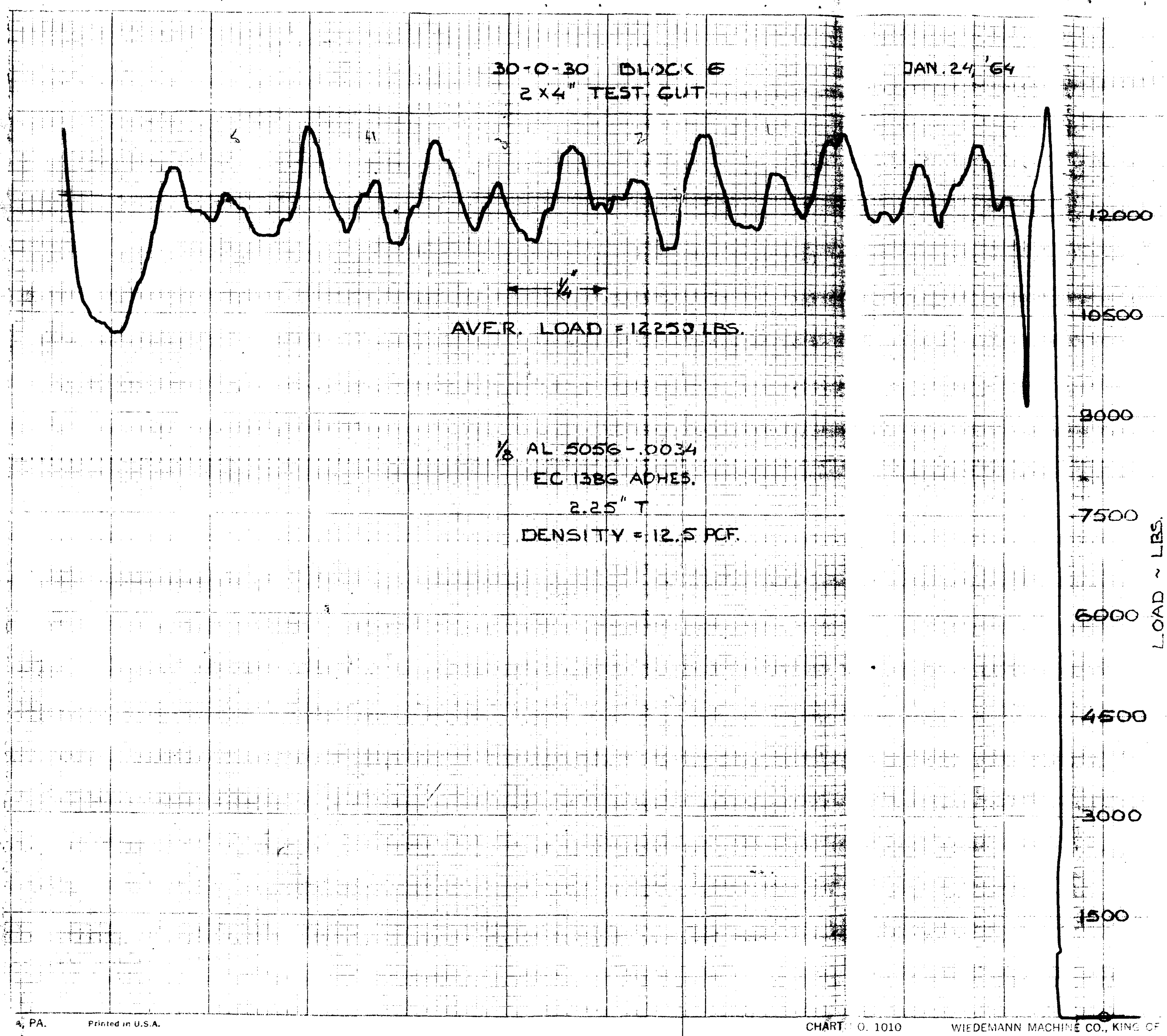
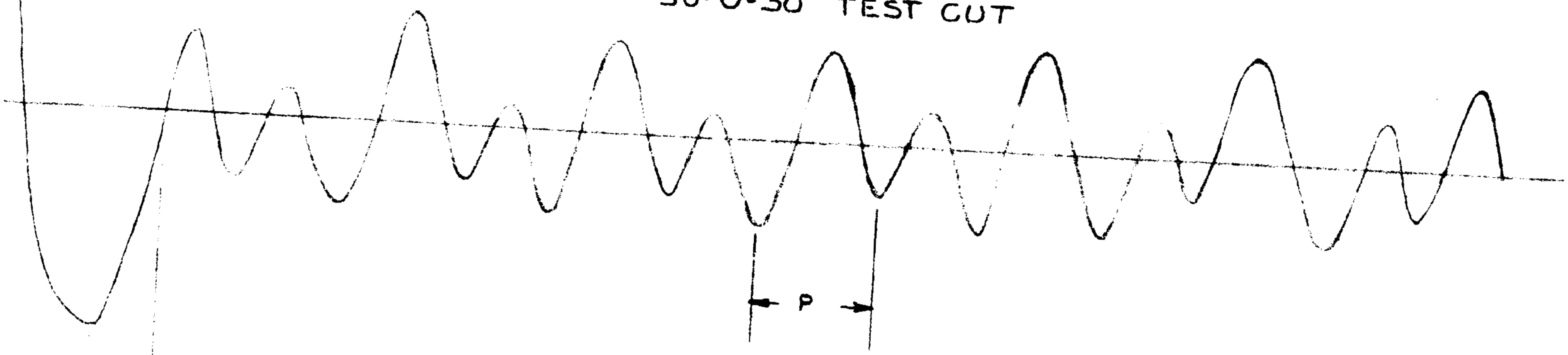

30-0-30 BLOCK 6
2 x 4" TEST CUT
JAN. 24 '64
1/4"
AVER. LOAD = 12250 LBS.
1/8 AL 5056 - .0034
EC 1386 ADHES.
2.25" T
DENSITY = 12.5 PCF.
12000
10500
9000
7500
6000
4500
3000
1500
LOAD ~ LBS.
PA.
Printed in U.S.A.
CHART NO. 1010
WIEDEMANN MACHINE CO., KING OF PRUSSIA, PA.

FIG. 13

PERIODICITY OF PEAKS

30-0-30 TEST CUT



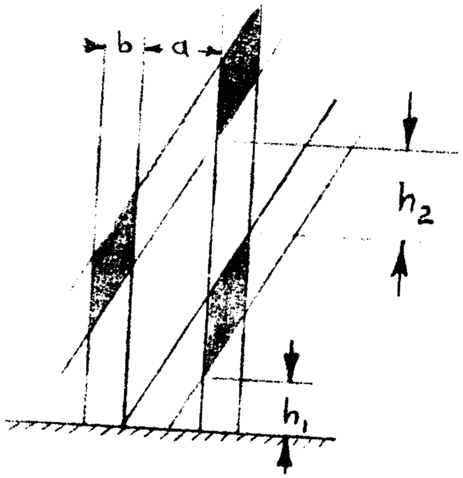
AVERAGE PERIOD $P = .17''$

FOR $\frac{1}{8}''$ CORRUGATION $b = \frac{1}{16} \frac{1}{\cos 30^\circ} = .0722''$

$$a = b + 2\,\frac{1}{16}\cot 60^\circ = .1444''$$

$$h_1 = a \tan 60^\circ - \frac{b}{\cos 60^\circ} = .106''$$

$$h_2 = \frac{a}{\cos 60^\circ} - b \tan 60^\circ = .164''$$



SHADED AREA
IS THE BOND

FIG. 14

MARCH 30, 64

PERCENT STROKE
30-0-30 CROSS-CORE

AL 1/16 5056-H39

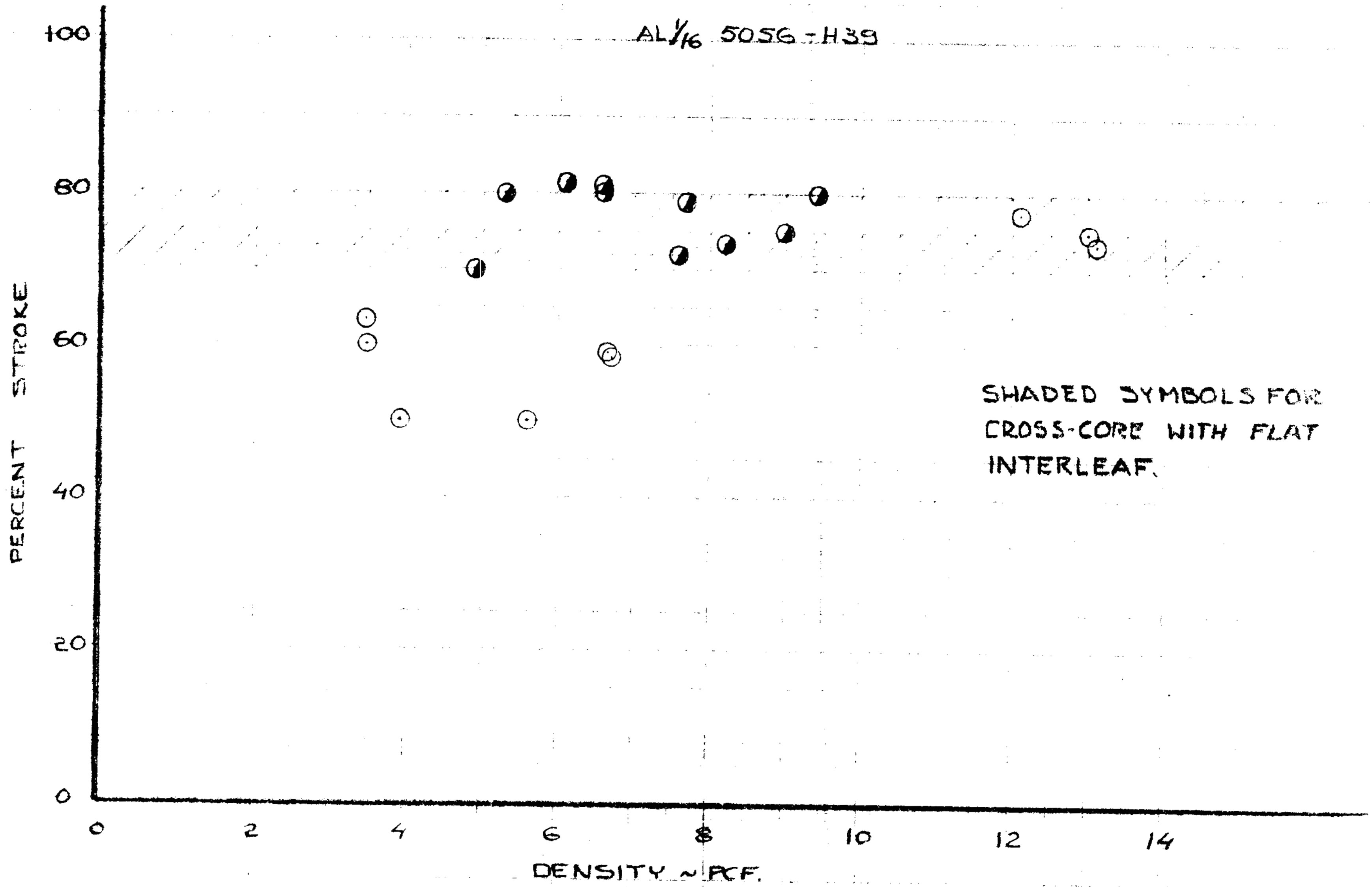
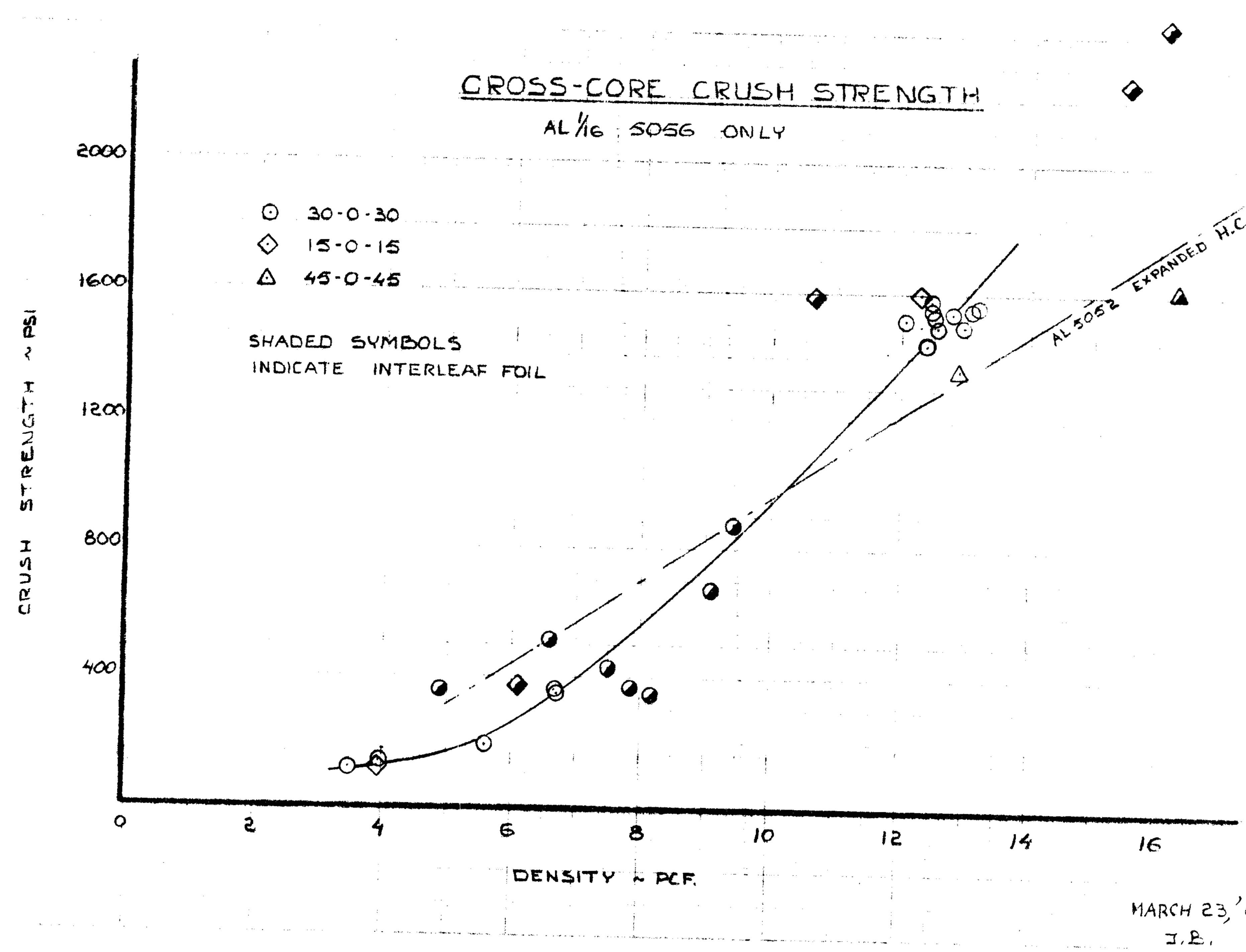
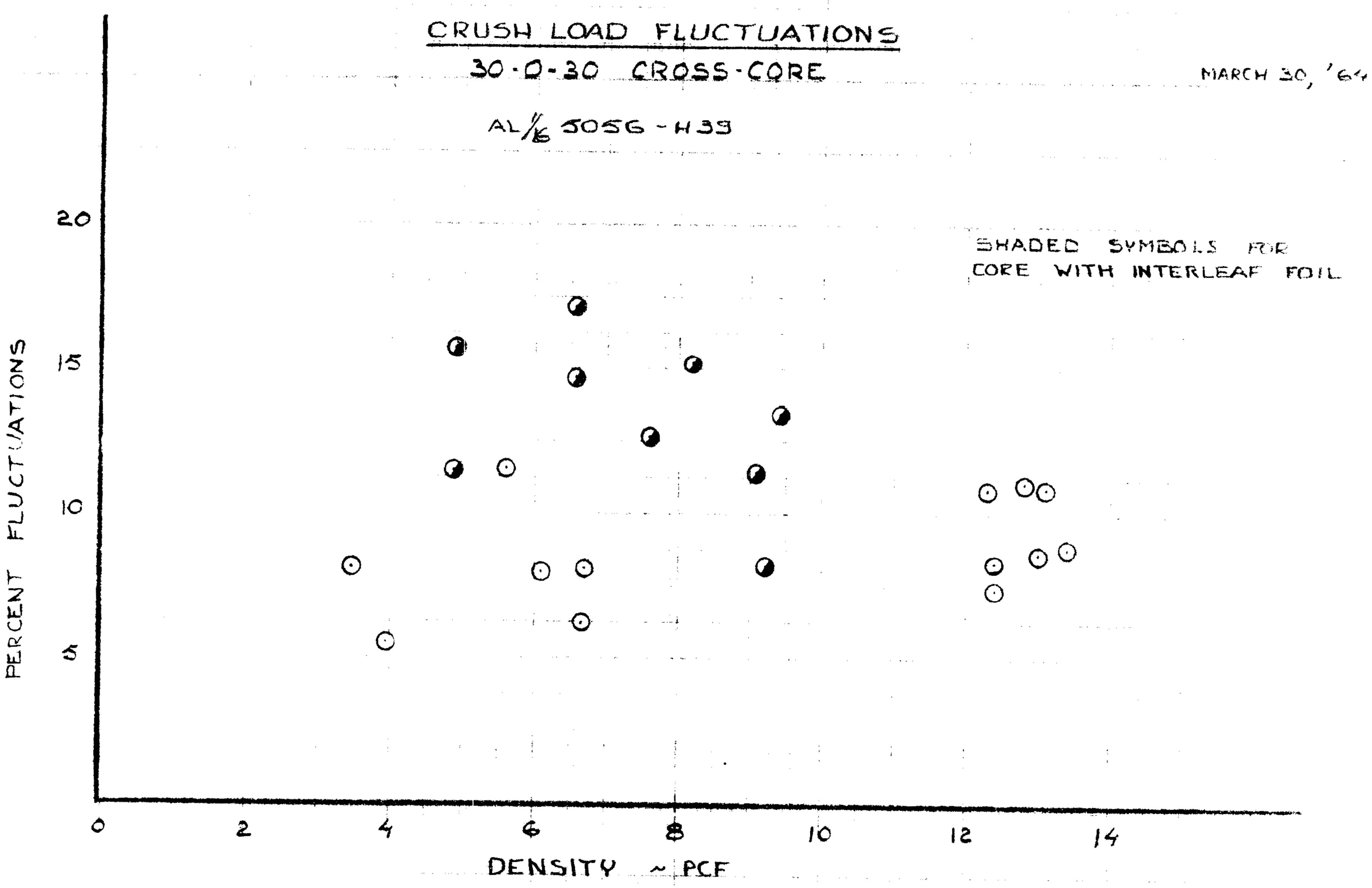


