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THE EFFECT OF UNDERWATER EXPLOSIONS ON SHIP AND SUBMARINE HULLS

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on the Experimental Program

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A Report of a Project in Cooperation with

THE BUREAU OF SHIPS, DEPARTMENT OF THE NAVY

and

THE UNIVERSITY OF ILLINOIS
DEPARTMENT OF CIVIL ENGINEERING

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THE EFFECT OF UNDERWATER EXPLOSIONS ON SHIP AND SUBMARINE HULLS

I. INTRODUCTION

1. Introduction

The purpose of this report is to summarize the experimental work done at the University of Illinois since February of 1951 under the contracts N6ori-07132, NObs 55889, and NObs 62250. A Technical Report [1*] summarizing the analytical phases of the project is being prepared concurrently with this report.

Most of the results of the experimental investigation have been presented previously in the form of technical reports. These will be reviewed in part II of this text. Descriptions of some work that was partially supported by project funds has been available previously only in the form of University of Illinois theses. The results of these investigations will be mentioned in part III.

The basic objectives of this investigation, both analytical and experimental, as set forth in the first contract were "to develop scaling parameters and numerical procedures for predicting the strength of submarine structures under explosive loadings, to investigate the feasibility of reproducing the action of full-size submarines by means of scale models (by determining the least possible scale factors at which reproducibility of structural action can be assured) to develop means for analyzing the dynamic response of stiffened cylindrical shells to blast pressures produced by underwater explosions with particular attention to numerical or approximate methods and with the objectives in mind of determining a

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[*] References are listed at the end of the text.

correlation between the results of analysis and such test results as have been obtained or which are likely to be developed in the future, and to determine the patterns of force on various types of structures at various aspects due to the underwater detonation of explosives." These were the stated objectives. The experimental program at the University of Illinois as it developed was concerned with the following questions.

1. What parameters are important in scaling the behavior of submarine pressure hulls?

2. What is the smallest scale at which reproducibility of full-scale behavior can be obtained?

3. What are the factors important in the failure mechanism under rapid loading as compared with those important under slow loading?

These were the major questions to be answered by the experimental program.

During the course of the experimental investigation some related problems were considered. These were:

1. The action of a shock wave during its impingement upon a cylindrical object as revealed by behavior of a water table analog.

2. The dependence of the lower natural frequencies of ring stiffened cylindrical shells upon external pressure of air and of water.

3. The slow and rapid uniaxial stress behavior of materials representative of those from which submarine pressure hulls are currently fabricated.

Of the various phases of the investigation stated above only the last one, the behavior of materials under slowly and rapidly applied stresses, has not been or will not be reported in the form of a separate technical report. Therefore, this phase of the investigation will be described in some detail in Section III of this final report.

2. Acknowledgment

The work described in this report was performed by the University of Illinois in cooperation with the Office of Naval Research; and the Department of the Navy, Bureau of Ships. The work was performed in the Structural Research Laboratory of the Civil Engineering Department which is under the general direction of N. M. Newmark, Professor of Civil Engineering. J. E. Stallmeyer, Research Assistant Professor of Civil Engineering, had the responsibility for the general supervision of the entire program, while supervisors of the experimental program have been W. J. Hall, and J. M. Massard, currently Research Assistant Professors of Civil Engineering.

Other persons who have contributed significantly to the investigation are H. E. Stevens then Lt. USN, F. E. Anderson then Capt. USA, E. D. Patterson, then Capt. USA, W. A. Walls, then Lt. USN, F. L. Howland, L. B. Smith, and J. W. Storm, all of whom were then Research Assistants in Civil Engineering.

The instrumentation used during the conduct of the investigation was the direct responsibility of V. J. McDonald, Research Assistant Professor of Civil Engineering, and his assistant, R. J. Craig, Laboratory Technician.

II. EXPERIMENTAL WORK PRESENTED PREVIOUSLY

3. Static and Dynamic Tests of Segments of Stiffened Steel Shells[4]

At the beginning of the experimental program a simple procedure was sought for determining the relative behavior of ring-stiffened cylindrical shells under both slow and rapid loadings. This procedure was desired so that comparisons could be made of the behaviors of various stiffener sections representative of variations in the parameters considered to be important in the behavior of ring-stiffened cylindrical shells. The form of specimen finally decided upon was a 60-degree segment of a full-ring section which was two bays wide with two stiffeners symmetrically placed about the circumferential center line of the specimen. The ends of a segment were attached by hinges to a supposedly nonyielding support. Several of these segments were tested under slow loading and a companion series was also tested under dynamic loading applied in a drop testing machine (see Fig. 1). For the first few specimens tested the loading was applied directly to the top of the stiffeners, but in later tests it was applied by means of a loading block directly to the crown of the arch shell between the stiffeners.

The results of the slow tests of the shell segments seemed to indicate that an H-Section stiffener could be represented fairly well by a rectangular stiffener having the same area, major moment of inertia, and area of the composite section as that of the specimen having the H-stiffener. In the drop tests the results are not as clear. Of the specimens having bar type stiffeners, those with the same single stiffener area, composite section area, and major moment of inertia of the composite section the same as that of the H-Section behaved most nearly the same as the H-Section stiffener specimen.

4. Static Diametral Loading Tests of Stiffened Steel Shells[5]

Another early series of tests was performed on full-ring sections of ring-stiffened cylindrical shells of three sizes: a 3/8 scale model of a full-size submarine pressure hull, a 1/8 scale, and a 1/14.7 scale representation of a submarine pressure hull. These full-ring sections were tested under statically applied diametral loading (see Fig. 2). The purpose of the test series was to determine how well the behavior scaled down to a size of specimen that was the largest that could be tested in the dynamic pressure tank then under consideration. The results of these tests are reported in the Third Technical Report[5] for the project. The summary of this report says that "(1) for the simple loading used the maximum loads (and the manner of failure) obtained experimentally in the two scale models agreed well with that obtained from the 'prototype' when the comparison was made using the proper power (F^2) of the basic scale factors (F) that had been obtained from consideration of the moments of inertia of the 'effective sections' obtained by the method of H. Bleich. However, the results would have been virtually the same had the scale factors been obtained using the moments of inertia of the 'as measured' section or those of the 'effective section' computed using the method of B. Thürlimann. (2) For the specimens that seemed to be relatively free of detrimental residual stress (that is those in which the experimental behavior was in fair agreement with elementary theory) the elastic regions of the experimental load-deflection and load-strain curves lay between the corresponding theoretical elastic curves computed from the effective sections obtained using Bleich's or Thürlimann's procedure and those obtained assuming that the effective width of the shell beyond the edges of the inner flanges of the external stiffeners was zero."

5. Static and Dynamic External Pressure Tests of Ring Stiffened Cylindrical Shells[2,3,6]

It became apparent during the course of the drop tests of the small arches that the method had many shortcomings. Therefore, it was decided to construct a dynamic pressure tank with which controlled long duration external (or internal) pressure loading could be applied rapidly to complete cylindrical shell models. The dynamic pressure tank, which is described in its early stages of development in the First Technical Report[2] produced under the contract, is shown schematically in Fig. 3.

After the initial development phases, which were carried on in the laboratory, indicated that it was necessary to place the tank in a protective shelter in a rather open area so that the blast resulting from its operation would not endanger personnel or cause destruction to the surrounding area, a considerable delay was incurred while the funds for constructing the testing shelter were obtained and the shelter was constructed.

After the dynamic pressure tank was placed in operation in its new location, three series of slow and rapid pressure tests of cylindrical shells were performed. The types of specimens tested in the last two series are described in Figs. 4 and 5. Using the dynamic pressure tank it was possible to apply levels of external pressure to the cylindrical shells in times as short as 3 or 4 milliseconds. With respect to the lowest natural frequency of the specimens these were really statical loadings. However, with respect to the behavior of the cylindrical shell model as regards the properties of the material under rapid loading and also as regards the buckling behavior of the shell, the loadings were rapid enough that they could be considered dynamic.

