SSC-86

EVALUATION OF WELD-JOINT FLAWS AS INITIATING POINTS OF BRITTLE FRACTURE

by

D. C. Martin, R. S. Ryan, and P. J. Rieppel

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September 4, 1956

Dear Sir:

As part of its research program to improve the hull structures of ships, the Ship Structure Committee is sponsoring at Battelle Memorial Institute a project to evaluate the effect of flaws such as may be found in welds on brittle behavior of ships. Herewith is the First Progress Report, SSC-86, of this project, entitled "Evaluation of Weld-Joint Flaws as Initiating Points of Brittle Fracture," by D. C. Martin, R. S. Ryan, and P. J. Rieppel.

This project is being conducted under the guidance of an advisory group under the Ship Structure Subcommittee.

Please submit any comments which you may have to the Secretary, Ship Structure Committee.

This report is being distributed to those individuals and groups associated with and interested in the work of the Ship Structure Committee.

Yours sincerely,

K K Cowart

K. K. Cowart
Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure
Committee

Serial No. SSC-86

First Progress Report
of
Project SR-131

to the

SHIP STRUCTURE COMMITTEE

on

EVALUATION OF WELD-JOINT FLAWS AS INITIATING POINTS OF BRITTLE FRACTURE

by

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Battelle Memorial Institute
Columbus, Ohio

under

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Washington, D. C.
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ABSTRACT

A literature survey was made to determine the fundamental factors and circumstances that are known about brittle fractures in ship steels and similar materials. The survey was the initial part of this investigation for the Ship Structure Committee under Bureau of Ships contract 61748 on the evaluation of flaws in weld joints. Various testing methods and specimens used in previous investigations involving brittle fracture were reviewed. Preliminary studies were made to determine the best method of introducing flaws into weld joints to simulate the flaws found in service failures.

A major portion of the effort on the project has been involved with determining: (a) what kind of test specimen and apparatus should be used to evaluate weld-joint flaws; (b) what kind of loading or types of loading are needed to simulate service conditions in ships or other large structures; and (c) what nominal stress is required to initiate a brittle fracture from large weld cracks and other flaws such as lack of weld fusion.

A significant result has been that brittle fractures initiate from the weld defects in the laboratory specimen under conditions very close to the reported conditions involved in some service failures of ships.

ACKNOWLEDGMENT

During the course of this survey, the problem of evaluating weld flaws as it relates to brittle fracture was discussed with the following personnel. We are grateful to these men who contributed their information and time.

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Advisory Group

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EVALUATION OF WELD-JOINT FLAWS AS INITIATING POINTS OF BRITTLE FRACTURE

INTRODUCTION

Previous extensive studies of many ship failures have shown that fractures frequently have initiated at various types of weld-joint flaws. Some of these weld-joint flaws have been located in areas of severe structural notches and stress concentrations. Other fractures have started in butt joints in plates located well away from major structural discontinuities. Although numerous investigations of the causes of brittle fracture in ships have been undertaken in the past twelve years, no extensive study has been made of the part that weld flaws play in initiating brittle fractures in welded structures. There is lack of knowledge concerning what types and sizes of flaws are potentially dangerous in a ship structure.

This investigation was advised by the Ship Structure Subcommittee and sponsored by the Ship Structure Committee through contract with the Bureau of Ships, Department of the Navy. The principal objective is to evaluate the influence of various sizes and types of flaws in welded butt joints in flat plates on the initiation of brittle fractures. It was hoped that a study of such flaws under conditions that closely simulated those of service might aid in establishing adequate production, inspection, and repair procedures for use in ship construction. The ultimate goal would be to aid the shipbuilder to eliminate potentially dangerous flaws from ships during construction. The work described in this report was conducted during the period from April 23, 1953, to December 30, 1955.