FIG. 15



CROSS-CORE CRUSH STRENGTH
AL 1/16 5056 ONLY
30-0-30
15-0-15
45-0-45
SHADED SYMBOLS
INDICATE INTERLEAF FOIL
AL 5052 EXPANDED H.C
CRUSH STRENGTH ~ PSI
2000
1600
1200
800
400
0
2
4
6
8
10
12
14
16
DENSITY ~ PCF.
MARCH 23, '64
J.B.

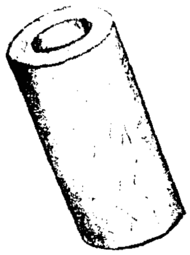
FIG. 16



CRUSH LOAD FLUCTUATIONS
30-0-30 CROSS-CORE
AL/16 5056 - H39
MARCH 30, '64
SHADED SYMBOLS FOR
CORE WITH INTERLEAF FOIL
20
15
10
5
PERCENT FLUCTUATIONS
0
2
4
6
8
10
12
14
DENSITY ~ PCF

FIG. 17

4.1.5 CONFIGURATION I-B



3"O.D. - 2"I.D.
(30-0-30)

The intitial attempts at making this configuration out of CROSS CORE material were unsuccessful in meeting the required crush characteristics. The foil gauges used were very small and the amount of adhesive used was inadequate to support the shearing loads during crushing. As a consequence, the cylinders would buckle and collapse. Such a specimen failure is shown in Figure 18. Subsequently, a thicker coat of adhesive was used and the foil gauges increased.

An attempt was made to hold the cylinder walls together and prevent the sliding and folding tendency by wrapping and bonding foil to the inside and outside of the cylinders. Although this resulted in an improved stability of the walls, the crushing of the heavy foil added peaks to the load curves during crush testing (see Figure 19). Each of the six peaks seen in the Figure 19 corresponds to a fold of the foil.

Following this, another attempt at stabilizing the cylinder walls was made by wrapping a glass filament tape, Scotch Tape No. 898, around the cylinder specimens. This gave satisfactory results. The tape has a high tensile strength, but does not contribute to the crush strength. Subsequently, it was decided that all the CROSS CORE specimens would be wound with filament tape. In order that the tape maintain its strength at higher temperatures, the #898 tape was decided to be substituted by the #870 tape which can endure 300°F.

4.1.5 CONFIGURATION I-B CONT'D.

We next directed our efforts towards obtaining the desired strength characteristics by increasing the foil gauge to .0034" and applying the EC-1386 adhesive undiluted. This gave a core density of about 12.5 pcf. The cylindrical specimens made in this manner were machined to three different outside diameters:

3.10", 3.00", and 2.90". The test results with these specimens are seen in Figure 20 which shows the resulting crush loads for the different cross sectional areas. The observations resulted in the selection of 3.10" O.D. - 2.00" I.D. as the final dimensions for the specimens.

Figure 21 shows a crush load deflection recording of one such specimen. The average load is 5500 lbs. but the fluctuations are as much as 9.3% which is much more than the allowance of $\pm$ 5%. Despite this fact, a shipment of four similar 6" T specimens was made to Bendix with the understanding that this fluctuation is inherent to the core and cannot be overcome at this time.

In order to fabricate capsules 54" long, the initial attempts were made by splicing shorter sections. While testing a spliced specimen, it was observed to buckle at the splice. To counteract this problem in another attempt, the sections were machined carefully, precrushed and bonded around a 2" O.D. mandrel. A .032" skin was used as a splice interface. However, despite the careful alignment and bonding, this column also accepted buckling (see Figures I-F and 22).

4.1.5 CONFIGURATION I-B CONT'D.

Another splicing attempt was made with several rectangular CROSS CORE blocks. The ends of these 2" x 4" blocks were cut into a V-shape and mated together as shown in Figure 23 without pre-crushing the ends. The idea behind this type of a splice was that the crushing action would gradually transfer through the splice without producing large fluctuations in the crushing load. This is what actually happened as seen in Figure 23; however, when passing through the splice, some node failures occurred and the specimen began to crush at an angle. (See Figure I-J) This accounts for the gradual drop in crush load and failure of the specimen.

The final splicing technique used was to incorporate the splicing of the 12" wide corrugated material into the block as laid up; in other words, the corrugated sheets were butted during the lay up with the spliced position varying throughout the block. The machining of the I.D. and O.D. was then performed on a 54" long block. The 2" I.D. was machined by die punching the full length, the O.D. was machined on a lathe to 3.1". Test slices were taken from each part and after obtaining the test curves it was realized some parts still had to be modified somewhat to raise the crush strength to the required 1400 psi. This was done by dipping the entire column in a diluted solution of EC-1386.

After dipping and modifying the full-length parts, they were retested to confirm meeting the 5500 lb. crush load. These parts also were wrapped with 3M's No. 870 glass filament tape. Figure 24 shows a typical load deflection curve for an end piece taken from one of the capsules provided to Bendix.

CONFIGURATION IB

NOV. 11, '63
FIG. 18

R & D # — LSR # 1111 TECH WN
DEPT. # — JOB # 2568
TEMP. RT TIME — DATE 11-11-63
MATERIAL AL - 1/8 - 5052 - .003 CROSS CORE
EC 1386 ADH. DILUTED 1:1 30-0-30

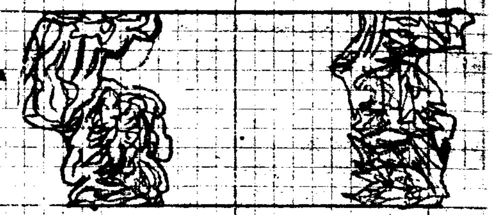
COMPRESSION TEST

SCALE 6000 LB. FULL RANGE
MAG INT 1" = 0.5

SPECIMEN NO. 1 & 3
SPECIMEN SIZE 3" OD x 2" ID x 6" T
FAILURE LOAD — LBS.
HEAD TRAVEL 0.5 INCH PER MIN.
TEST ANGLE —

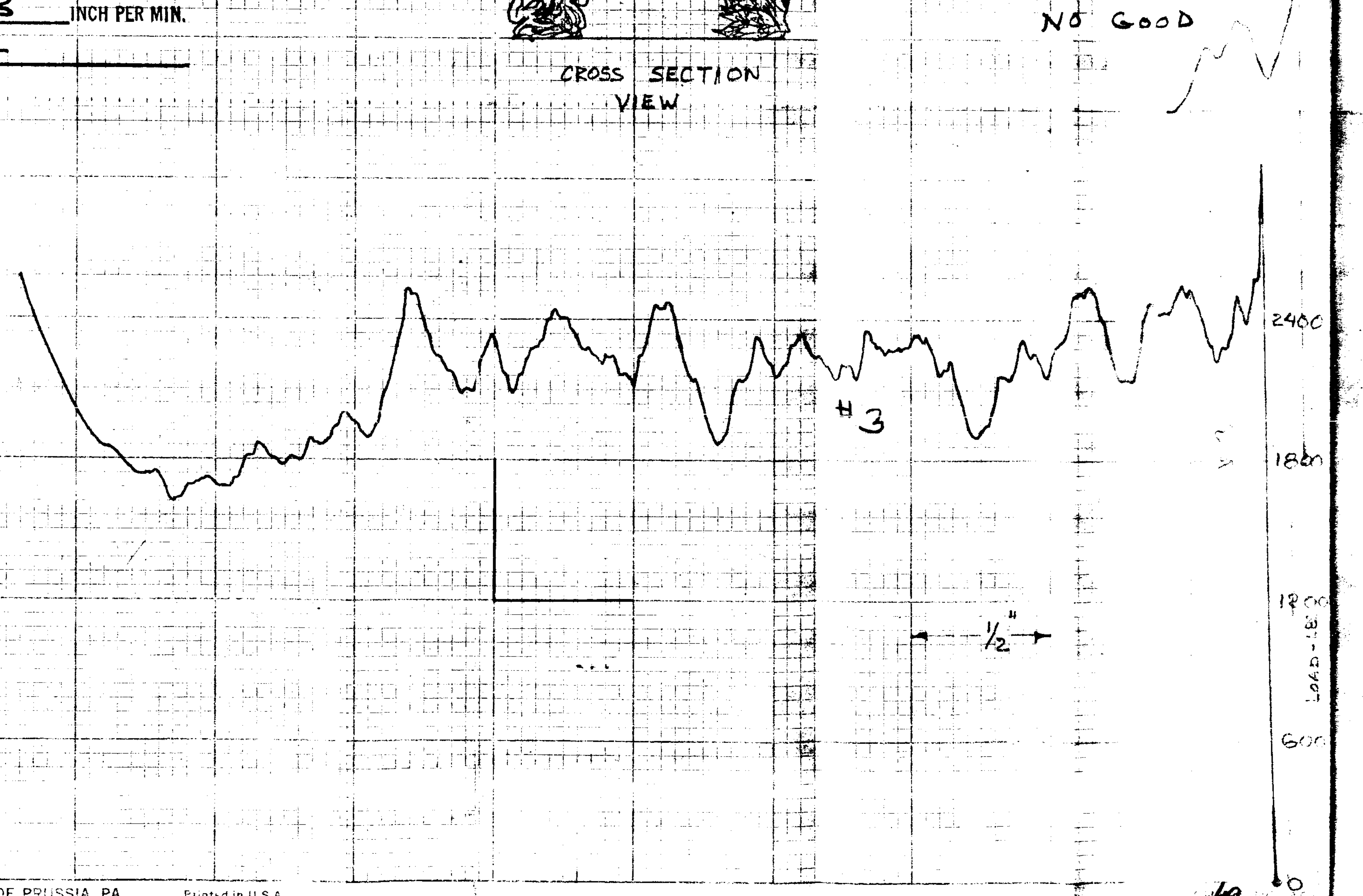
TYPE OF FAILURE

FOIL FOLDED OVER



CROSS SECTION VIEW

#1 NO GOOD



WIEDEMANN MACHINE CO., KING OF PRUSSIA, PA. Printed in U.S.A.