The specimen series, the testing techniques, and the results of the tests are presented in the Fifth Technical Report[6]. The summary of results given in this report states: "(1) It cannot be said that the types of failure obtained in the dynamic tests were similar to those obtained under static testing. The relative stiffener strength had little effect upon the shell yield failures obtained in most of the static tests but apparently did influence the time to collapse of the specimens tested dynamically. (2) The results of these tests indicate that the cylindrical shell specimens withstood for short periods dynamic external pressures considerably greater than those producing static collapse. (3) In the cylindrical shell specimens tested there was little if any delay in the commencement of shell yielding following the application of dynamic pressures in excess of those producing yielding under static conditions. (4) However, in the dynamic tests an appreciable time was required for the failure process to progress from an initial yielding of the shell to the point of shell buckling and subsequent failure of the stiffeners. In the tests of specimens having H-Stiffeners the main delay in specimen collapse apparently was connected with the relatively gradual yielding of the shell that seems to bear some relation to the rate of yielding phenomena common to most mild steels. (5) The test results indicate that specimens which are similar except for the stiffeners and their spacing will behave comparably in both static and dynamic testing, providing the effective clear widths of the shells between the stiffeners are similar, and providing that the major moments of inertia and areas of the stiffeners alone are similar." A general comment follows which states that "the results listed above were obtained in tests of specimens made of mild steel which had a marked rate of yielding behavior but a delayed yielding behavior considerably less pronounced than that normal in most mild steels. Furthermore, the specimens had geometrical proportions and material properties such that the initial stages of failure were associated with extensive yielding of the shell. It is not suggested that these results would be directly applicable to similar structures made of materials less time sensitive or to those in which the mode of failure was not equivalent."

III. EXPERIMENTAL WORK NOT PRESENTED PREVIOUSLY

Other work that has been wholly or partially supported by project funds but which has not been presented previously in the form of technical reports is described in this section.

6. Drop Testing Pulse Attenuator

In connection with the drop tests of small shell segment specimens attenuation of the loading pulse was necessary. A device having a relatively high effective spring constant but a virtual mass as low as possible was required. The device finally decided upon was a double displacement piston arrangement in which the compressibility of water was used to achieve the desired spring constant. This unit was interposed between the falling weight and the crown of the segment being tested. The calibration of the dynamometer piston of this unit is described in a M. S. dissertation by F. L. Howland[7]. The test series performed using this device is described in reference 3.

7. Elastic Vibration Tests of Ring Stiffened Cylindrical Shells

One of the sideline investigations mentioned earlier was the basis for a M. S. dissertation by R. K. Gregory, University of Illinois 1954, which was entitled, "Determination of the Natural Frequencies of a Ring-Stiffened Cylindrical Shell Under External Pressure."[8] Mr. Gregory's dissertation is being revised concurrently with this report for presentation as a technical report[9] under the project.

8. Static and Dynamic Tests of Various Steels

a. Introduction

In the course of the investigation concerned with differences in the behavior of ring-stiffened cylindrical shells under rapid loading as compared with their behavior under slow loading, it became evident that information concerning the uniaxial stress behavior of materials under rapid loading would be of considerable value in understanding the shell test results. An apparatus with which such testing could be performed was developed as a part of a Ph.D. thesis project[11] supported mainly by University funds. However, approval was given by project monitors to defray from project funds a part of the cost of preparing and testing specimens.

Following the development of the rapid loading equipment, three series of tests were performed as a service to the government agencies requesting them. The results of these tests have been described previously only in the form of memoranda distributed to the various agencies involved,[13, 14, 15] so pertinent information will be included in this report.

Two other thesis investigations were partially supported by this project. These are described in Reference 10, "A Device to Permit Reversed Loading in the University of Illinois 20 kip Pulse Loading Machine," by L. B. Smith; and Reference 12, "A Device for the Rapid Loading of Small Beams in the University of Illinois 20 Kip Pulse Loading Machine," by J. W. Storm.

A brief description of the material studies will be given in the following sections.

b. Testing Apparatus

The 20 kip rapid loading machine is a piston device in which the load output is the result of differential pressure obtained using compressed nitrogen or helium as the energy source. The load application and release are achieved using solenoid triggered slide valves to obtain timed pressure release from the two chambers of the device. Control of the time required for load application and release is possible by variation of the orifice areas. The device is a general purpose unit which permits the application of a loading pulse to any structural component to which it may be attached. The applied pulse may begin from a static level ranging from 20 kips tension to 20 kips compression, undergo a rapid change of plus or minus 20 kips with the restriction that the prepulse load plus the dynamic change in load cannot exceed the limits of plus or minus 20 kips, and then return rapidly to zero. The rise and decay times of the loading pulse are controllable from a minimum of approximately 5 or 6 milliseconds to a maximum of several minutes. The duration of the peak load may be varied from a few milliseconds to an indefinite period.

Essentially, the device produces a loading pulse (that is, a pulse which is nearly independent of specimen response) so that the desired loading can be achieved without the need of accurate knowledge of the specimen's response characteristics. This is true for the particular specimen type which was used in most of the studies, since the resulting machine-specimen system was such that the most rapid loadings of which the machine was capable without impact were virtually static in the mechanical sense of the word. In use with a specimen which when combined in the machine system would result in a much lower elastic fundamental frequency, account would have to be taken of the inertia forces produced as a result of truly "dynamic" excitation. However, by measuring the resistance of the specimen with a dynamometer attached to the end of the specimen opposite that to which the load was applied, inertia effects would be taken into account, at least in a nominal way, since these loadings are slow enough that wave phenomena are not considered influential. A general view of the rapid loading apparatus is given in Fig. 6, and the form of tensile specimen used is shown in Fig. 7.

In the early tests cathode ray oscillographs which were virtually flat in amplitude of response and linear in phase shift to 30 kc were used. As a result of these tests it was seen that magnetic oscillographic equipment available in the laboratory would have response characteristics quite adequate for the accurate recording of the test results with the considerable advantages of better stability and greater ease of use. This equipment was used for the majority of the testing.

c. General Discussion of Yielding Behavior of Mild and Low Alloy Steels

The apparatus described in the previous section has been used to test several steels in slow and rapid uniaxial tension. In general, the tests were of two types; (1) slow tests at nearly constant rates of nominal straining, and (2) rapid loading (0.006 sec.) to constant levels of nominal stress. The chemical compositions of the steels for which results are included in this report are listed in Table 1.

The nature of the information obtained from the uniaxial tests is indicated in Figs. 8 and 9 which show respectively the stress-strain and strain-time information for a few tests of mild steel (Fig. 8) and high strength steel (Fig. 9). To clarify the writer's interpretation of the results of the tests represented by such information, a few introductory remarks may be helpful.

It is a characteristic of mild and low alloy steels that under a slow relatively constant rate of nominal uniaxial straining at room temperatures their resistance goes through four rather arbitrary stages: (1) the elastic range terminating in (2) microstraining followed by the development of a condition of (3) general yielding (in which the level of resistance is a function mainly of the rate of straining) which in turn is terminated by the advent of (4) strain hardening and subsequent fracture. The four stages in the nominal resistance-deformation characteristics of these metals are quite evident in the slow straining rate tests, but, of course, are no less present in tests run under other conditions, such as slow constant rate of increase in nominal stress.

Of these four stages the middle two, microstraining and general yielding, are quite time sensitive; the elastic range is almost insensitive to time; and the range beyond the commencement of strain hardening is only slightly time sensitive.

The time sensitivity associated with the microstraining phenomonon has been termed the "delayed yield" effect[16]. This is best revealed under tests involving rapid stressing to a constant stress level such as can be performed in the University of Illinois 20 kip pulse loading machine. In the material studies presented in this report the time delay in yielding is defined arbitrarily as the interval between the time at which the stress first reaches a value corresponding to the lowest upper yield stress obtained in slow tests, and the time at which yielding has become general enough that the apparent modulus (nominal stress/nominal strain) has dropped to about 25 x 10^6 psi. Delay time so defined has engineering significance in that it is related at one end to a stress level high enough to result in yielding under slow loading or deforming conditions, and at the other end to a parameter involving both stress and strain which has an arbitrary value indicative of an amount of yielding sufficient to mark the beginning of general yielding.

The rate of general yielding effect (usually termed somewhat ambiguously the strain rate effect[17]) is most evident perhaps in tests performed at various constant rates of nominal strain, but it also will be apparent, of course, in tests in which nominal stress rather than nominal strain is the factor most nearly independent of specimen behavior. Such is the case in the rapid loading to constant stress level tests. After general yielding has begun (following the delay in yielding if present) the specimen will deform at a rate which is dependent upon the stress level being maintained by the pneumatic loading unit. Since the several tests are run at different constant stress levels, both delayed yield and rate of general yielding information can be obtained from a single test series.