The initial problem in this study was to select or devise a test specimen and a means of loading it so that flaws in welded joints could be tested under a variety of simulated severe service conditions. Since many other investigators of brittle fracture have faced this same problem, the first phase of this investigation was a study of the literature dealing with brittle fracture. This study was made to obtain background information and at the same time to search for a specimen and testing procedure that might be suitable for use in evaluating weld-joint flaws. This selected survey of literature was supplemented by discussions with several leading investigators in the field of brittle fracture in steels.

As a result of the survey and discussion, a test specimen and method of testing were devised by which it is believed that service conditions in large welded structures can be simulated. The testing apparatus is a sphere, approximately 9 feet in diameter, made from a high-strength low-alloy steel with good notch toughness. The test specimen is a 24-in. diameter circular disk of ship plate steel containing a previously prepared weld flaw, and which is welded into and is part of the wall of the sphere. The test disk has the same thickness and contour as the wall of the sphere and contains full-size welded butt joints in which various welded flaws of controlled size are located. During testing, the entire sphere is cooled to a selected temperature and then loaded by hydrostatic pressure. After testing, the specimen is removed from the sphere wall, and a new specimen is welded in place. Various schemes have been devised to complicate and concentrate the basic 1:1 ratio of biaxial tension stresses in the test panel, to simulate complex stress patterns and stress gradients in actual structures. In addition, tests have been made with the test panels subjected to cyclic loading.

A preliminary series of tests was conducted to determine the type, or combinations of loading conditions necessary to simulate service conditions. The results of these tests indicated that various weld defects could be evaluated by static load tests.

The test results described in this report have been made with 3/4-in. Grade M Code Type E, modified ABS-B, and ABS-B* steel specimens. The E and modified ABS-B steels were selected as the first materials to be tested because of their high transition temperature (80 F and 100 F, respectively, at 15 ft-lb Charpy V-notch).

Cracks and lack of fusion are the two types of flaws that have been evaluated in this investigation. The results of the present testing program indicate a correlation between crack length and the nominal stress required for fracture. Disks containing weld

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*This refers to ABS-B requirements in effect before January 31, 1956.

cracks initiate at lower nominal stresses than equal length lack-of-fusion-type flaws.

SUMMARY

The following is a resume of the important findings so far obtained on this investigation.

With regard to the test technique:

(1) The testing technique produced brittle fractures from weld flaws when tests were made at temperatures below the 15 ft-lb Charpy V-notch transition temperature of the test plate being used.

(2) Sufficient energy was stored in the test apparatus to propagate the fracture after it was initiated.

(3) The fracture stopped or turned ductile and ran only a short distance after meeting the weld joining the test plate to the test vessel.

With regard to welds containing cracks as flaws:

(1) Brittle fractures initiated without visible signs of ductility from cracks which ended in the base metal. Fractures initiated at nominal stresses well below the yield strength of the test plate provided the crack was 4 in. long or longer.

(2) As the length of the crack increased, the nominal fracture stress decreased. An increase in crack depth decreased nominal fracture stress only slightly.

(3) When weld cracks ended in sound weld metal, brittle fractures did not initiate. In some tests ductile fractures occurred.

(4) The addition of residual or reaction stresses to the stress system in general lowered the nominal fracture stresses. In some cases a brittle fracture initiated as a result of residual or reaction stresses alone, that is, at zero nominal stress.

(5) Brittle fractures initiated from lack-of-fusion flaws in welds. There was some decrease in nominal fracture stress with increase in length of flaw. There was a considerable decrease in nominal fracture stress with increase in depth of the flaw.

In general:

(1) The data obtained did not indicate that cracks in welds were more serious flaws than lack of fusion.

(2) The nominal fracture stresses obtained are much higher for small flaws than might be predicted by nominal stresses calculated to be present in structures which have failed. This indicates that the calculated nominal stresses in the structures may be lower than the stresses actually present in some areas in the structure by factors of 2, 3, or more.