CONFIGURATION 1B

3" OD - 2" ID - 4" T

...SSION TEST

LB. 1/2 RANGE

1" = 1/2

FIG. 19

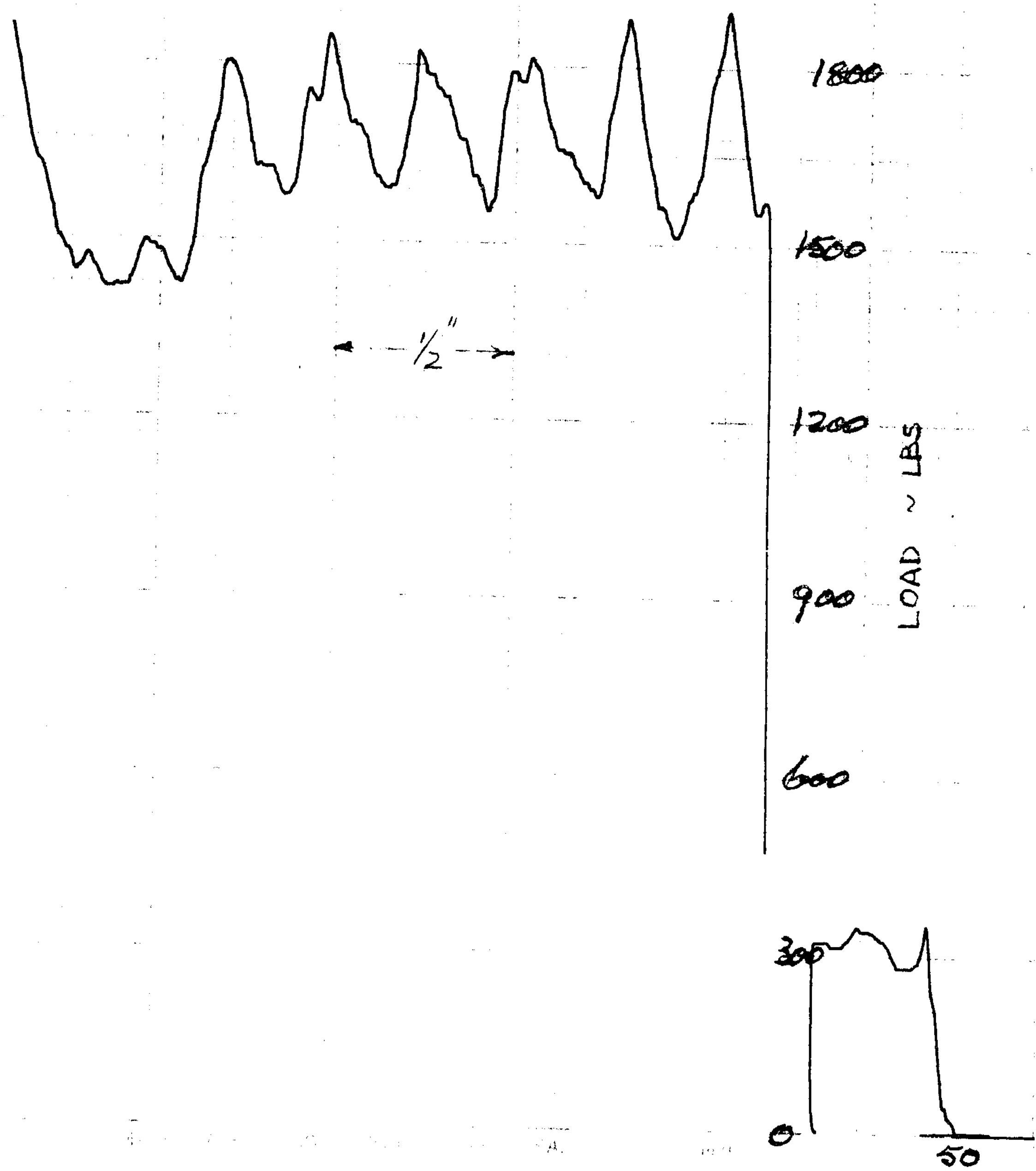
LSR # 1111

DEPT. # ______ JOB # 2568

TEMP. RT TIME ______ DATE Dec 14 '63

MATERIAL 1/8 Al 5052 - .0013 30-0-30

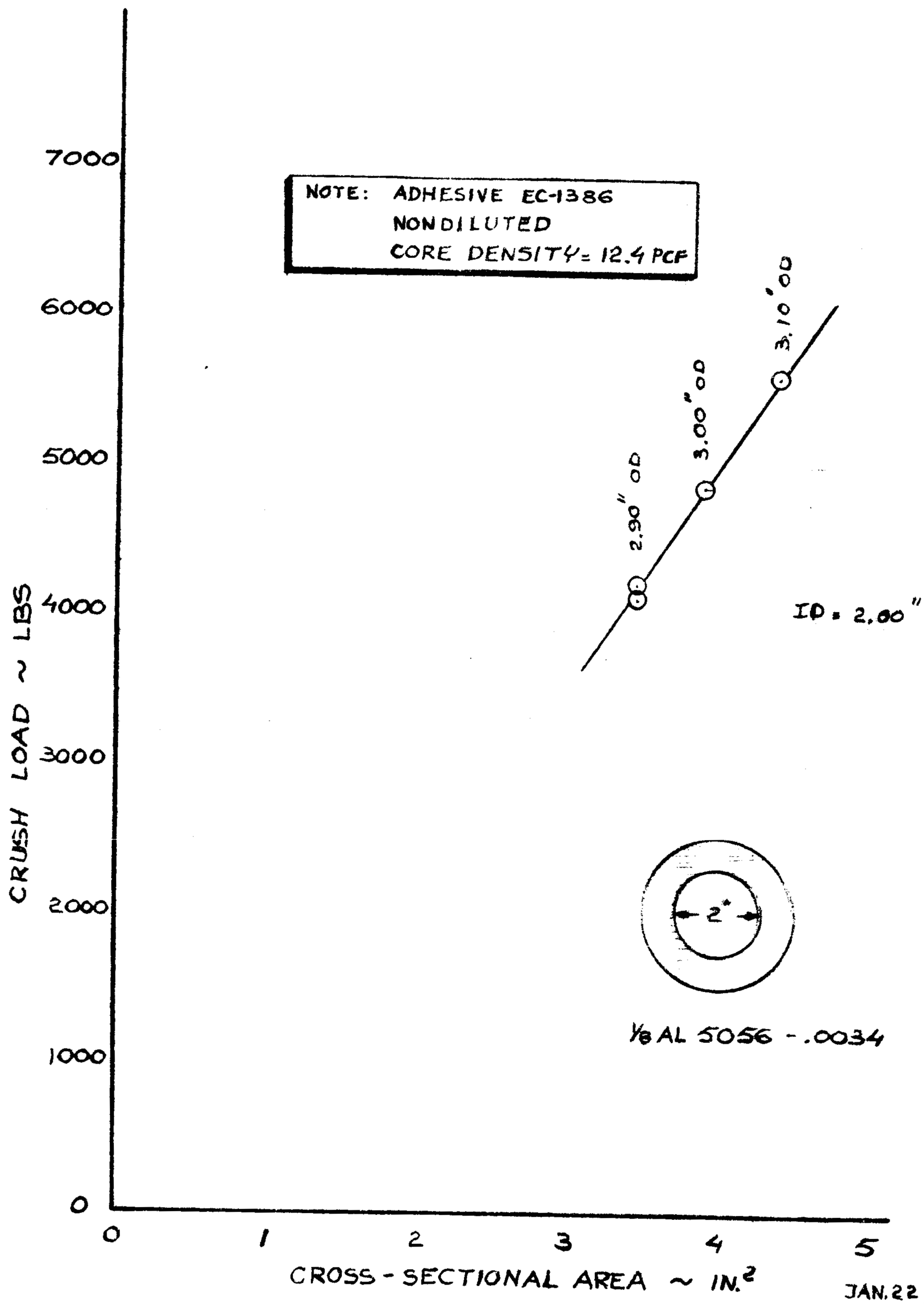
AL .004 SKIN INSIDE & OUTSIDE CYLINDER WALL



EFFECT OF DIAMETER ON CRUSH LOAD

FIG. 21

30° CROSS CORE CYLINDER



JAN. 22, '64
LSR 1111
JOB 2568
BENDIX ENERGY ABS.

FIG. 27

COMPRESSION TEST

DATE 3.2 ... RANGE ... 1/2

MAX. I ... 1/2"

SPECIMEN NO. 1 B 10

SPECIMEN SIZE 3.1"OD - 2.0 ID 4.0"T

FAILURE LOAD — LBS.

HEAD TRAVEL 1.0 INCH PER MIN.

TEST ANGLE 0°

... # — LSR # 1111 TECH J.D.

DEPT. # — JOB # 2568

TEMP. RT TIME DATE Jan 15, 64

MATERIAL 1/8 Al 5056 -.0034 30-0-30

BL. BR. 1386 ADHES.