The sharpness of the transition between the general yielding condition (flat yield region in the constant rate of straining test) and the region of strain hardening is somewhat more gradual than that between the other stages. (Of course, the "gradualness" is mainly dependent upon the time resolution possible with the recording techniques used.) However, the tests run at the University of Illinois on mild and low alloy steels indicate that for a particular steel the transition begins at about the same total strain regardless of the rates involved.

In a test to a constant stress level the straining finally ceases at a total strain which usually agrees well with that corresponding to the strain obtained at the same nominal stress under slow loading or deforming conditions.

d. Results of Material Studies

The results of tests performed at the University of Illinois (and elsewhere[16]) indicate that when subjected to rapid loading to a constant stress level mild steels (such as RBA and SPA) begin to deform almost immediately but the straining is limited in extent until sufficient time has passed and/or microstraining has occurred to result in a condition of general yielding. This phenomenon has been termed delayed yielding by Clark[16]. For rapid loadings used at the University of Illinois in the investigation of mild steels (rise times of load ranging from 0.005 to 0.5 sec.) the delayed yield condition can be expressed in terms of the stress at the time of general yielding and the interval between the time at which the loading passed a critical level and that at which general yielding began. This result is illustrated in Fig.10. It is not believed that such a yield condition which virtually neglects stress history would apply to all types of loading, particularly those associated with fluctuations in stress.

For mild steels, general yielding once begun continues at a rate which bears a definite relationship to the instantaneous stress level (see Fig.11), until the total strain is about that at which strain hardening begins under a slowly applied loading. Then the rate of yielding gradually decreases until straining virtually ceases at a total deformation which agrees well with that obtained under slow loading to the same stress level. (See Fig. 8)

The slow and dynamic properties of the materials representing the pressure hulls of PAPOOSE and SQUAW (Series NN and NL respectively) were somewhat different from those typical of mild steel. In general there was a delayed yield behavior of sorts. As to the rate of general yielding behavior, this cannot be indicated very definitely, since, at that time, overall strain of the gage region was measured only by SR-4 gages, so that once yielding had progressed to one per cent or so, no further measurement was possible. But on the basis of the static straining tests which indicated a flat yield region a fairly pronounced rate of general yielding behavior would be expected.

In the tests of the HY-80 material there was virtually no delayed yielding nor any very definite rate of general yield behavior as can be seen from Fig. 9. In general, therefore, this material is not very time sensitive and it is to be expected that compared with mild steel (Fig. 8) there would be very little increase in resistance of the HY-80 material under rapid loadings corresponding to those used in the coupon tests.

As was indicated by the theses titles mentioned earlier, a few reversed loading tests were performed[10] on mild steel coupons. A delay of one or two or so minutes occurred before rapid reversal of stress. Thus, there is a possibility that some strain ageing occurred. However, the results did indicate that after having been yielded by a stress pulse applied in one direction, no (or only a very greatly diminished) delayed yield behavior was evident upon rapid reversal of stress. The tests were too limited in extent to signify whether or not the rate of general yielding behavior was affected significantly by a previous history of yielding under a stress of the opposite sense.

Another brief series of material studies that was performed as a thesis investigation was concerned with slow and rapid loading tests of beams of rectangular section under pure flexure[12]. The loadings were achieved by an attachment to the 20 kip pulse loading machine with which third point loadings could be applied to the beams. There were some instrumentation difficulties connected with these tests so that the results are somewhat questionable. Still, it is clear that the resistance obtained at any particular deformation produced rapidly was substantially greater than that obtained under the same deformation produced slowly.

An attempt was made to correlate the behavior of these small beams under flexure with the known uniaxial stress properties of the material from which the beams were made. In the correlation it was necessary to assume that the distribution of strains was linear throughout the depth of the beam section and that the material behaved the same in both tension and compression. Making these assumptions and proceeding from the measured strains and deflections of the beam, resistances in the region of pure flexure were computed using the instantaneously measured values of the deformations and the known delayed yielding and rate of yielding behaviors of the materials from which the beams were made. The resistances obtained by this computation were always less than those that were determined from the loads as measured by the dynamometers with respect to time. (Of course, in the elastic region the resistances computed from the measured deformations using the "static" stress-strain relationship agreed quite well with measured resistance-time information.) The discrepancy in resistance mentioned above was on the order of 8 or so per cent for outer fiber strains in the regions of three times the elastic limit strain to approximately 10 times the elastic limit strain. Beyond this, the discrepancy increased until in the slow test it was approximately 25 per cent at an outer fiber strain of approximately 100 times the elastic limit strain.

In trying to arrive at the reason or reasons for the discrepancy, there are at least four possibilities to be considered: (1) that there are possible errors in measurements in either the uniaxial stress tests or the flexural stress tests, (2) that the material did not behave the same in tension and compression (on the basis of the coupon tests in both tension and compression the difference in behavior is insignificant), (3) that the distribution of strain is not linear through the depth of the section, and (4) that the uniaxial stress coupons were not really representative of the material in the beams. Of these possibilities only (1) and (3) seem significant.

A quick check on whether or not the required values of resistance could be obtained by adjusting the assumed distribution of strain was made by assuming the distribution to be square or uniform through the depth of the section; this should be the bounding case of maximum resistance computed on the basis of measured outer fiber strains. The resistances computed using this assumption still were not quite as great as the measured resistances although they approached them much more closely. Therefore it is reasonable that there were errors in measurement. The flexural tests, therefore, cannot be considered as being very conclusive but there is a definite indication at least that substantial increases in resistances are obtained in rapid versus slow flexure, and that a partial explanation of this increase can be achieved through consideration of the delayed and rate of yielding behavior of the material from which the specimens were made.

IV. SUMMARY OF RESULTS OF EXPERIMENTAL PROGRAM

9. Summary of Results

A restatement of the questions which were the basis of the experimental investigation follows along with the "answers" obtained.

1. What factors are important in scaling the behavior of ring stiffened cylindrical pressure hulls? On the basis of the shell segment tests results obtained under both slow and rapid loading, and the series of cylindrical shells which were tested in the dynamic pressure tank, it appears that for comparable behaviors H-section stiffeners can be replaced by bar-type stiffeners having the same areas and major moments of inertia. For other behaviors to be comparable, particularly in specimens which fail by shell yielding, the effective widths of the shells must be the same between stiffeners. In the stiffener types which did not have corresponding areas and moments of inertia different behaviors were obtained in both the slow tests and the dynamic tests. Therefore, it seems reasonable to assume that these are major factors affecting the behavior of the ring-stiffened cylindrical shells to both static and dynamical loadings.

2. What is the smallest scale size which will faithfully duplicate the behavior of the prototype under both slow and dynamic conditions? This question cannot be answered positively, since the only experiments that were performed at the University of Illinois which would apply to this question were three tests of full-ring pressure hull sections under static diametral loading. In these particular tests the prototype was a 3/8 scale model of an actual submarine pressure hull, and the smallest model tested

was a 1/14.7 scale model of an actual submarine pressure hull. The values of loads, deformations, and strains did scale reasonably well down to the 1/14.7 size. This was the smallest specimen that was actually used in any of the experiments at the University of Illinois. Therefore, if this very limited series of tests can be taken as an indication, it should be possible, on the basis of scaling at least, to apply the results of the tests run at the University of Illinois to the behavior of 3/8-scale submarine pressure hulls.

3. What are the critical factors influencing the behavior of ring stiffened cylindrical shells under slow and dynamical loadings? This question cannot be answered completely on the basis of the experimental results alone, since most of the tests only permit comparisons to be made between the behaviors obtained with slow loadings and those obtained under rapid loadings. But on the basis of the dynamic pressure tests, and restricting application of the results to other situations in which the mode of failure of the particular model is more or less the same and in which the materials behave comparably under both slow and rapid loadings, it can be said that under loadings rapidly applied to a constant pressure level, the specimens or pressure hulls can resist for a substantial period of time pressures considerably greater than those which would cause collapse under slow loading conditions. It also appears that in rapid tests yielding of the components of the pressure hull begins almost immediately but that the straining progresses at a relatively slow rate until the deformation has reached a state which results in a buckling condition of the shell and a final failure of the complete section. The particular time associated with the delay in complete collapse following application of pressure seems to

be relatable to the rate of general yielding behavior of the mild steels from which were made the shells of the particular specimens tested. The few specimens on which strains were measured as a function of time began to yield almost immediately, therefore it is not believed that delayed yielding alone has a very significant effect upon the delay in actual collapse of the specimens obtained under the rapid pressure loadings.