BRIEF REVIEW OF BRITTLE FRACTURE KNOWLEDGE

An early investigation* of ship failures showed that there were several factors that contributed to the occurrence of brittle failures. They are classified under three main headings: (1) design; (2) material; and (3) construction. Each of these three items have been improved since the early days of the accelerated program of mass-producing welded ships. It is now believed that defects built in during construction, sometimes resulting from poor workmanship, may be the major focal points

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*<u>Final Report of a Board of Investigation to Inquire into the Design and Methods of Construction of Welded Steel Merchant Vessels</u>. Washington, D. C.: Government Printing Office. July 15, 1946.

of failure. This does not necessarily mean that such built-in flaws result from deliberate spoiling of work. As long as the welding process is controlled predominately by the human element, defects will never be eliminated completely. These defects in the form of small nicks, cracks, and notches are built into the structure.* It would be desirable if the fabricator knew to what degree the flaws affect service performance of the weld joints so that intelligent decisions can be made as to which defects must be repaired and which may be tolerated.

It would not be too difficult to evaluate the effect of various weld-joint flaws if a simple laboratory specimen and testing method were available which simulated actual service conditions. Unfortunately, at the start of this investigation such a specimen and method were not available. This difficulty was first encountered about 10 years ago when the first major attempts were made to study brittle fracture. It became apparent that there was no single simple laboratory specimen because the brittle fracture problem was too complex. A great deal has been learned since those early years, but the selection of a laboratory specimen for this study was still a difficult task.

The laboratory specimen selected for this investigation necessarily must simulate service conditions on a full-sized weld joint. In order to make this selection, it was necessary to

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*Young, R. T. "Strength of Welded Ships," <u>The Welding Journal</u>, 1945, pp. 471--474.

consider: (1) the conditions present when brittle fracture occurred; and (2) the basic facts which were known about brittle fracture. It was impossible to answer these two questions completely, but the available information was reviewed and is presented briefly in the following paragraphs.

Failures have occurred in ship sections subjected to low nominal stresses at temperatures between 20 F and 40 F. A few failures have occurred at temperatures above 50 F but have not been so extensive or serious as the ones which occurred at lower temperatures. Fractures were of a brittle type and showed very little ductility, although material through which fracture occurred had normal strength and ductility in ordinary tests*,** at room temperature. The starting point of many fractures could be traced to a point of stress concentration at a notch resulting from structural or design details, welding defects, metallurgical imperfections, or accidental damage. Notches resulting from design details or welding defects were undoubtedly present in all ships of a given type. Research has shown that fractures originated only when high stress concentrations at critical

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*Shank, M. E. "A Critical Survey of Brittle Failure in Carbon Plate Steel Structures other than Ships," Survey Report, Ship Structure Committee Report Serial No. SSC-65, December 1, 1953. (See also ASTM Technical Publication No. 158). (See also Welding Research Council Bulletin No. 17).

**Hoyt, S. L. "Brittle Fracture Studies in the United States," Paper No. 452 presented at the Conference on Brittle Fracture in Steel, The West of Scotland Iron and Steel Institute, May 15, 1953.

locations in the structures or serious flaws occurred in combination with plates of unusually low notch toughness*.

The compositions of the ship steels investigated indicated that the notch sensitivity was increased by increasing amounts of carbon or phosphorus and decreased by increasing amounts of manganese. Notch sensitivity also was decreased by decreasing grain size. Silicon decreased notch sensitivity when added to perform the function of a deoxidizer and increased notch sensitivity when added as an alloying element.

It has been shown in tests of fractured plate* from ships that the plates in which fracture originated were generally more notch sensitive than the general run of plates used in ship construction. This was true using as the criterion of notch sensitivity either the 15 ft-lb transition temperature or the energy absorbed by Charpy V-notch specimens at the failure temperatures of the respective plates.

Apparently, little energy is required to propagate the fracture once it is initiated, but the energy that is expended must be available at a rate sufficient to propagate a high speed crack. When the fracture is initiated, it progresses with increasing velocity until it approaches the theoretical maximum of about

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*Williams, M. L., and Ellinger, G. A. "Investigation of Structural Failures of Welded Ships," <u>The Welding Journal</u>, Res. Suppl., October 1953, pp. 498-s--527-s.