STROKE = 72.7%

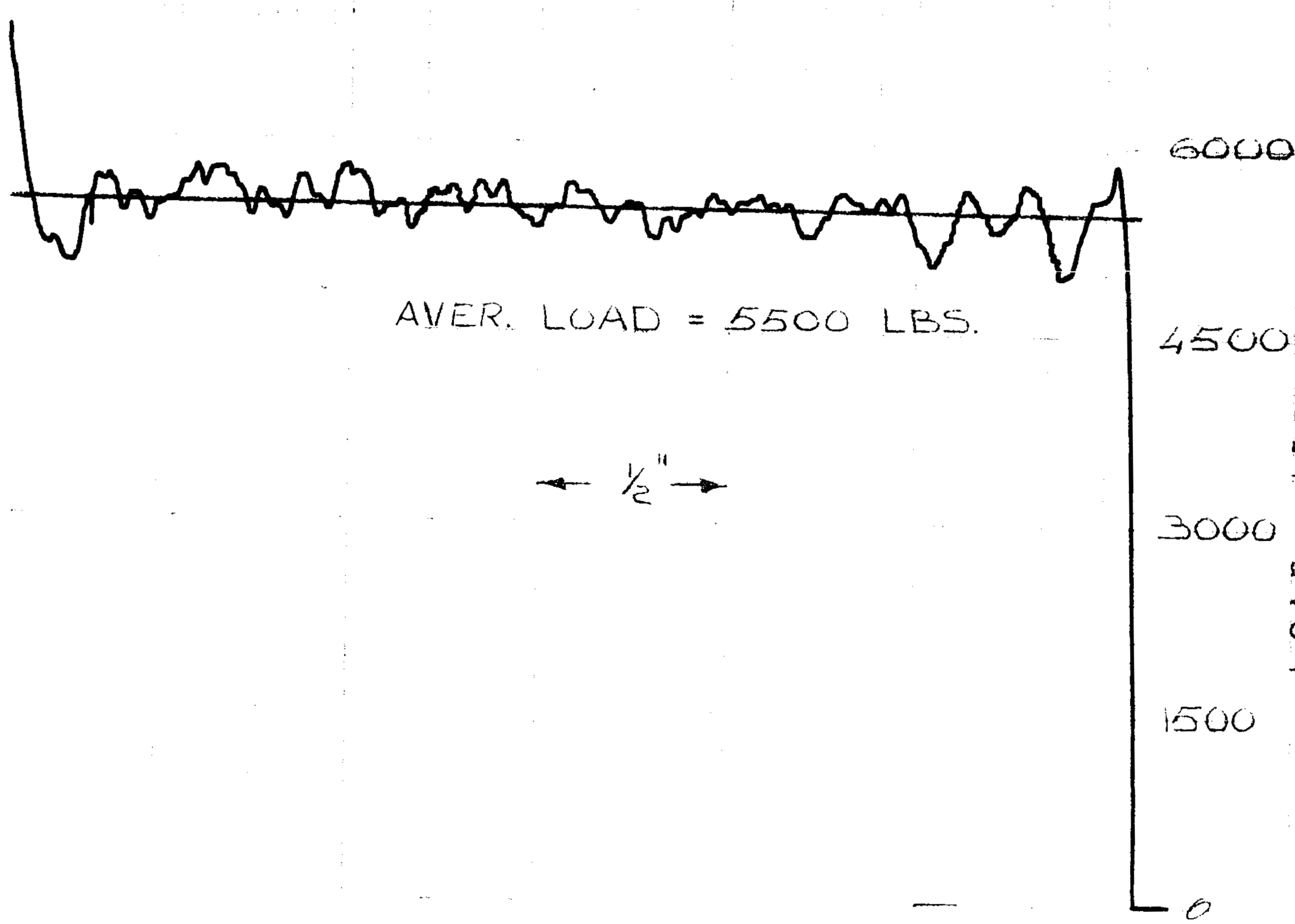


FIG. 22

FEB. 3, '64

CONFIGURATION I-B

3.10 OD - 2.0 ID

2 SPLICED SECTIONS

.032" INTERFACE

30-0-30 CORE

SEE FIG. 1.F

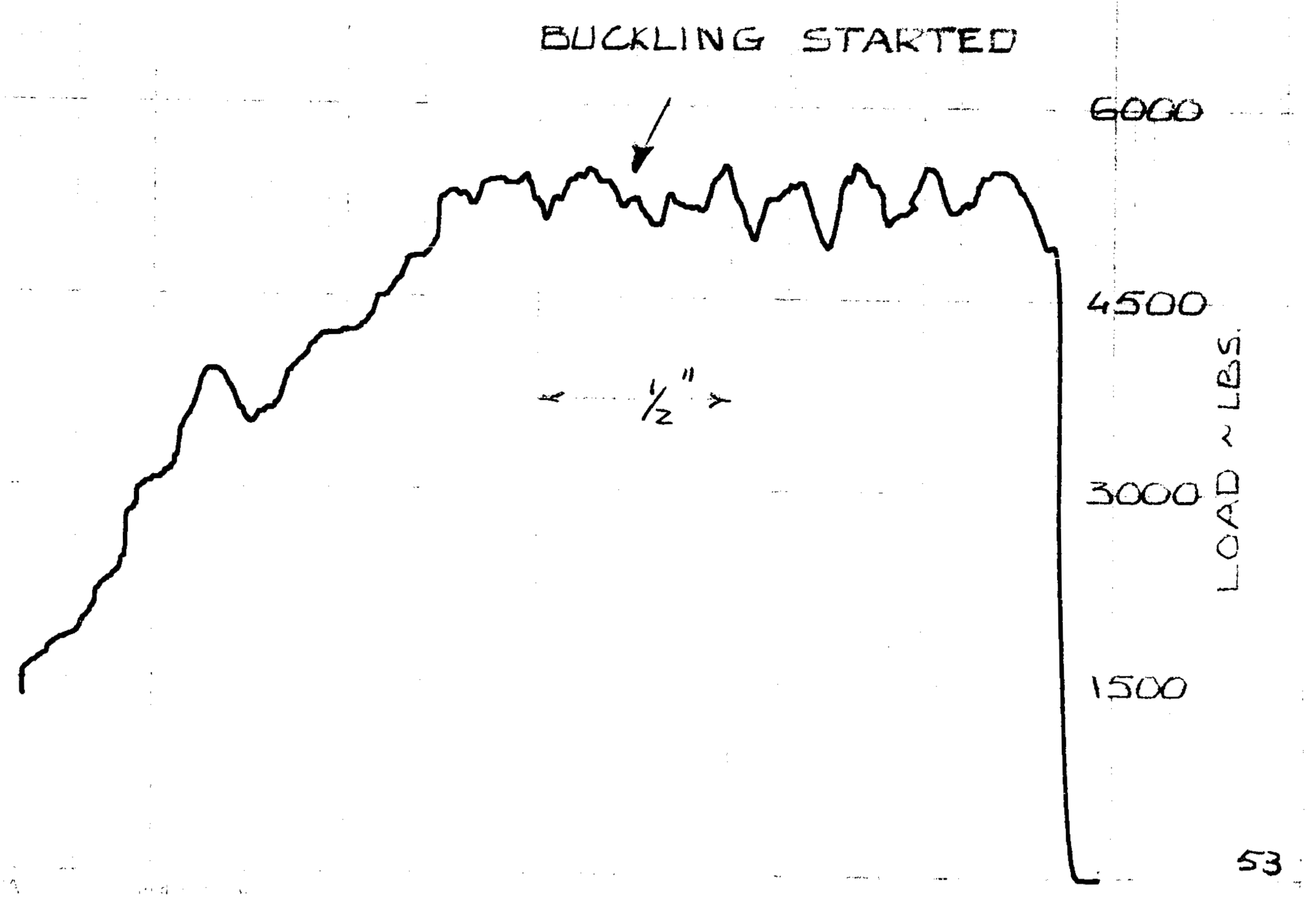
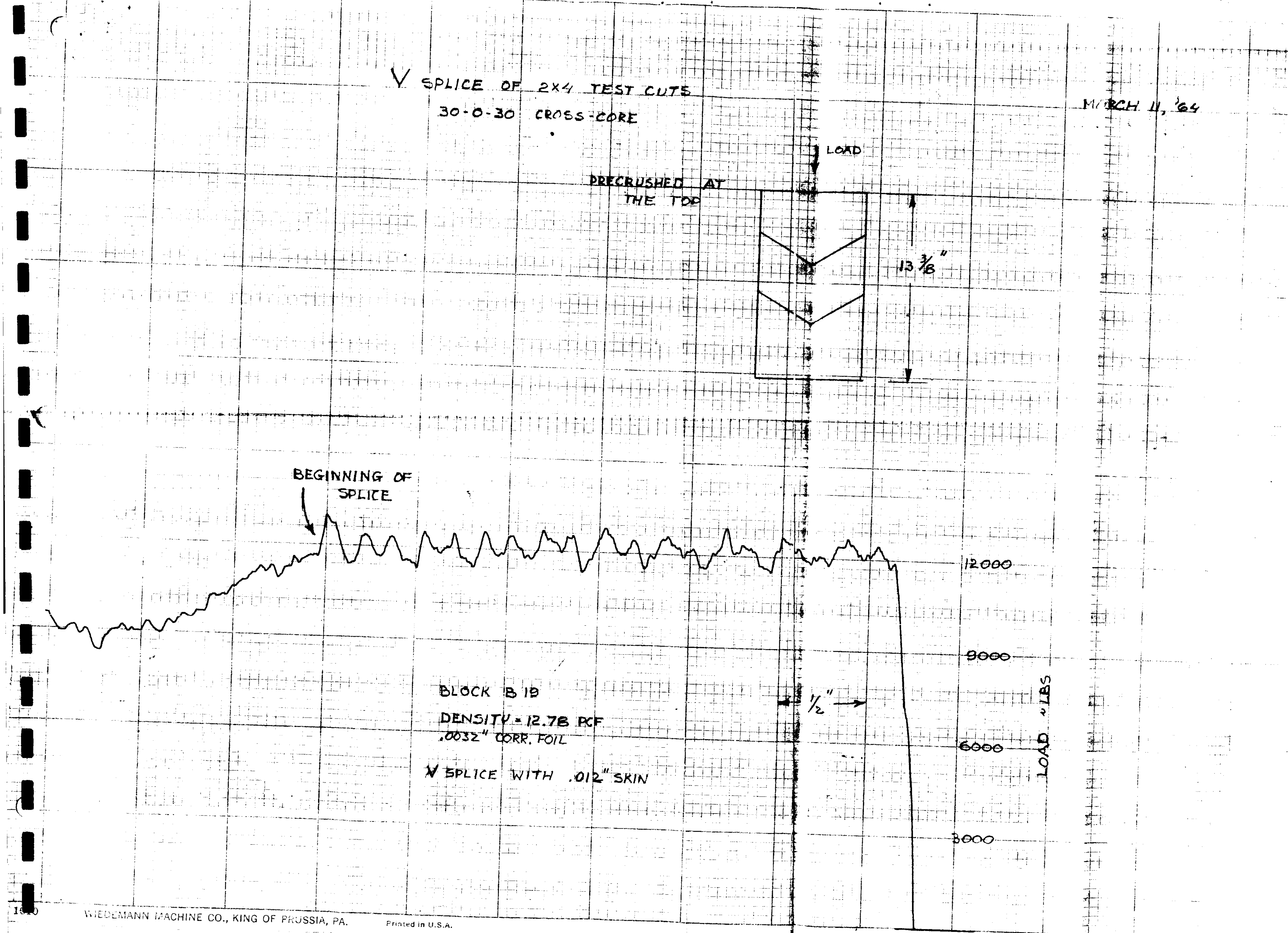


FIG 23


V SPLICE OF 2x4 TEST CUTS
30-0-30 CROSS-CORE
MARCH 11, '64
LOAD
PRECRUSHED AT THE TOP
13 3/8"
BEGINNING OF SPLICE
1/2"
12000
9000
6000
3000
LOAD ~ LBS
BLOCK B 19
DENSITY = 12.78 PCF
.0032" CORR. FOIL
V SPLICE WITH .012" SKIN

CONFIGURATION 1B
SPX 168 TYPE B
END CUT 1B-5
3"OD - 2"ID - 3.36"T

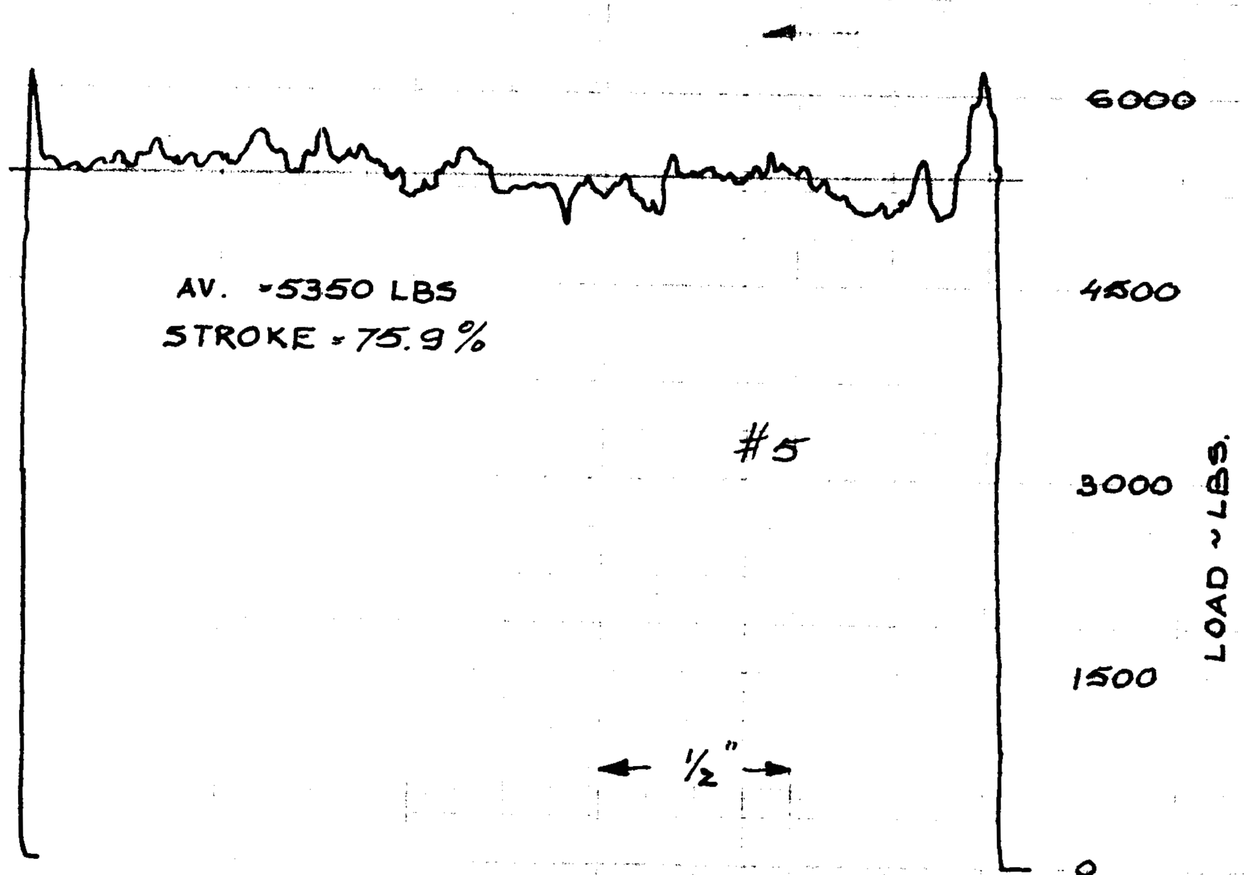
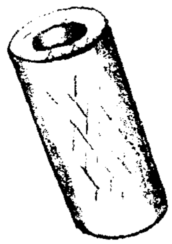


FIG. 24

4.1.6 CONFIGURATION I-A

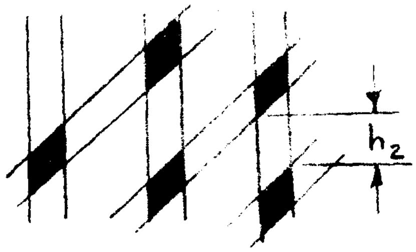


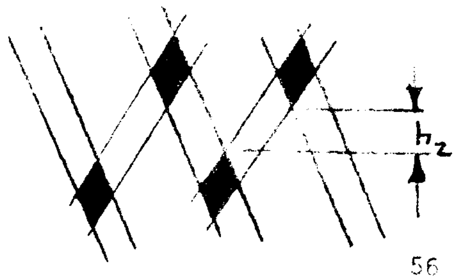
3" O.D. - 2"I.D. 15° CELL ORIENTATION

Until the use of a flat foil interleaf was considered, as discussed in the "CROSS-CORE Characteristics" section, the 15° oriented CROSS-CORE cylinders which were tested exhibited very unsatisfactory crushing characteristics. Without the interleaf, the cylinder walls buckled and folded over non-uniformly resulting in wide fluctuation of the crush load.

The initial specimens were made of the 15-0-15 CROSS-CORE type, using a light foil gauge and a thin application of diluted EC-1386 adhesive. A typical load curve and the resulting failure observed in these low-density cylinders are shown in Figure 25.