It is possible, however, as indicated by the analytical phases of the project and work by Hoff[18], that a major factor contributing to the time required for collapse to occur following the application of pressure is associated with the time required for buckling to occur as a dynamic process independent of the effect of time sensitive properties of material. Whether or not the buckling effect or the time required for buckling to occur can be divorced from the material properties cannot be stated conclusively at this time. (This could be settled, perhaps, by running tests of geometrically similar specimens, some made of a material known to be time sensitive, and others, of a material relatively insensitive to time effects in the ranges concerned.) The fact that a delay in collapse does occur seems to be the really significant thing and indicates that any theories of failure which are predicated upon collapse following immediately the initiation of yielding are not applicable to these tests.

4. Material Studies. For the low alloy steels which have been tested at the University of Illinois (PAPOOSE and SQUAW shell material) the delayed yielding and rate of yielding behavior is somewhat less pronounced than that which is characteristic of most mild structural steels. The HY-80 material tested has virtually no delayed yield or rate of general yielding behavior, and apparently behaves nearly the same regardless

of the rate of loading (at least within the range of load-time relationships which were used in the investigation conducted by the University of Illinois).

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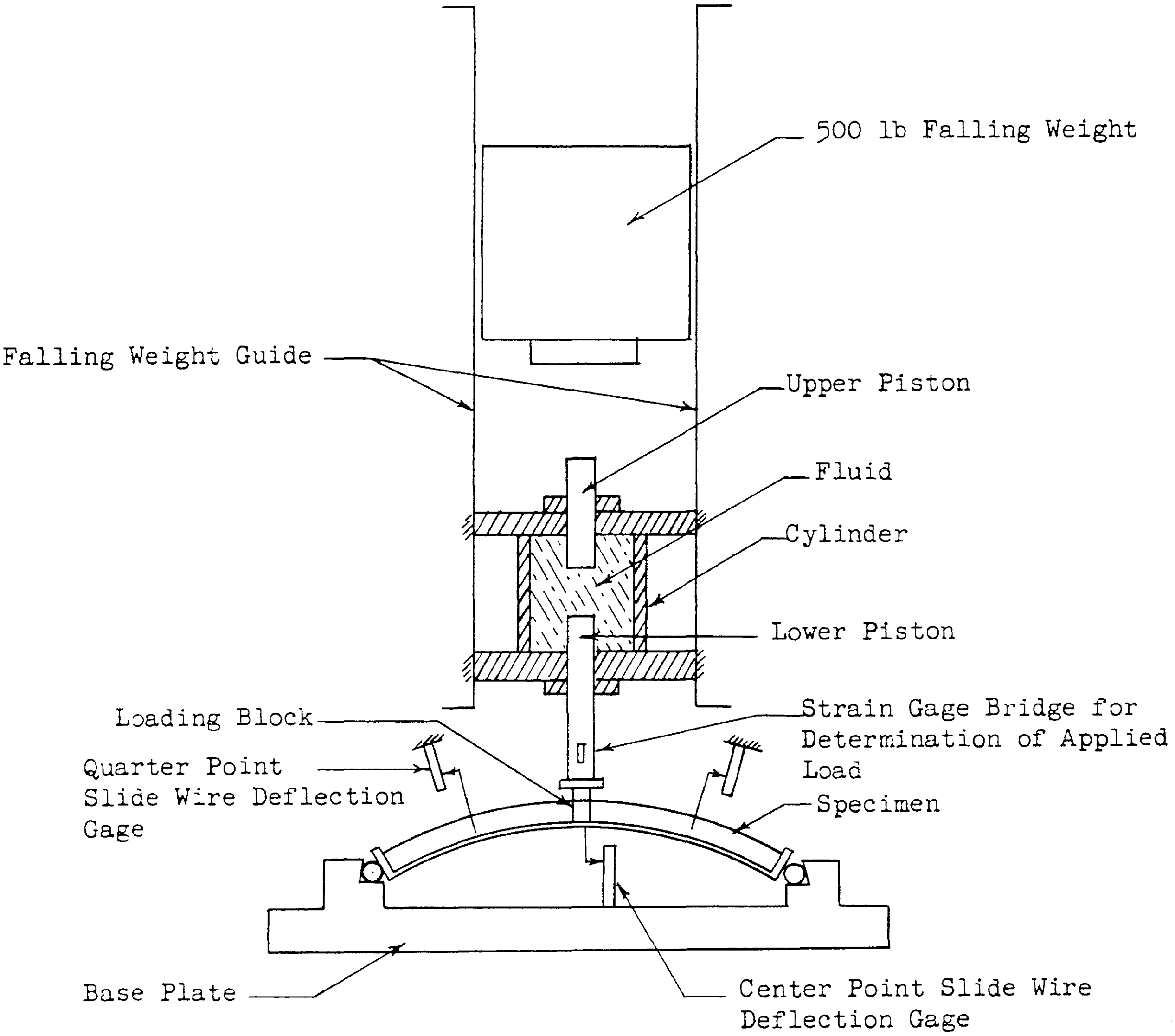
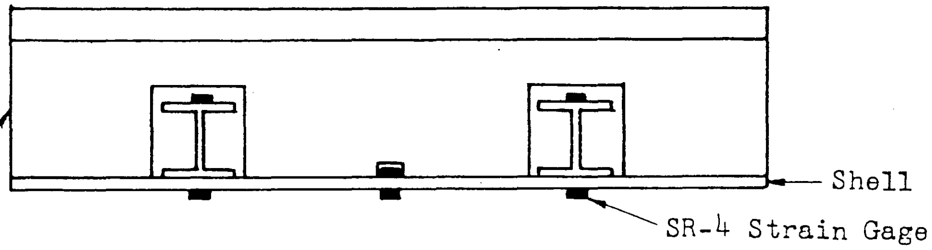


FIG. 1 ARRANGEMENT FOR DROP TESTS OF 60° STIFFENED SHELL SEGMENTS



Typical Strain Gage Layout (Sections A,B,C,D)