5500 fps, which is related to the velocity of a transverse elastic wave in steel*. The loud noise which has been reported for large fractures indicates an almost instantaneous release of a large amount of energy**.

Using the information obtained in the survey as a basis, specifications were set up to aid in the selection of a laboratory test specimen and testing apparatus. The factors present in service failures which the test method should provide were the following:

(1) Stress patterns similar to severe conditions would include a certain degree of biaxial tension stress (possibly a 2:1 or 1:1 ratio) throughout the thickness of the plate. Superimposed on this would be flaws in welded joints to provide stress concentration and triaxiality.

(2) Store sufficient elastic energy to propagate fractures at mean rates ranging from 1000 to 5500 fps.

(3) An essential feature is that the fractures should be of the brittle type.

(4) The fractures must pass through material subjected to low nominal stress levels of 10,000 to 20,000 psi. Provisions for higher stress levels should be available if needed.

(5) Fractures should occur in the temperature range from 20 to 45 F. Lower temperatures should be available if required.

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*Parker, Earl R. Brittle Behavior of Engineering Structures. New York: John Wiley & Sons, Inc. (In press).

**Acker, H. G. "Review of Welded Ship Failures," Review Report, Ship Structure Committee Report Serial No. SSC-63, December 15, 1953.

(6) Fractures which initiate in weld-joint defects should propagate into the base plate of the test piece.

(7) Material for test specimens should have a high Charpy V-notch transition temperature. The plates should be selected from production quality of ship plate.

DEVELOPMENT OF A SPECIMEN AND TESTING METHOD

The various specimens and methods of testing presented and discussed in Appendix A were studied, and discussions were held with some of the leading investigators in the field of brittle fracture. On the basis of this review and the basic facts presented in the previous section, a sphere was selected as the testing apparatus because it had certain advantages as described below.

The idea of removing a test section from the testing apparatus (the sphere) and inserting a test panel is presented in Appendix A in the section on Structural Tests of Ships. Briefly, the idea would be to insert a test panel in a structure, such as a ship, and test this panel under actual service conditions. However, if the panel failed, the whole structure would be in potential hazard.

The sphere was devised from this idea. The apparatus is unique in that the sphere becomes a part of the test specimen after the disk is welded in. That is, the specimen is no longer a 24-in. disk but a 3/4-in. thick specimen having a surface area of 275 sq. ft. The sphere is sufficiently strong and notch tough at test temperatures to resist a fast-running fracture. In addition to static pressures, cyclic pressures can be applied to the structure. The diameter of the sphere is large enough to provide elastic energy to propagate fractures across the test panel at velocities ranging from 1000 to 5000 fps. The complete apparatus is described in detail in the next section.

Testing Methods. The testing apparatus is a 110 3/4-in. ID sphere made of 3/4-in. high-yield-strength alloy steel. The specimen, a 3/4-in. by 24-in. circular curved disk containing a weld flaw, is welded into the wall of the sphere. A sketch of the complete testing device which includes the testing apparatus, specimen, protective enclosure, lid, refrigeration unit, and pressuring equipment are shown in Fig. 1. A photograph of the sphere is shown in Fig. 2 with the enclosure in the background.

Sphere. The mechanical properties of the steel, the fabrication details, and other pertinent data of the sphere are described in Appendix B.

Specimen. The disks were made of several types of steel of the quality used in ship construction: (1) Grade M, Code Type E; (2) modified ABS-B; and (3) as-received ABS-B. Grade M, Code Type E steel has low notch toughness. The modified ABS-B steel was heat treated to raise its Charpy V-notch transition temperature to approximately that of the Type E steel. The as-received ABS-B steel is a standard material used in ship construction.