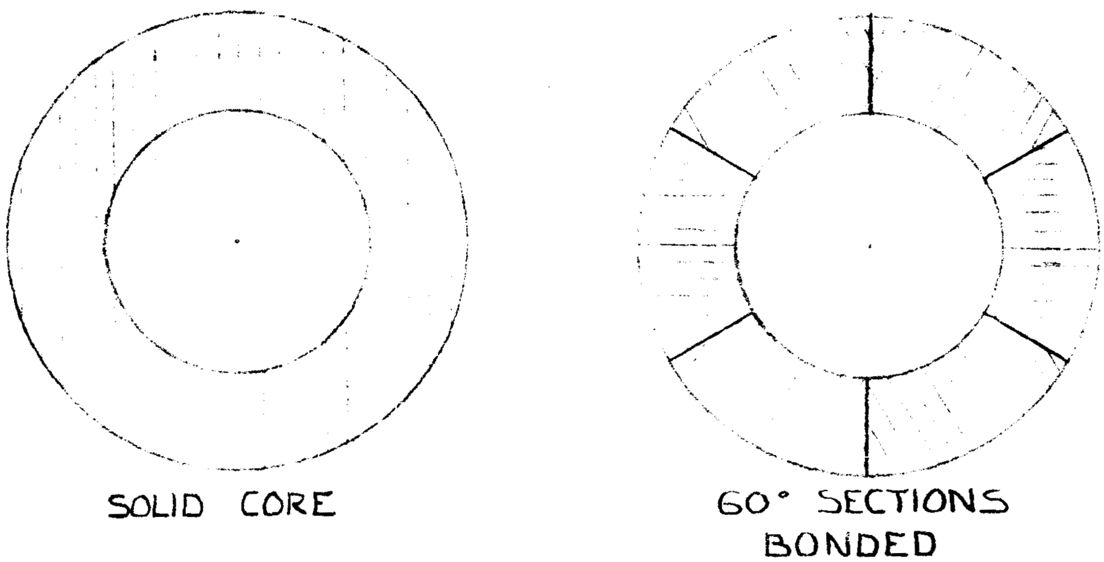
One reason for such behavior is the distance "h_2" (see Figure 14) of unsupported foil between nodes. In order to reduce this distance, the sheets were laid up in a 15-15-15 pattern instead of a 15-0-15 pattern by eliminating the sheets with corrugations at 0° to the reference axis and alternating the +15° and -15° sheets. The sketch below illustrates the reduction in "h_2" obtained in this manner. In addition, the foil thickness was increased and undiluted adhesive was applied in an effort to obtain the desired crush load. Another solution attempted was wrapping the specimens with 898 filament tape. However, in spite of these efforts, the cylinder walls still exhibited buckling and folding. The load curve and the drop off in load under these circumstances are shown in Figure 26.





4.1.6 CONFIGURATION I-A CONT'D.

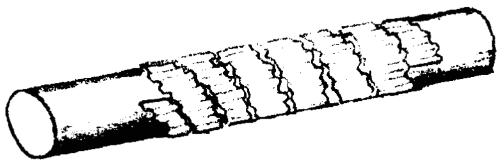
On examination of the specimen failures, it was noticed that all of them occurred in the direction perpendicular to the ribbon (see sketch below). The reason for this was believed to be the non-symmetrical orientation of the cells with respect to the specimen centerline. To counteract this, some specimens were made from six sections cut at 60° and bonded together, with the ribbon in each section pointing towards the center.



The specimens prepared in this manner were machined to three different diameters, wrapped with tape and tested. However, the results were again disappointing. The load curves of six such specimens are shown in Figure 27. A photograph of the type of failures for specimen numbers 1A-10 and 1A-15 is seen in Figure I-A.

4.1.6 CONFIGURATION I-A CONT'D.

Another method that was attempted for fabricating specimens of this capsule type was "helical wrapping". This method involved wrapping narrow corrugated foil strips around a mandrel. The angle at which the strips were wrapped was 15° as illustrated below.



On testing, however, this type of core was found to have extremely poor crushing characteristics. During loading, the edges of the strips cut into each other and folded over, producing unfavorable results. The actual test results obtained were shown in Figure 28 and no uniform crushing was obtained with this type.

Finally, the idea of using a flat foil interleaf occurred to us and was tried out. Figure 29 is a crush load recording of two cylinders made in this manner. The first specimen again failed by folding over at the edges but the second one crushed uniformly for the total length. The load fluctuations, however, were still found to vary as much as 14% from the average.

This configuration also was finally made by interleafing the splice in the block during lay up and then machining the I.D. and O.D. as discussed in Section 4.1.5. Despite the fact that in some cases this 15° oriented

4.1.6 CONFIGURATION I-A CONT'D.

CROSS-CORE exhibited buckling during crushing, it was believed to be the best effort Hexcel could provide in making this configuration to the original requirements. Figure 30, again, shows a typical load deflection curve of a short end sample taken from one of the parts provided to Bendix. Although this is a short section and exhibits a fairly good crush curve, subsequent tests by Bendix indicated that for the long capsule buckling was still occurring.

FIG. 25

CONFIGURATION IA

COMPRESSION TEST

SCALE 6000 LB. Half RANGE

MAG I 1" = 0.5

SPECIMEN NO. 9

SPECIMEN SIZE 3" OD. 2" ID 4" T

FAILURE LOAD — LBS.

HEAD TRAVEL 0.5 INCH PER MIN.

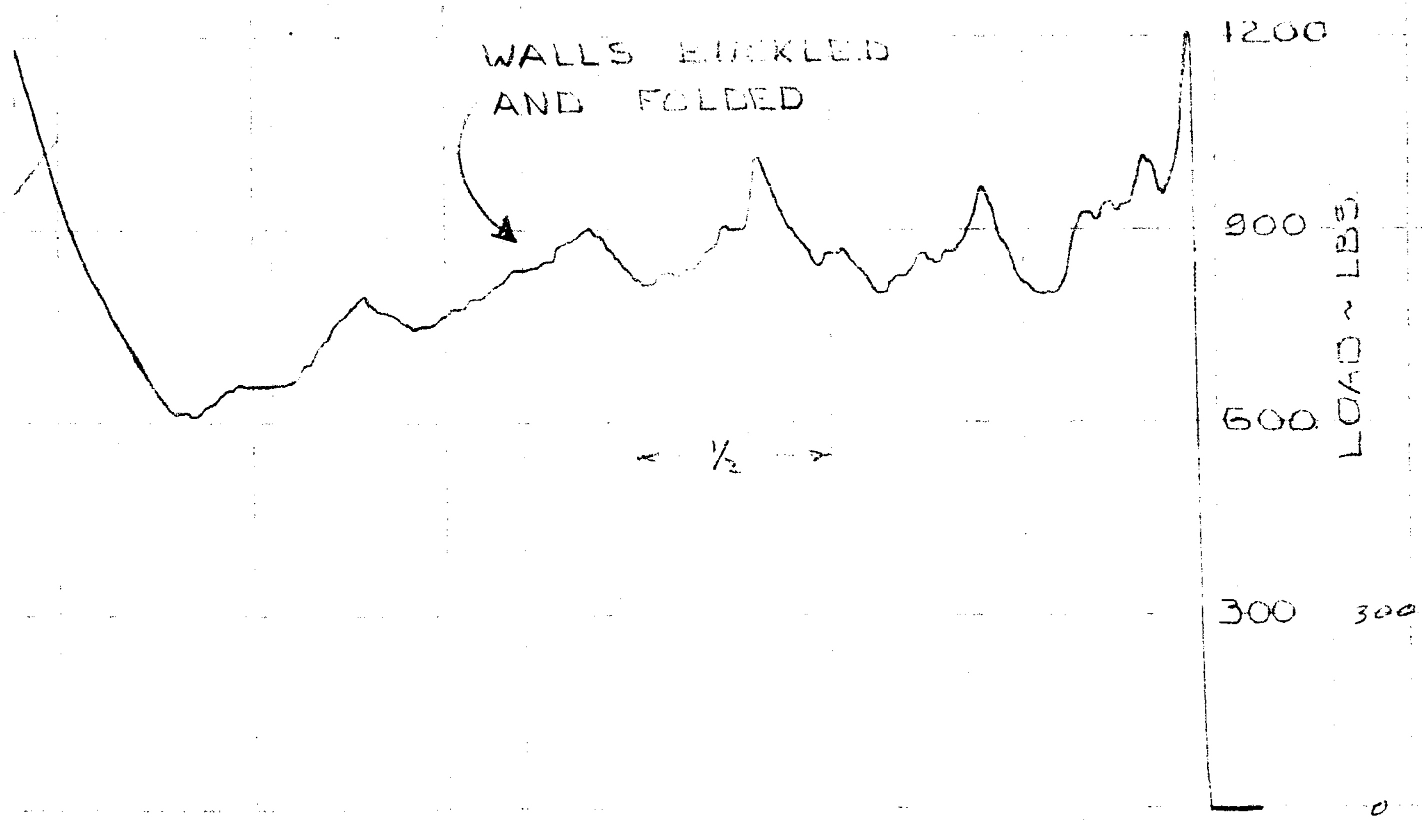
TEST ANGLE —

I.D. # — LSR # 1111 TECH JD

DEPT. # — JOB # 2568

TEMP. RT TIME — DATE 11-10-63

MATERIAL Al 1/8 5052 - .0013" - Cross Core 15-0-15



CONF[illegible]TION IA
3" OD - 2" ID - 4" T

FIG. 26

R & D # ______ ESR # [illegible] TECH. [illegible]

DEPT. # ______ JOB # [illegible]

TEMP. RT TIME ______ DATE DEC 19, 63

MATERIAL 1/8 AL 5056 - .0026 15-15-15

LBS.

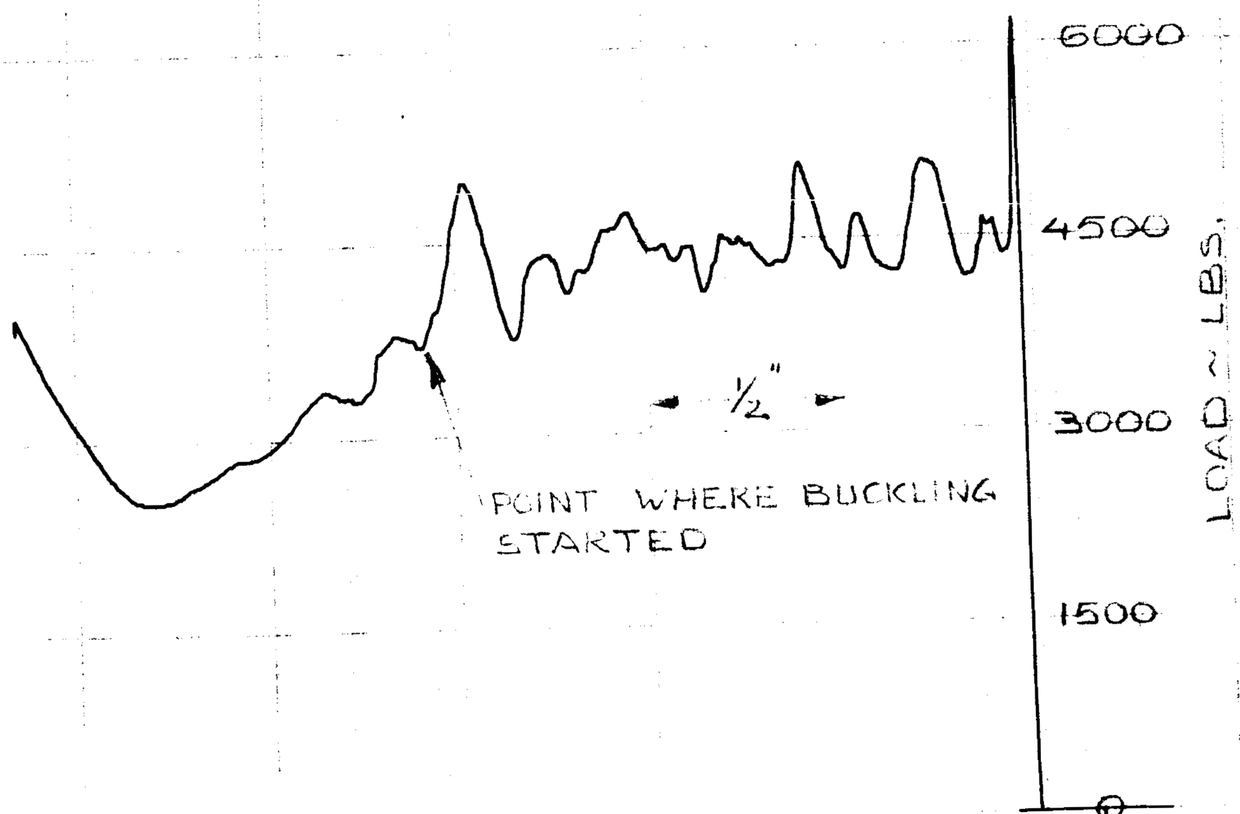
INCH PER MIN.