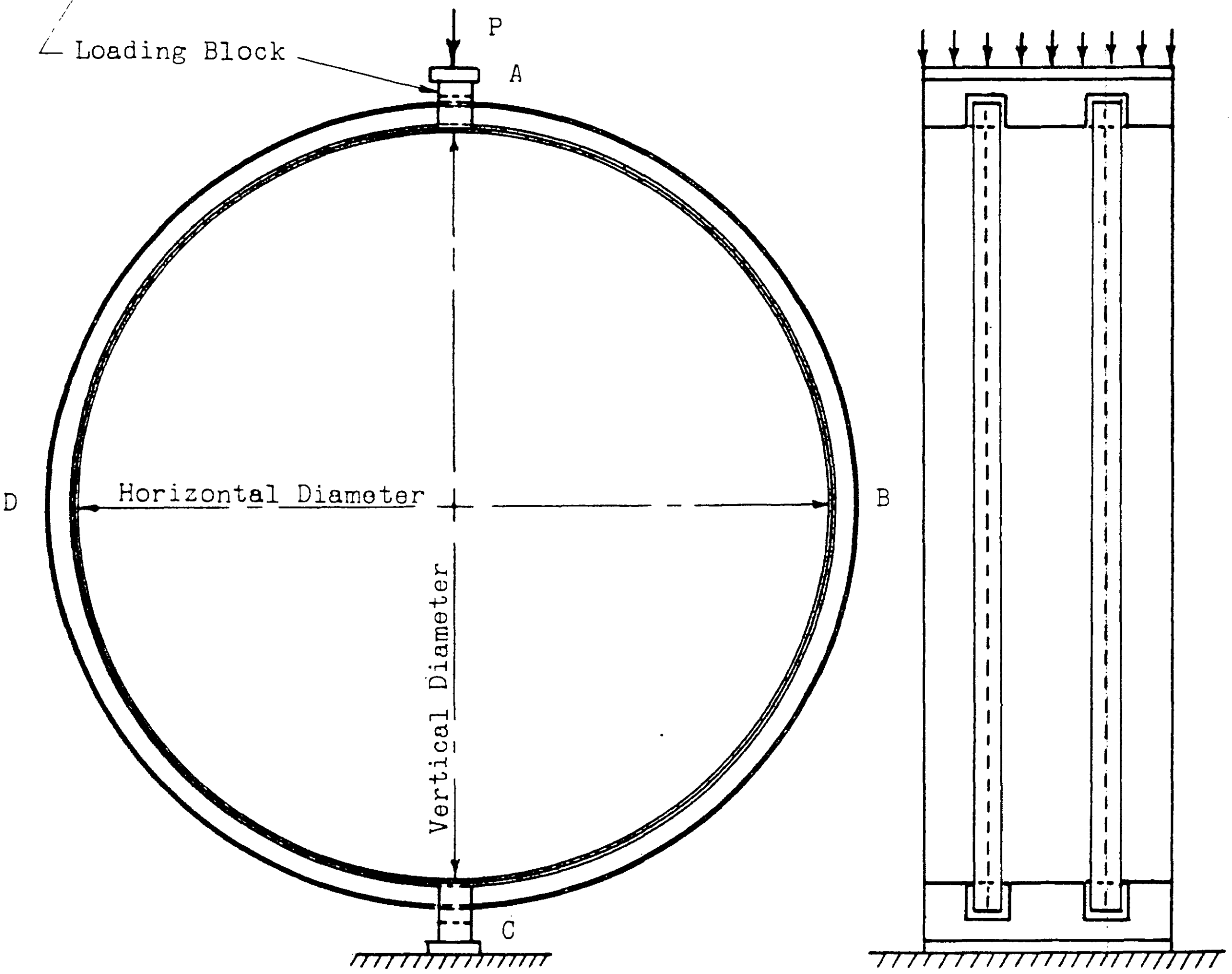


FIG. 2 SCHEMATIC VIEW OF ARRANGEMENT FOR FULL RING TESTS

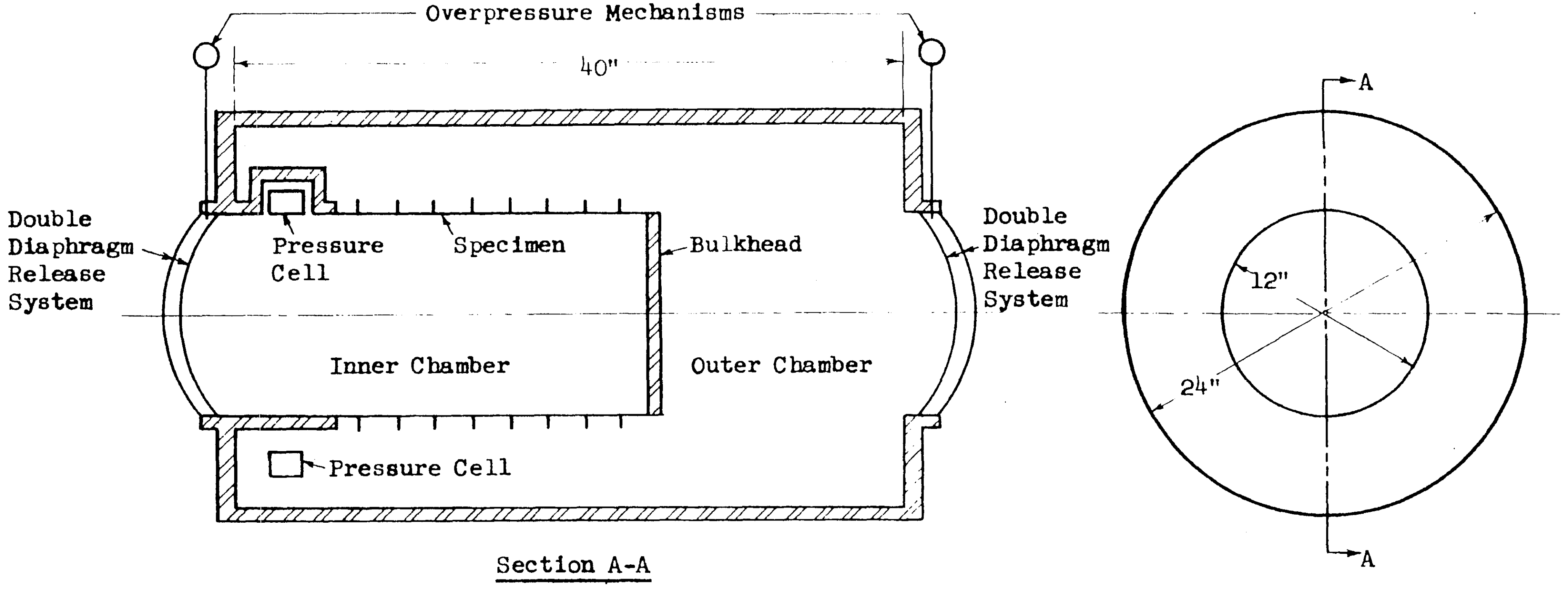
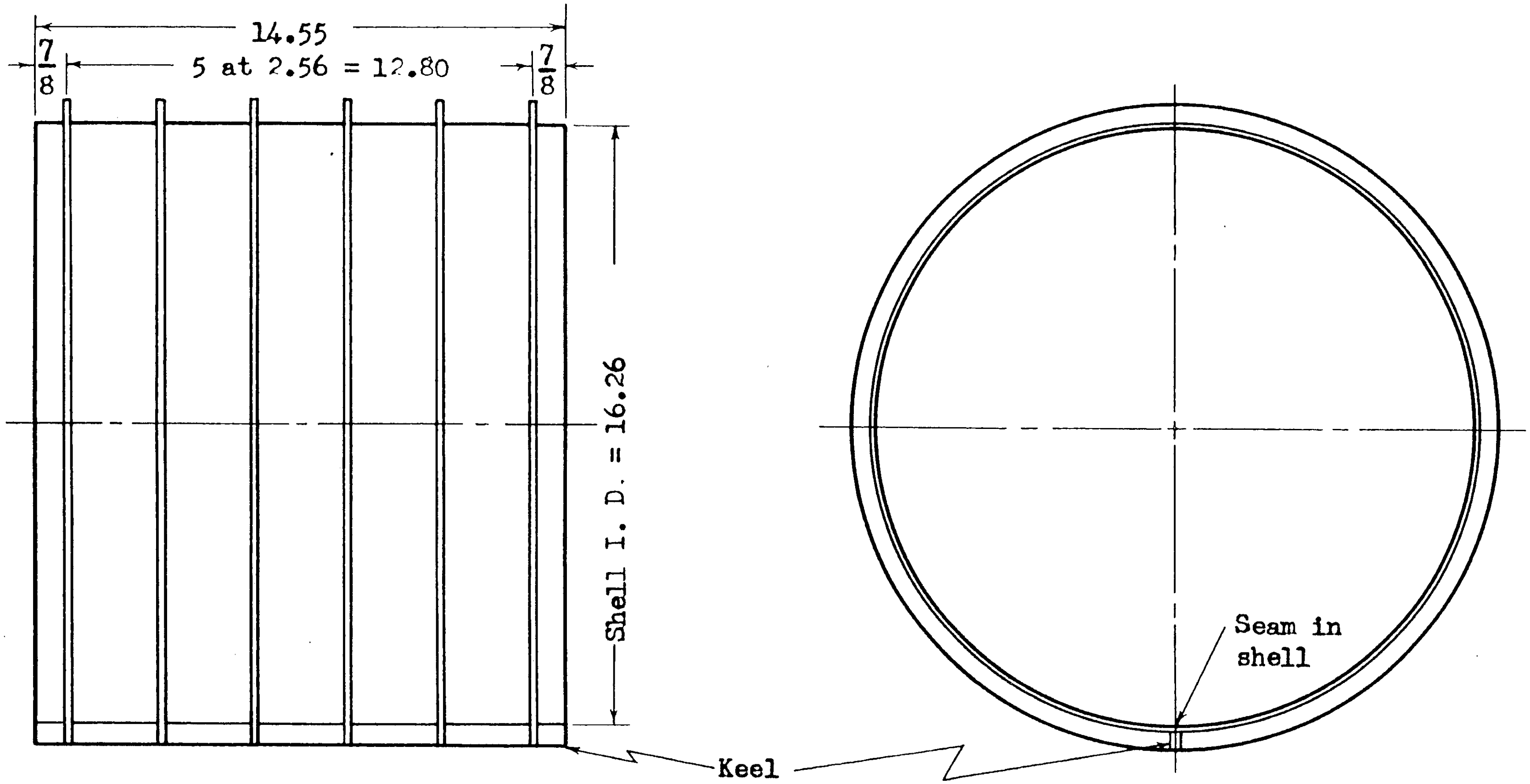


FIG. 3 SCHEMATIC REPRESENTATION OF THE STATIC AND DYNAMIC PRESSURE TANK



All dimensions are in inches

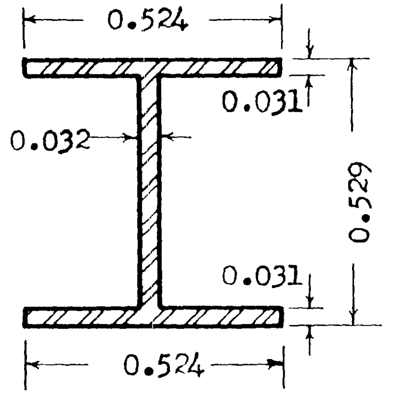
Shell: Rolled from 14 ga. (0.072) x 17.9 x 51.52 sheet (Includes allowance for 1/16 gap after rolling.)