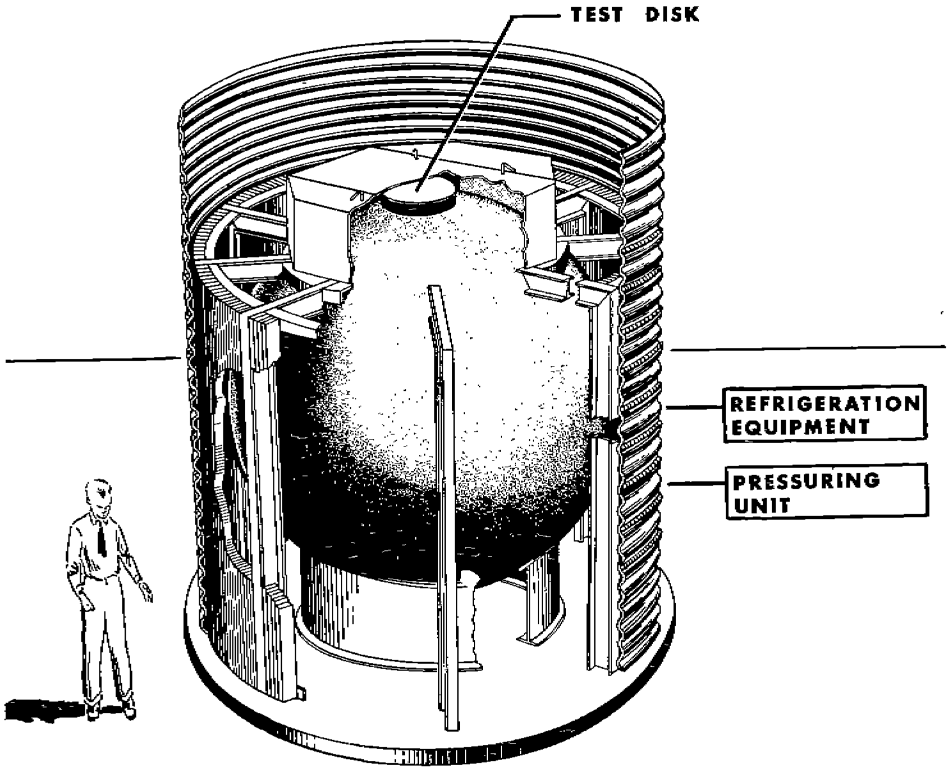

FIGURE 1. Cutaway drawing showing apparatus and supplementary equipment

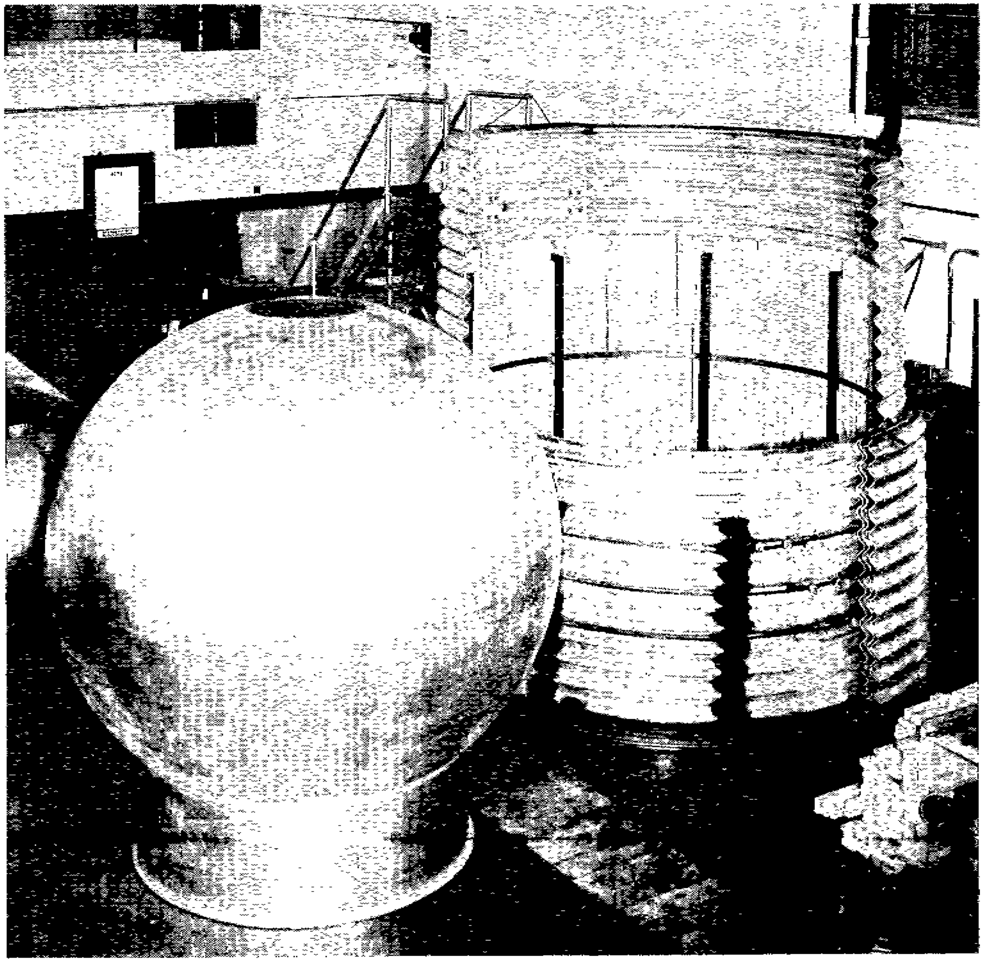

FIGURE 2. Photograph of sphere beside enclosure

It is less notch sensitive or has a lower notch transition temperature than the other two steels. The chemical and mechanical properties of the steels are shown in Table 1.

TABLE 1. CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF DISK MATERIALS

	Chemical Composition, %			Mechanical Properties		
	Project Steel E*	ABS-B Steel**		Project Steel E*	ABS-B Steel**	Modified ABS-B†
Carbon	0.20	0.21	Yield strength, psi	30,950	30,700	33,000
Manganese	0.33	0.80	Ultimate strength, psi	58,430	59,400	59,500
Phosphorus	0.013	0.019	Thickness, in.	3/4	3/4	3/4
Sulfur	0.020	0.034	Elongation in 2 in., %	-	55.3	35
Silicon	0.01	0.04	Elongation in 8 in., %	30.6	31.7	-
Aluminum	0.009	0.003	15 ft-lb Charpy V-notch transition temperature, F	80	40††	100††
Nickel	0.15	0.10				
Copper	0.18	0.05				
Chromium	0.09	0.04				
Molybdenum	0.018	0.01	Tear test transition temperature, F	140	100	-
Nitrogen	0.005	0.005				
Vanadium	0.02	0.01				
Titanium	-	0.004				

*Klier, E. P., and Gensamer, M., "Correlation of Laboratory Tests With Full Scale Ship Plate Fracture Tests", Final Report, Project SR-96, Ship Structure Committee, January 30, 1953, SSC-30.

**Ginsberg, F., Foster, M. L., and Imbembo, E. A., "Notch Toughness Properties and Other Characteristics of Medium Steel Ship Plate", New York Naval Shipyard Report, August 31, 1954.

†Modified by annealing at 1650 F and cold forming.

††Transition temperature of cold-formed disks, tests performed at Battelle.

Disks for test specimens, 24 in. in diameter, were cut from the plates and formed to match the curvature of the sphere.

Flaws. The flaws were placed in butt welds or simulated butt welds in nearly all tests. Two types of flaws were used--cracks and lack of penetration. Cracks were made by placing cast iron in the weld joint when making the weld in the test specimen. Lack-of-fusion flaws were made by laying a 1/8-in. thick plate along one of the surfaces of the groove in which the flawed weld was made. This prevented fusion of the weld metal to the face of the groove and simulated a lack-of-fusion flaw. Both types of flawed welds were made in a jig to preserve proper curvature in the test specimen.

Supplementary Equipment. Additional equipment was necessary to enclose the sphere, cool the specimen, and apply pressure to the sphere.