COMPRESSION TEST

SCALE 30000 LB. 1/4 RATIO

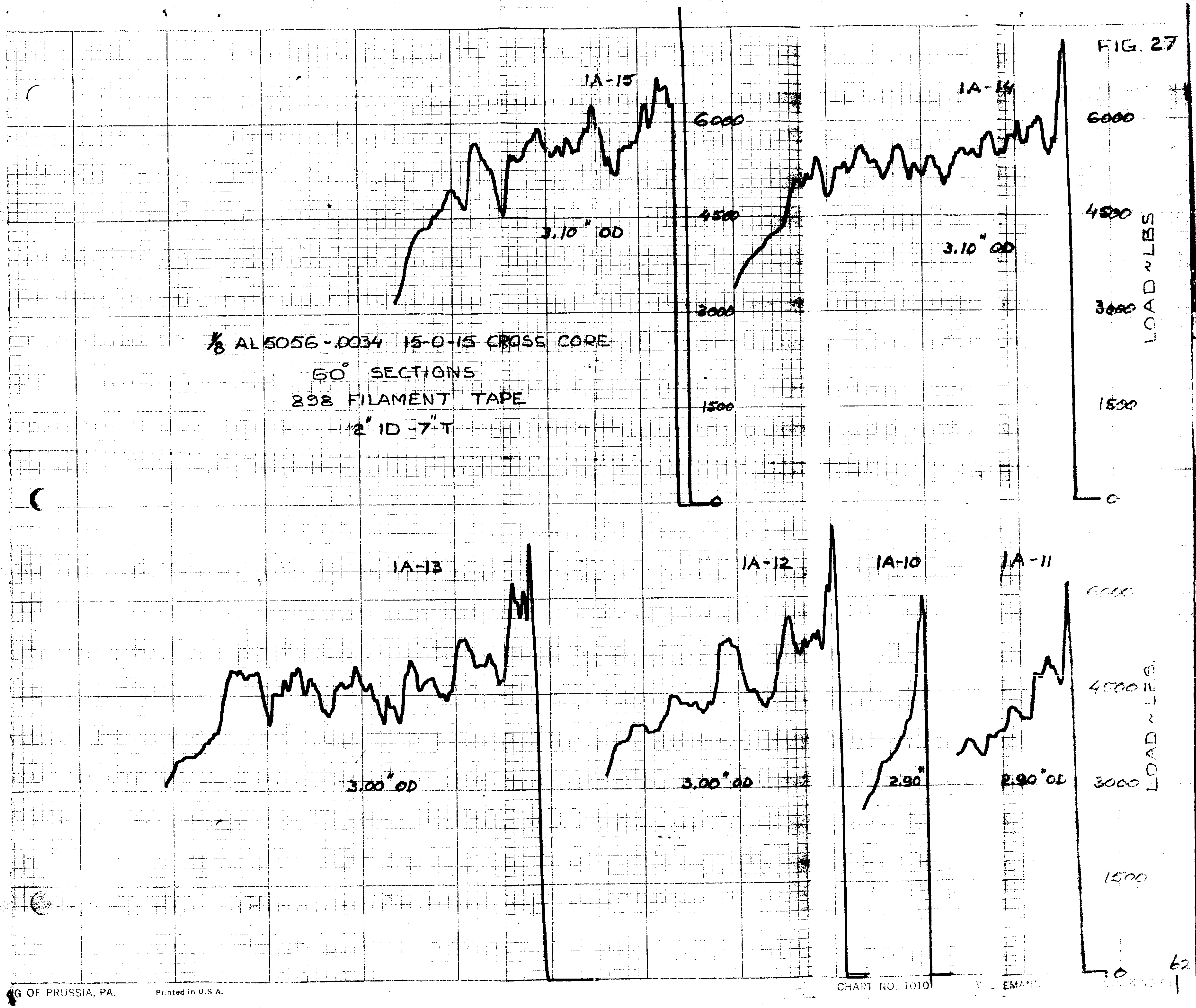
MAG [illegible] 1/2

WRAPPED WITH 898 TAPE



6

FIG. 27



1A-15
3.10" OD
1A-14
3.10" OD
6000
4500
3000
1500
0
LOAD ~ LBS
1/8 AL 5056-.0034 15-0-15 CROSS CORE
60° SECTIONS
898 FILAMENT TAPE
2" ID - 7" T
1A-13
3.00" OD
1A-12
3.00" OD
1A-10
2.90"
1A-11
2.90" OD
4000
CHART NO. 1010
G OF PRUSSIA, PA.
Printed in U.S.A.

FIG. 28

JAN. 24, '64

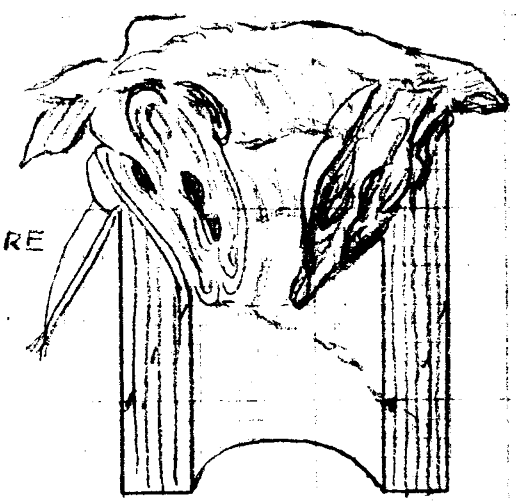
HELICALLY WRAPPED CYLINDER

1/8 AL 5056 - .0014 - .0014
DENSITY = 8.45 PCF

2.78" OD - 2" ID · 7.0" T

REICHHOLD EPOTUF ADHESIVE

TYPE OF FAILURE



1½" WIDE FOIL CORRUGATED
TO 9° OFF THE VERTICAL
WRAPPED WITH 1½" WIDE SKIN

AVERAGE STRENGTH = 256 PSI
OR ABOUT 1/3 OF SPIRAL
WRAPPED CYLINDERS

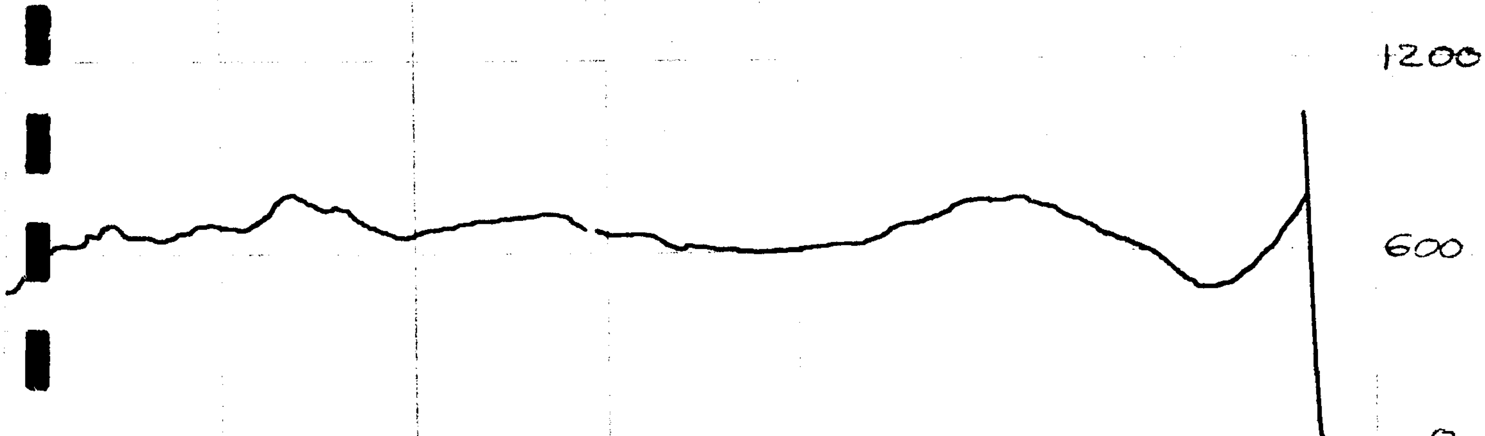
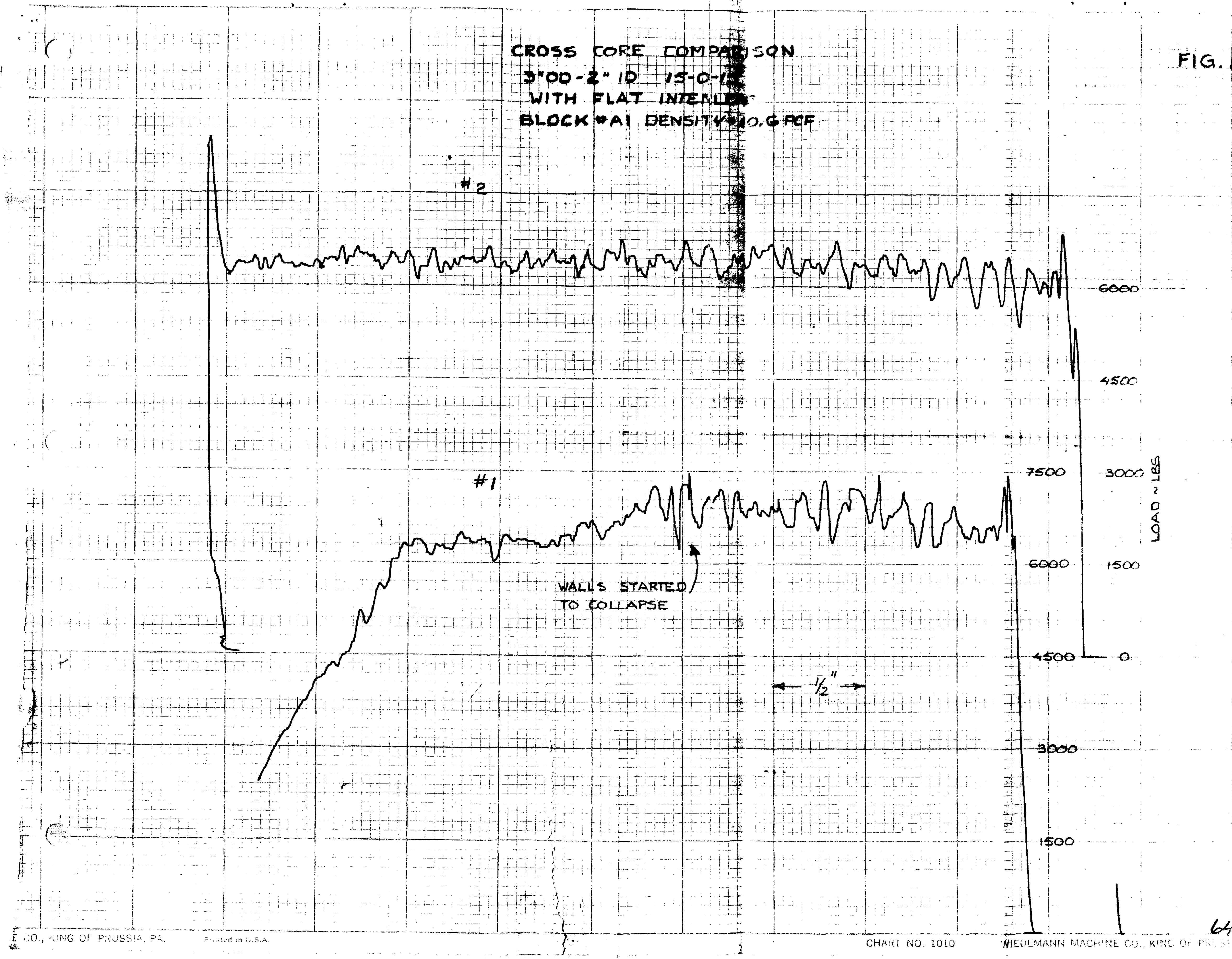


FIG. 25


CROSS CORE COMPARISON
3"OD-2" ID 15-0-15
WITH FLAT INTERLINER
BLOCK #A1 DENSITY 10.G PCF
#2
#1
WALLS STARTED TO COLLAPSE
1/2"
6000
4500
3000
1500
0
7500
6000
4500
3000
1500
LOAD ~ LBS

64

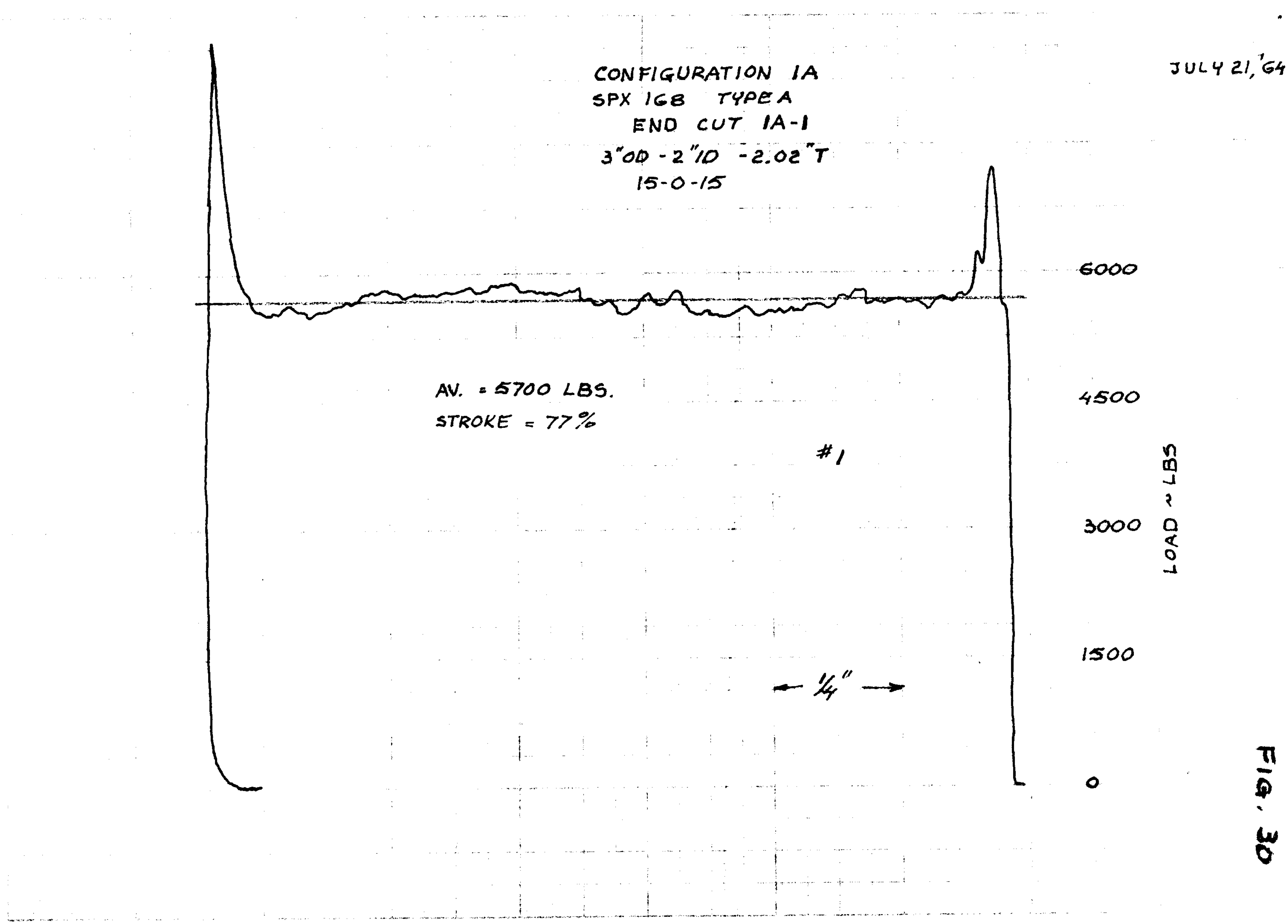
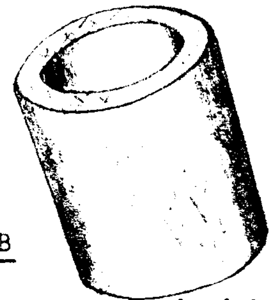

JULY 21, '64
CONFIGURATION IA
SPX 168 TYPE A
END CUT IA-1
3"OD - 2"ID - 2.02"T
15-0-15
AV. = 5700 LBS.
STROKE = 77%
#1
← 1/4" →
6000
4500
3000
1500
0
LOAD ~ LBS

FIG. 30



4.1.7 CONFIGURATIONS 2A AND 2B 6.8"O.D. - 6.0"I.D. CROSS CORE

Much difficulty has been enountered with these configurations. The initial attempts with CROSS CORE were completely unsuccessful for these configurations. Instability of thin walled core caused buckling and folding of the cylinder walls as soon as the crushing load was applied. Figure 31 shows the load curve of two specimens made from 30-0-30 CROSS CORE. The cylinders were made from six 60° sections bonded with the foil ribbon in each section pointing towards the center following which the O.D. and I.D. were machined. The specimens were wrapped with 898 filament tape. Figure IB is a photograph of the type of failure encountered. Helical wrapping of this type has been completely unsuccessful due to the folding of the foil edges as described previously. Figure IC is a photograph of the results. Note, a section has been cut out to show the inside details.