Stiffeners: Machined from 18 O. D. "pipe"

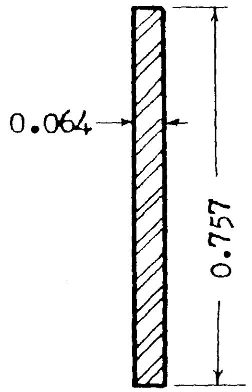
Keel: 1/4 x 3/4 x 17.9

Assembly: Metallic arc (reversed polarity) using 3/32 rod. (AWS - ASTM E6012 and E6013)
(After assembly specimens were trimmed in band saw to length given above.)

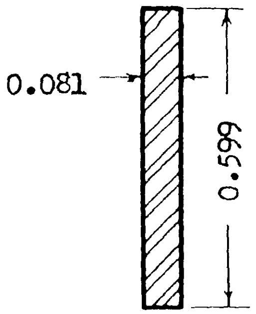
FIG. 4 DETAILS OF "1954" AND "1955" SERIES RING STIFFENED CYLINDRICAL SHELL SPECIMENS



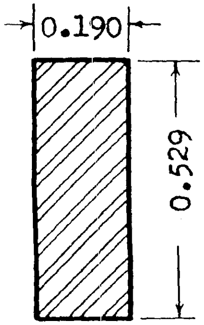
TYPE I



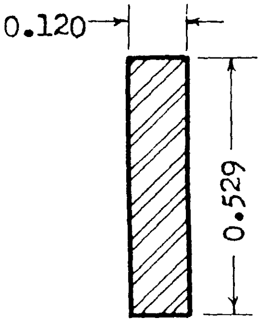
TYPE II



TYPE III



TYPE IV



TYPE V

Specimen Type	Area, $in.^2 \times 10^{-2}$	Major Moment of I., $in.^4 \times 10^{-2}$	Composite* Area, $in.^2 \times 10^{-2}$	Composite* Moment of I., $in.^4 \times 10^{-2}$
I	4.7	0.23	23.2	0.51
II	4.8	0.23	23.3	0.90
III	4.8	0.14	23.3	0.59
IV	10.0	0.23	28.5	0.83
V	6.3	0.15	24.8	0.58

All dimensions are in inches

The inside diameter of all stiffeners = 16.40

All stiffeners were machined from 18 O.D. x 1 inch wall "pipe".

*Refers to composite section of stiffener plus portion of shell one bay wide (0.072 x 2.56)

FIG. 5 STIFFENER TYPES FOR "1954" SERIES RING STIFFENED CYLINDRICAL SHELL SPECIMENS
("1955" Series Specimens have Type I Stiffeners)

TABLE 1 CHEMICAL COMPOSITIONS OF SPECIMEN STEELS

Steel Desig.	Specimen Checked	Description	Chemical Composition (Check Analysis)											
			C	Mn	P	S	Si	Cu	Ni	Cr	N	Mo	Ti	Va
RBA	2SRBA28	Rimmed Steel Hot Rolled 1" φ bar	0.29	0.35	0.021	0.052	0.01	--	--	--	0.014	--	--	--
SPA	2SSPAL11	Semi-killed Hot Rolled 1" plate	0.27	0.51	0.033	0.036	0.03	--	--	--	0.013	--	--	--
NN	NNL11	3/16" Plate Representing PAPOOSE	0.18	1.01	0.042	0.039	0.22	0.10	None	0.11	0.017	--	--	--
NL	NLT1	1" Plate Representing SQUAW	0.16	1.11	0.027	0.029	0.23	0.33	None	0.13	0.016	--	--	--
NHY	NHYL2	HY80 Steel	0.13	0.19	0.006	0.011	0.05	None	2.32	1.34	0.010	0.11	None	0.05

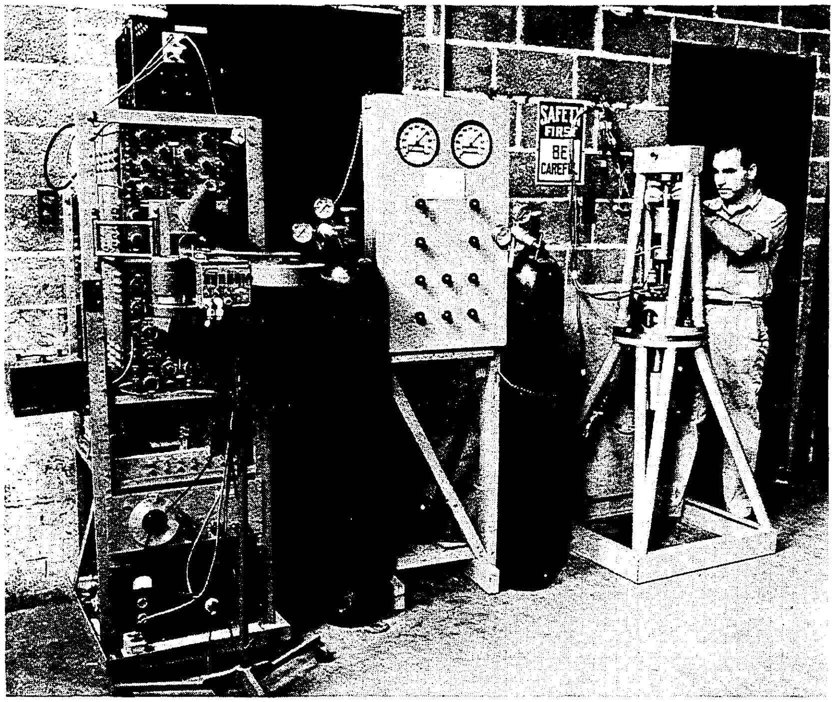


FIG. 6 FOUR CHANNEL CRO EQUIPMENT, PRESSURE PANEL,
AND 20 KIP PULSE LOADING MACHINE
(As arranged for testing tension-compression coupons)
(L. B. Smith in Photograph)

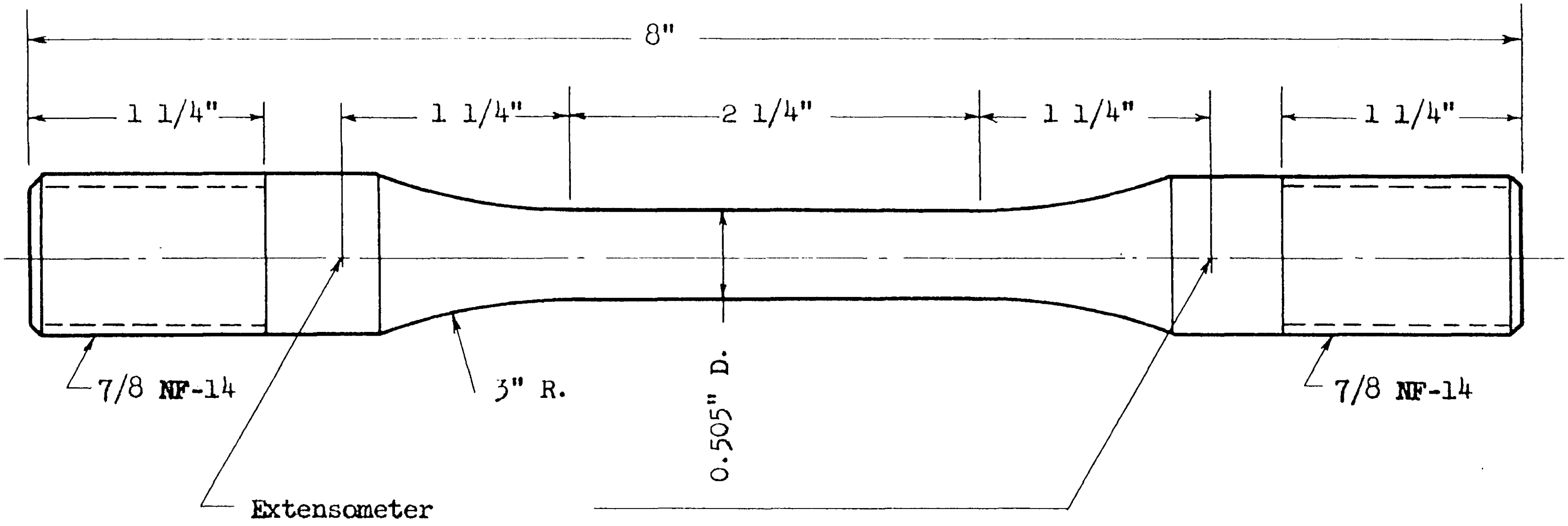


FIG. 7 DIMENSIONS OF TENSILE SPECIMENS
(Except 3/16" Plate Series, NN)