A protective enclosure was installed to prevent any possible damage in the event the sphere should break open. Experience at Battelle in bursting large-diameter pipe has shown that wood alone will not contain the escaping liquid when pressures are very high. On the basis of this experience, the enclosure was built to withstand the worst situation. The enclosure is an 11-ft diameter 1/4-in. thick pipe made of several plates of corrugated steel. The 11-ft pipe is assembled from sections and bolted together. Steel-wire rope is bolted together with U-bolts around the outside of the pipe in the grooves to provide additional protection. The inside of the enclosure is lined with 2 in. by 4 in. lumber to provide an insulating material between the cold sphere and room temperature and to provide a shock absorber between sphere and enclosure. A 6-ft octagonal lid made from 3/4-in. plate is placed over the top of the sphere during testing. An I-beam section is placed over the lid and secured to weights on the floor by means of cables.

Cooling is obtained from a coil in the test sphere, as shown in the sketch of a cross section in Fig. 3. Brine solution is used to fill the sphere, and relatively uniform temperatures are obtained by circulating the brine. Temperatures as low as 0°F can be reached in the test plate. The composition of the brine is described in Appendix B.

Test plates are stressed by hydrostatic pressure, which produces biaxial tension stresses in the sphere wall. Pressures are obtained with an air-driven high-pressure water pump.

Testing Procedure. The test disk containing a flawed weld was welded into the sphere with low-hydrogen electrodes (AWS E10016). The sphere was filled with brine and all air was removed. After the temperature of the sphere and disk was reduced to testing temperature, the sphere was loaded by hydrostatic pressure. A 100-psi increase in pressure results on about a 3700-psi increase in nominal stress in the test plate. The pressure in the sphere was increased until the disk fractured or until a pressure of 900 psi was reached. Strain measurements were taken at each 100-psi