An agreement was made with Bendix to investigate the effect of increasing the wall thickness in an attempt to eliminate this instability. At the same time, the use of an interleaf foil would also be tried out for these configurations. To this effect, four sizes were chosen for this comparison, all with a 5.5 I.D. viz:

a. 6.30" O.D.

b. 6.62" O.D.

c. 6.94" O.D.

d. 7.26" O.D.

4.1.7 CONFIGURATIONS 2A AND 2B CONT'D.

The first attempt of this comparison was made with heavy-density core. It was found that all the 6-1/4" T specimens crushed without buckling but the loads were too large to make the comparison valid. The second attempt was made with lower-density core, the interleaf foil added. Figure 32 shows the load recording for the 6.62" O.D. specimens. The specimen crushed well but because of the interleaf foil, the core strength was still found to be well above the desired 5500 lbs. The load fluctuations were as high as 9.1%.

Because of the difficulties in obtaining specimens that would not buckle and also have the desired crush strength, a second agreement was made with Bendix that Hexcel would attempt to make specimens of such dimensions that buckling would not occur and that presently available foil gauges could be used. This necessitated increasing the cell size for a 1/16" depth corrugation to a 3/32" depth corrugation. Again, by interleafing the butt splice during the lay up of the core, the capsules could be made the full length without and difficulties of splicing sections together. Capsules were fabricated in this manner and shipped to Bendix. Figure 33 shows an end sample from one of these capsules.

CONFIGURATION 2B

FIG. 31.

1/8 AL 5056-.0034 30-0-30

JAN. 20, '64

6.8" OD-6.0" ID 7" T
60° SECTIONS

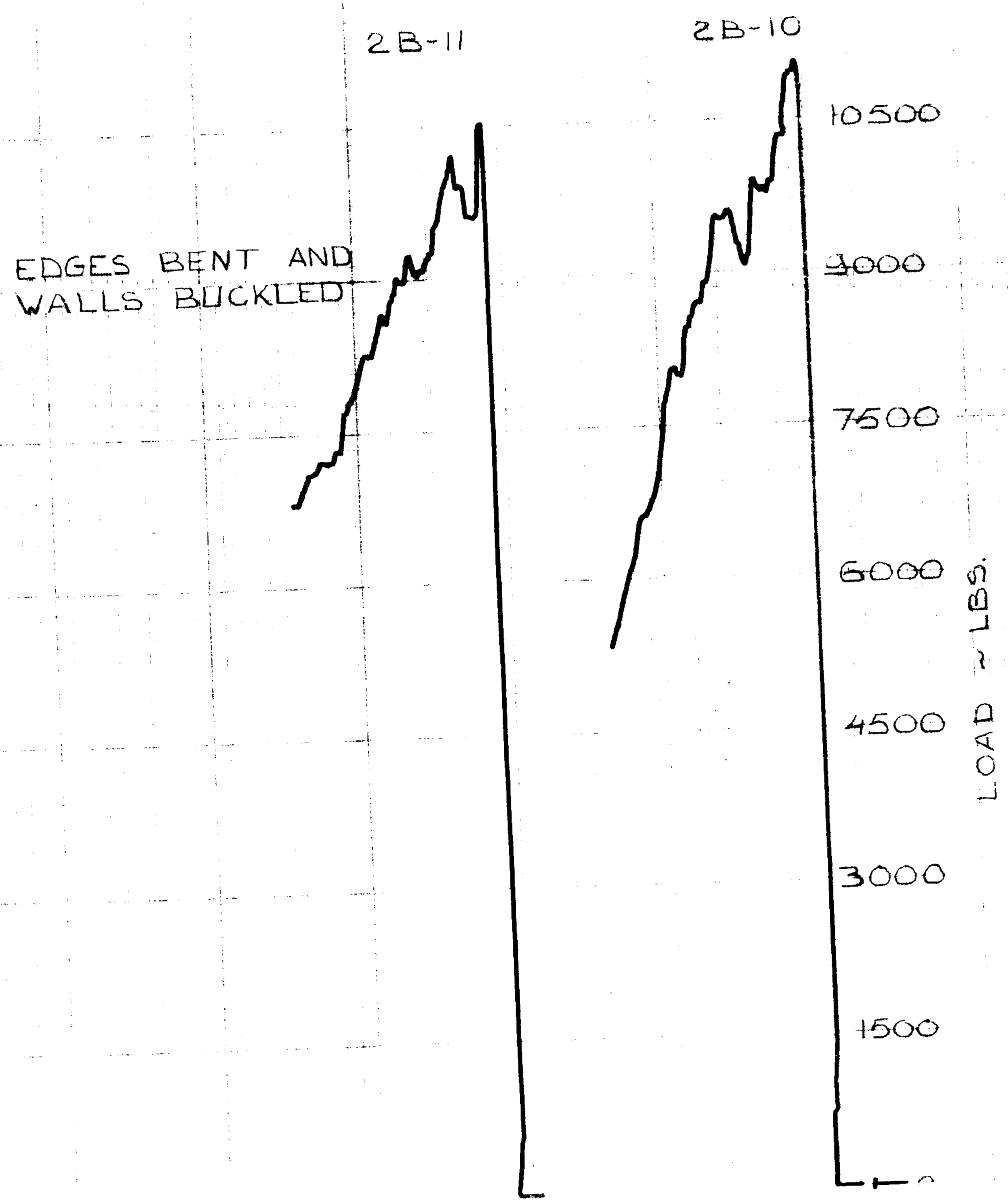
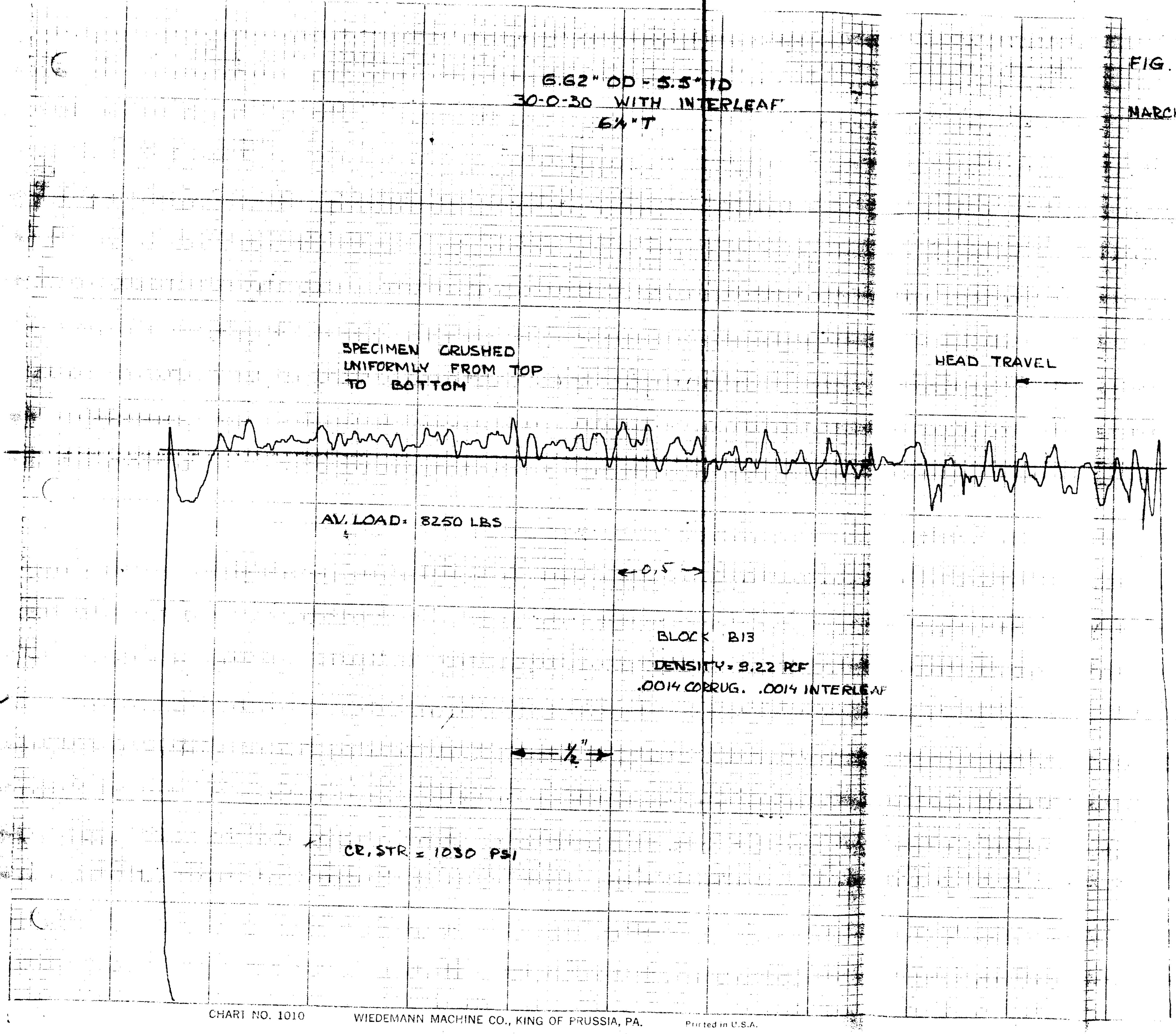


FIG. 32

MARCH 3, 1964



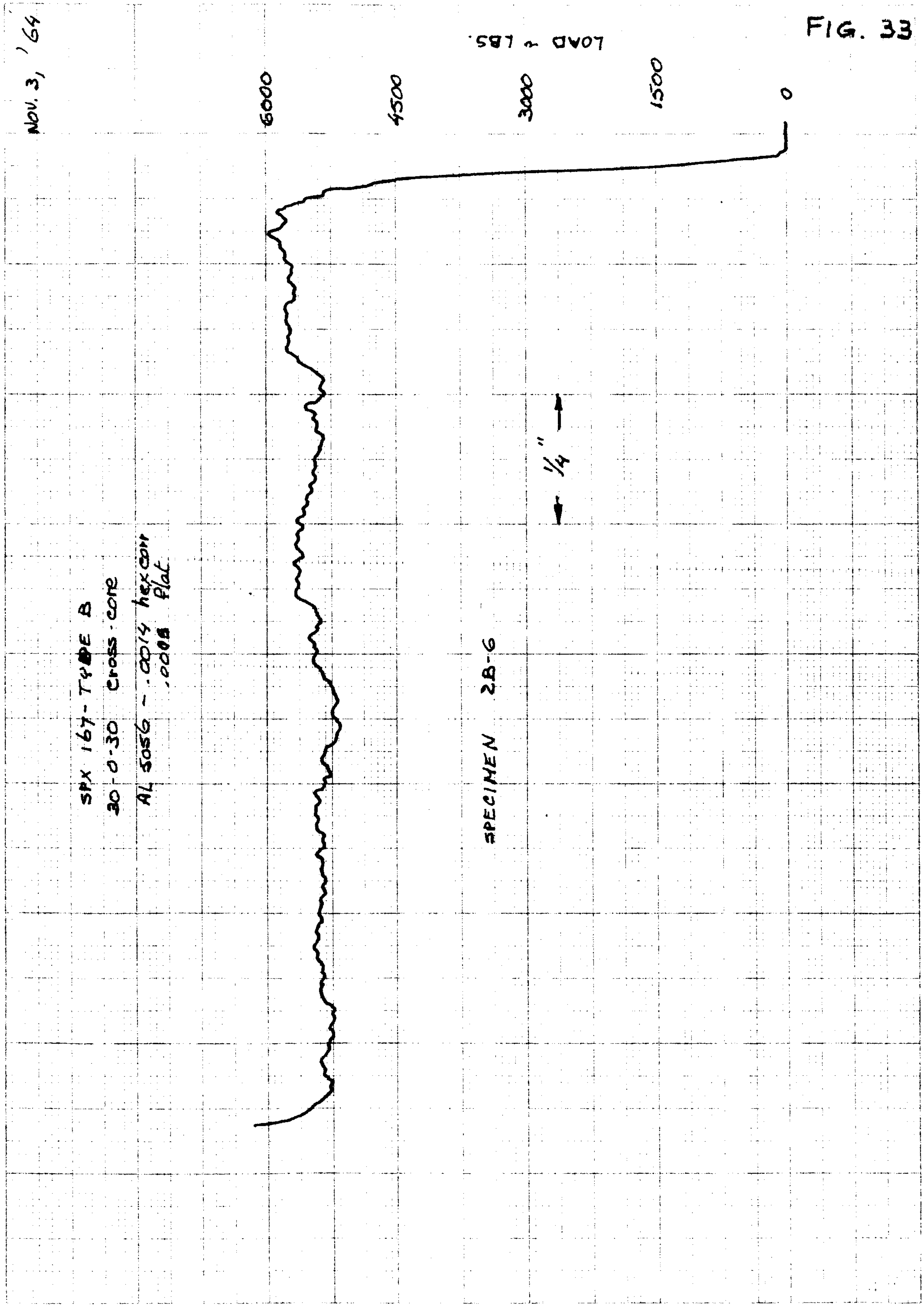
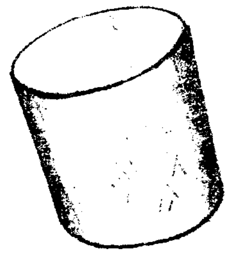

NOV. 3, '64
LOAD ~ LBS.
6000
4500
3000
1500
0
SPX 167- TYPE B
30-0-30 cross-core
AL 5056 - .0014 hexcore
.0008 flat
SPECIMEN 2B-6
1/4"

FIG. 33



6-1/4" SOLID CROSS-CORE

4.1.8 <u>CONFIGURATIONS 3A AND 3B</u>

These configurations required a crush strength of only 180 psi which necessitated using a very low-density core. The thinnest available AL 5056 foil was .0009" gauge. Although this foil has been very difficult to corrugate and handle, we were finally able to make some CROSS-CORE with it.