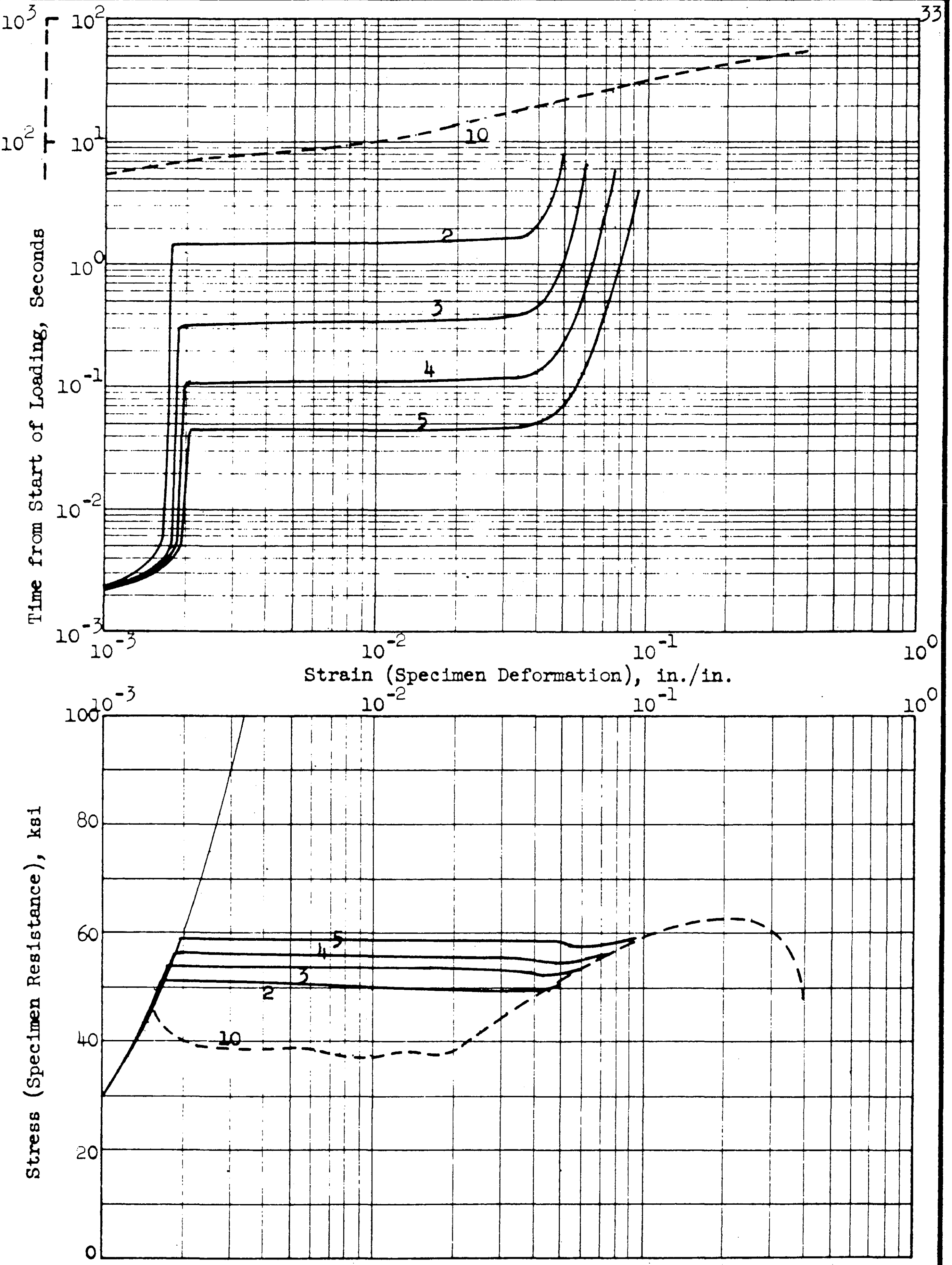


FIG. 8 TYPICAL STRESS-STRAIN AND STRAIN-TIME RELATIONSHIPS FOR MILD STEEL (MRBA 2, 3, 4, 5, and 10)

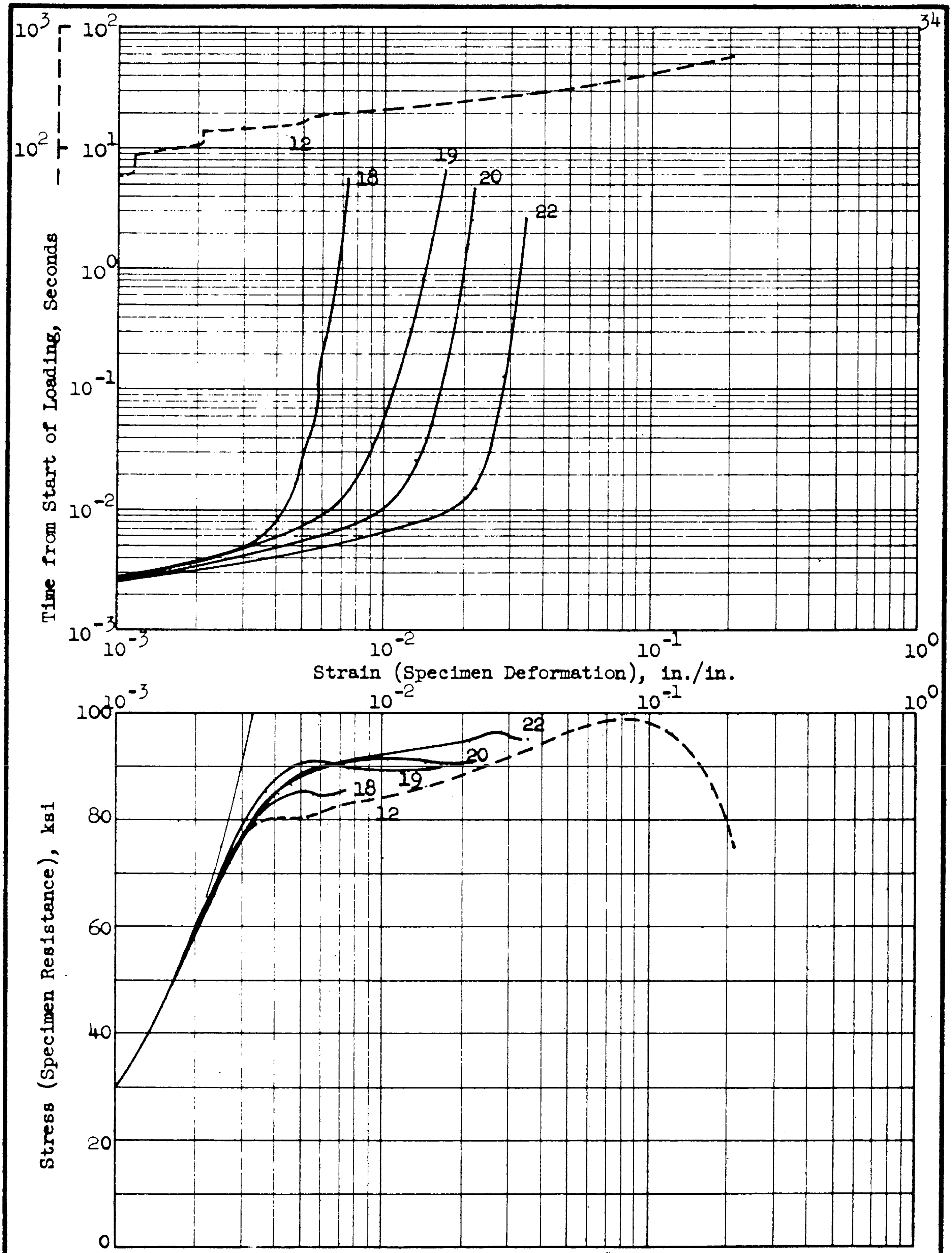


FIG. 9 TYPICAL STRESS-STRAIN AND STRAIN-TIME RELATIONSHIPS FOR HY80 MATERIAL (NHYL 12, 18, 19, 20, and 22)