As discussed in the general "CROSS-CORE section, low density, CROSS-CORE behaves very strangly during crushing and may result in a stroke of only 50%. Figure 34 is a crush load recording of such a test specimen. The stroke of this particular sample was only 40%.

To overcome this difficulty, a flat foil interleaf was used. This produced a stroke of 70 - 80% but increased the crush strength.

The lightest density core we have been able to make using the specified 1/16" corrugations was with .0009" corrugated foil, .0009" interleaf, and a thin coat of Epotuf adhesive. The crush strength of this core was 350 psi which is almost double the desired strength.

Because of these difficulties, a decision was made and approved by Bendix to increase the cell size from the 1/16" corrugation to 1/4" corrugation and to use a flat foil interleaf. Small blocks were initially laid up to verify the design crush strength. Additional six-inch samples made this way were provided to Bendix. Although the crush strength of this material was significantly decreased, it was still somewhat above the

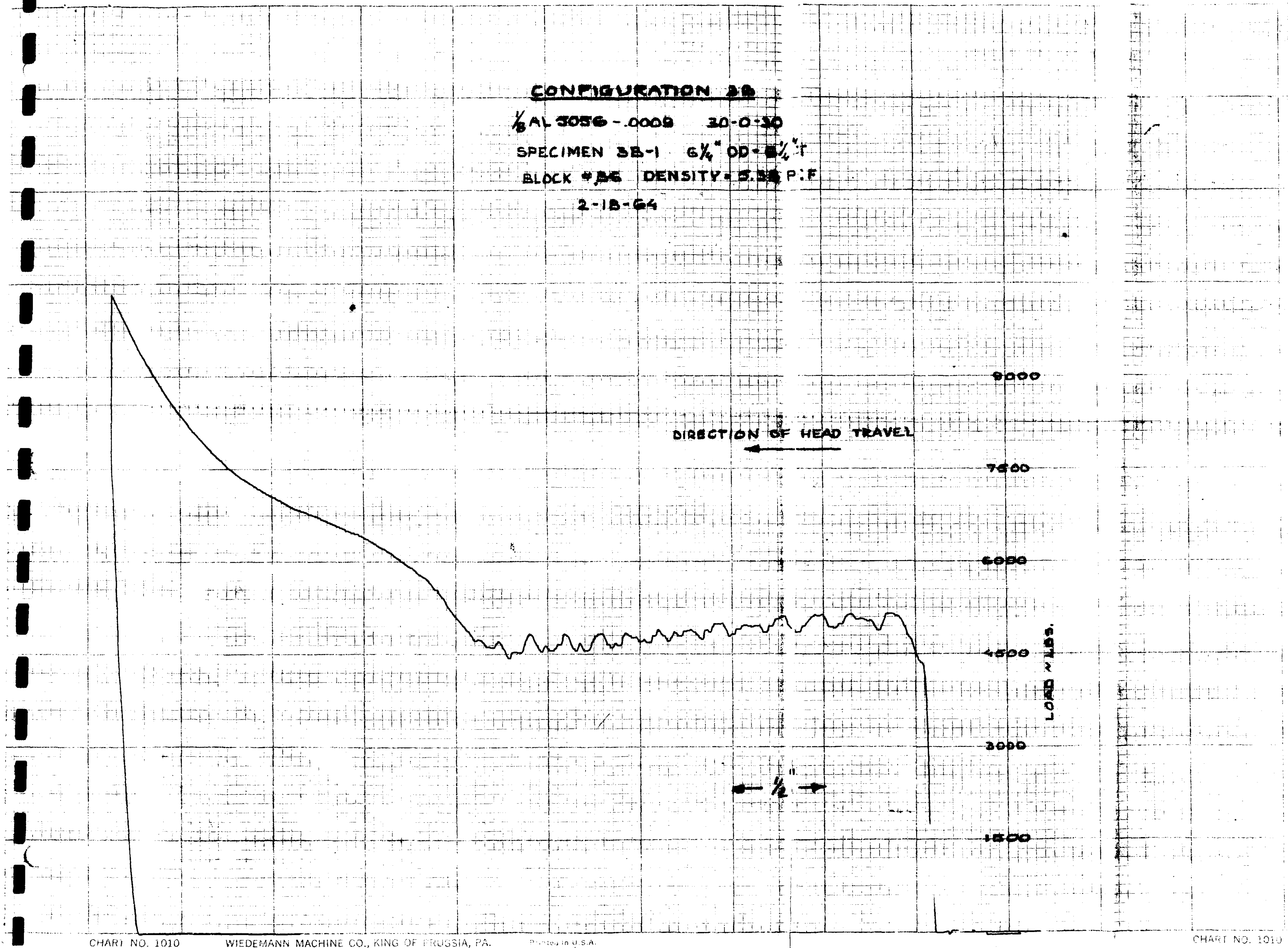
4.1.8 CONFIGURATIONS 3A AND 3B CONT'D.

180 psi requirement; in fact, for Configuration 3A, the average crush strength obtained was approximately 225 psi and for Configuration 3B, 205 psi. Based upon these values, the capsule diameter was decreased to give a crush load of 5500 pounds.

The long capsules were made using these dimensions and laying up the block by interleafing the butt splice and machining the entire cylinder from one block.

Figure 35 shows a load deflection curve for an end sample for one of these parts. Notice that this core still exhibited large variations in crush load. In fact, Bendix' test of the full length configurations resulted in major catastrophic failures which indicate that this low density, CROSS-CORE is not very suitable for energy absorption.

FIG. 5
34



CONFIGURATION 3[illegible]
1/8 AL 5056 - .0009 30-0-30
SPECIMEN 3B-1 6¼" OD - [illegible]¼" T
BLOCK #[illegible] DENSITY = 5.[illegible] P.C.F
2-18-64
DIRECTION OF HEAD TRAVEL
9000
7500
6000
4500
3000
1500
LOAD ~ LBS.
½"
CHART NO. 1010 WIEDEMANN MACHINE CO., KING OF PRUSSIA, PA. Printed in U.S.A.

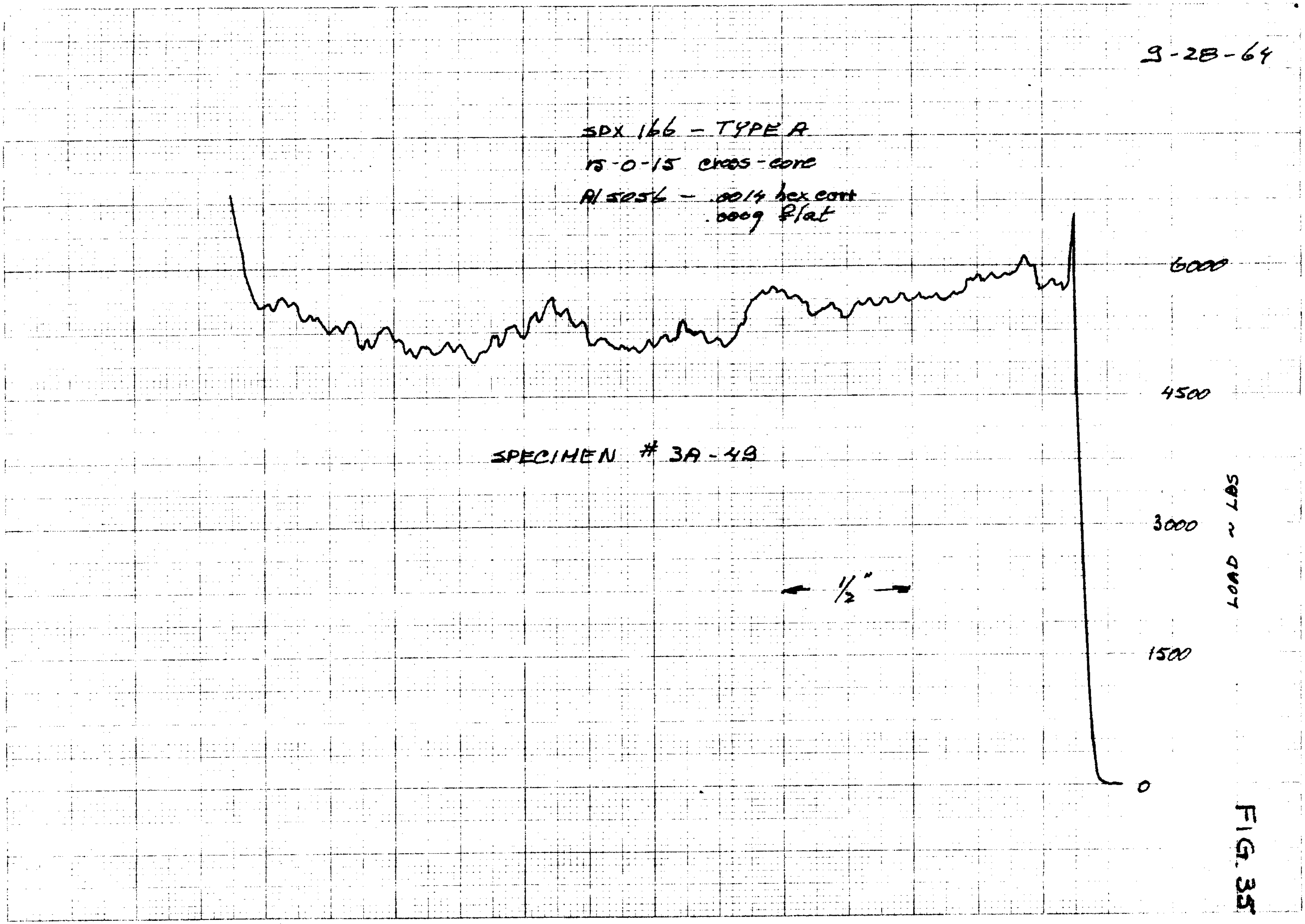

9-28-64
SDX 166 - TYPE A
15-0-15 cross-core
Al 5056 - .0014 hex corr
.0009 flat
SPECIMEN # 3A-49
← 1/2" →
6000
4500
3000
1500
0
LOAD ~ LBS

FIG. 35

5.1.0 CONCLUSION

This program for the design, development, and fabrication of honeycomb attenuators for energy absorption has resulted in a more advanced and broader understanding of the many variables, phenomena, and core characteristics associated with aluminum honeycomb as a media for energy absorption. When this program was initiated, it was thought that the "state of the art" was adequate to specify in detail the requirements for this test series; however, during the development phase, it was soon realized that the first suggested design and statement of work needed several modifications. The many types of failures encountered, the attempts to overcome these failures, the consequential new-product developments, and the final successful fabrication techniques as discussed in Section 4.1 of this report, can be summarized as follows:

1. The most efficient honeycomb core for relatively low crush strength levels (150 to 500 psi) is regular expanded honeycomb. Solid six-inch cylinders of this type have resulted in energy absorption capsules with an exceptionally smooth crush response.

5.1.0 CONCLUSION CONT'D.

2. Solid cylinders of CROSS-CORE exhibited better crush characteristics in the higher crush strength levels than in the low strength range. The use of light density CROSS-CORE, under static and dynamic loading, resulted in catastrophic failures in buckling and an angular shear plane. CROSS-CORE is difficult to fabricate to a specified crush strength level.

3. Annular cylinders for energy absorption can best be made of TUBE CORE, a vertically oriented cell honeycomb specifically designed for this purpose. This core can be made to operate successfully between crush strength levels ranging from 500 to 5000 psi.

4. The physical dimensions of the capsule are extremely important in obtaining uniform crush characteristics. Thin-walled cylinders of large ℓ/d ratios tend to buckle and deform excessively during loading. No specific criteria has as yet been determined but care should be exercised in the design phases to provide maximum cross-sectional areas.

5.1.0 CONCLUSION CONT'D.

5. Splicing sections together to obtain long capsules should be eliminated because of the inherent problem of buckling at the splice. If absolutely necessary, a single splice without precrushing the sections has proven successful.

Additional findings include the following:

a. Wrapping the capsules with a glass filament tape prevents peeling of the "dog-ears" or outside cells without effecting the crush strength.

b. CROSS-CORE made with a flat sheet between each corrugated sheet results in more uniform crush characteristics.

c. Crush strength can be reduced by annealing aluminum honeycomb at 450°F; increased by dipping or spraying adhesive on the outside.

5.1.0 CONCLUSION CONT'D.

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c. Crush strength can be reduced by annealing aluminum honeycomb at 450°F; increased by dipping or spraying adhesive on the outside.