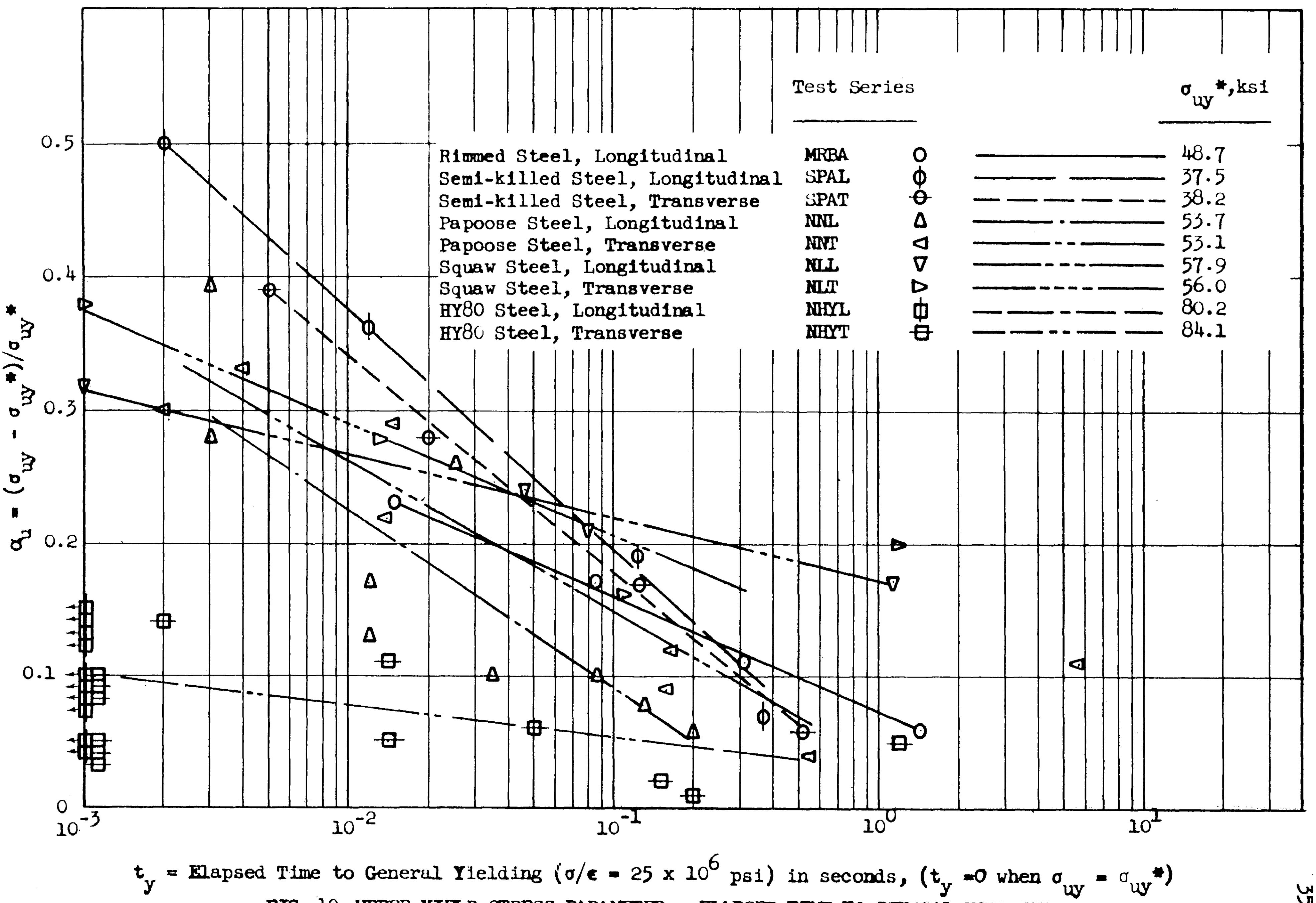


FIG. 10 UPPER YIELD STRESS PARAMETER - ELAPSED TIME TO GENERAL YIELDING

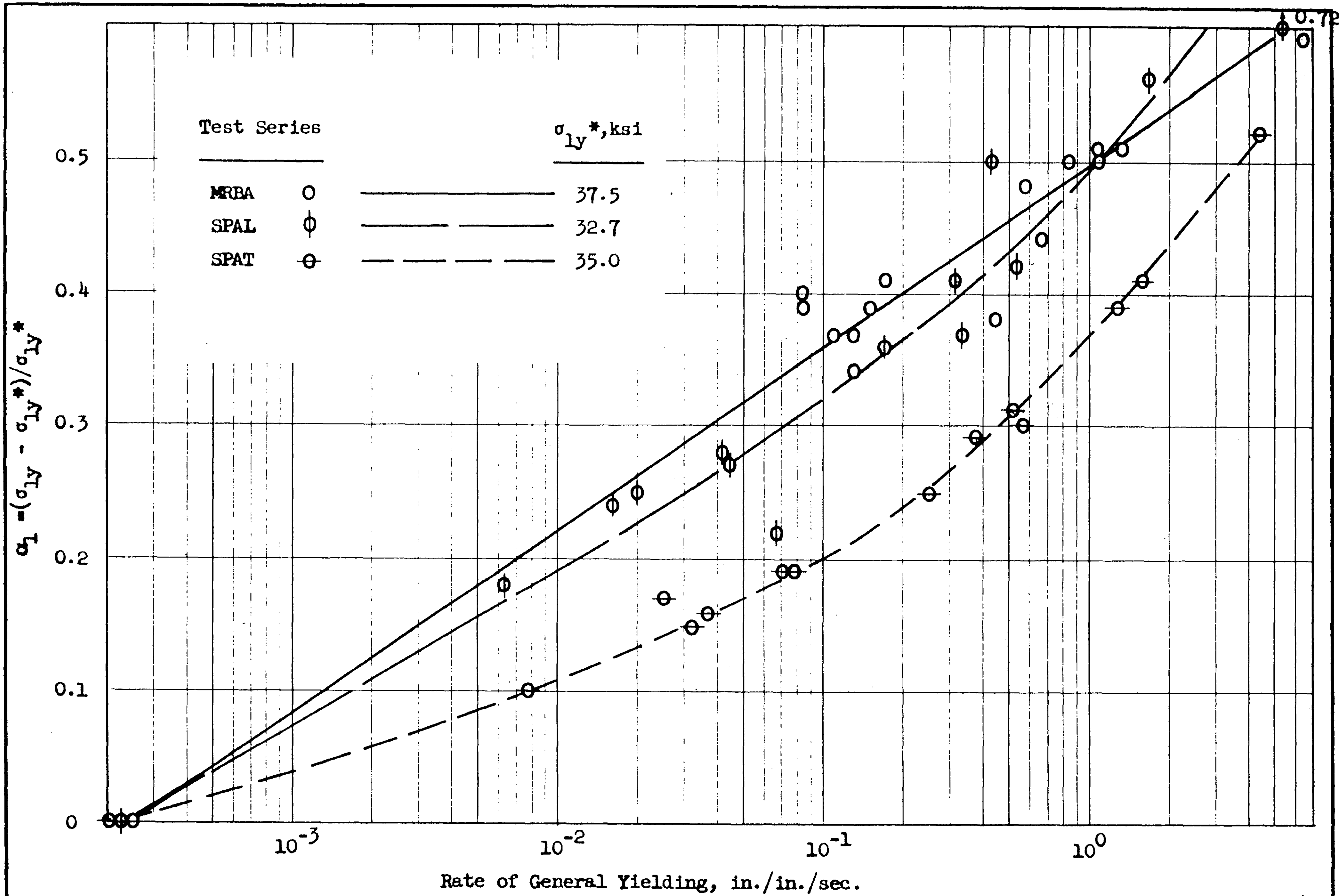


FIG. 11 **LOWER YIELD STRESS PARAMETER - RATE OF YIELDING AT CONSTANT STRESS**

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