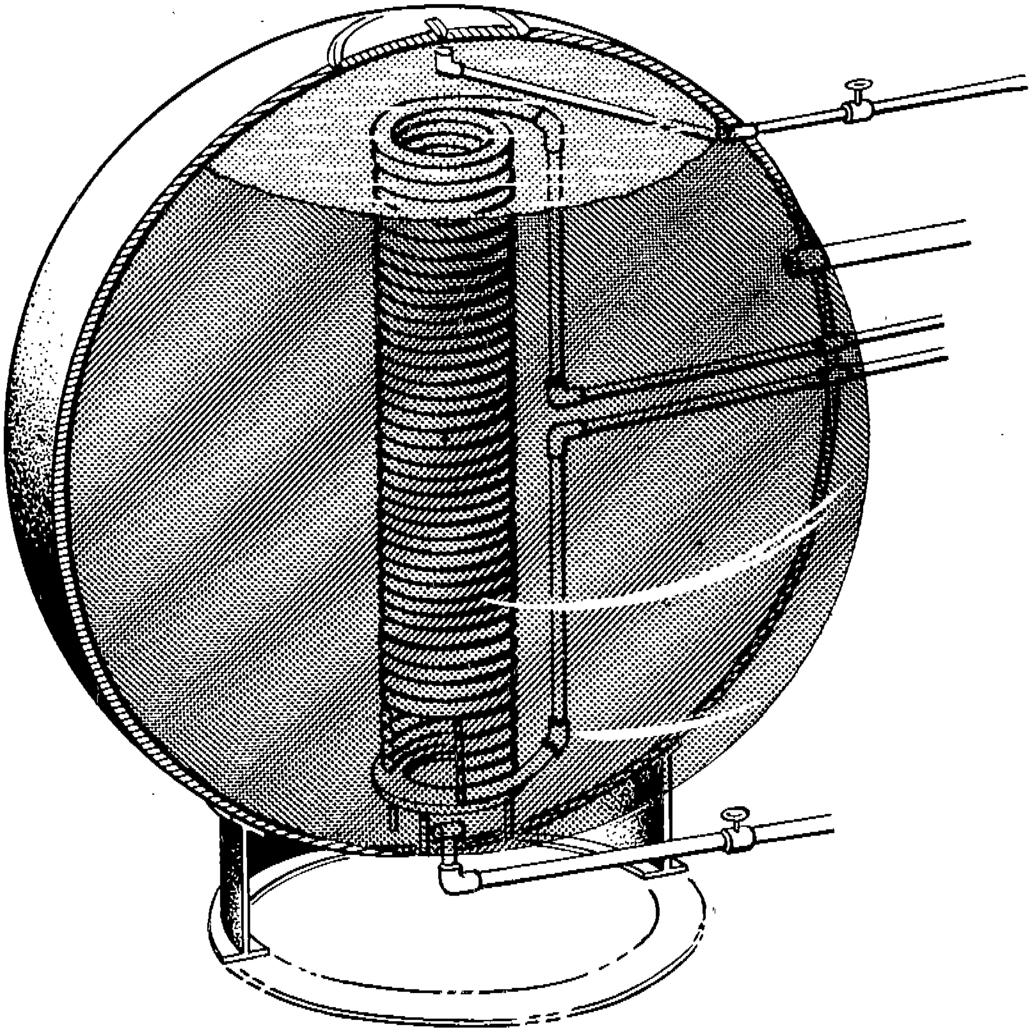

FIGURE 3. Cross section of sphere

increase in pressure.

The testing temperatures were chosen in most tests to be equivalent to those at which the Charpy V-notch energy value for the plate being used was 2 to 6 ft-lb. The tests in E steel and the modified ABS-B steel were made around 20 F and in the as-received ABS-B steel around 10 F.

The nominal stress in the sphere was in most cases determined from the pressure measurement using the equation $S = \frac{PD}{4t}$. There was good correlation between this calculated stress and that measured by strain gages placed on the sphere and disk away from the flaw. The nominal stress required to initiate a brittle fracture has been the major criterion used to evaluate and compare test results. Throughout this report this stress will be referred to as the nominal fracture stress.

In only a few of the tests made was the nominal stress raised above 33,000 psi. Generally, if fracture had not occurred at 33,000 psi, loading was stopped. There were two reasons for this. One was that at nominal stresses above 33,000 psi the test plate began to bulge and the stress conditions in the plate changed radically. This was the major reason for stopping. A second reason for stopping at 33,000 psi was to protect the test equipment.

INFLUENCE OF FLAWS IN WELDS ON INITIATION OF BRITTLE FRACTURE

Studies of the influence of weld flaws on the initiation of brittle fracture in mild steel plates were made using cracked welds and welds containing lack of fusion. Cracked welds were studied first since this type of flaw appears to be more severe than other types*,**. Consistent results were obtained in making cracks by laying a cast iron rod in the joint and welding over it with an E6020 electrode. If further welding was done in the joint, E6010 electrodes were used. A crack made by this method in the root passes of a double-V joint is shown in Fig. 4.

Influence of Cracks in Welds on Initiation of Brittle Fracture. Four types of cracked welds were used. Sketches of cross sections of each of these types are shown in Fig. 5. Most of the tests were made using Type A and Type D cracks. Seventy-nine plates containing cracked welds were used. Of these, 30 contained Type A cracks, 3 contained Type B cracks, 18 contained Type C cracks, and 28 contained Type D cracks. The results of all tests are described in detail in the tables in Appendix D.

In considering the physical attributes of a crack that might influence fracture initiation, length and depth were the ones obviously controllable. Other factors (for example, the sharpness of the ends of the crack) would also influence the behavior of the flaw, but it was believed that only length and depth could be

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*Puzak, P. P., Eschbacher, E. W., and Pellini, W. S. "Initiation and Propagation of Brittle Fracture in Structural Steels," The Welding Journal, Res. Suppl., December 1952, pp. 561-s--581-s.

**Warren, W. F. "Fatigue Tests on Defective Butt Welds," Welding Research, vol. 6, no. 6, 1952, pp. 112r--117r.

FIGURE 4. Crack in both root passes of a double-vee butt joint welded with E6020 Electrode. Subsequent passes welded with E6010 Electrode.

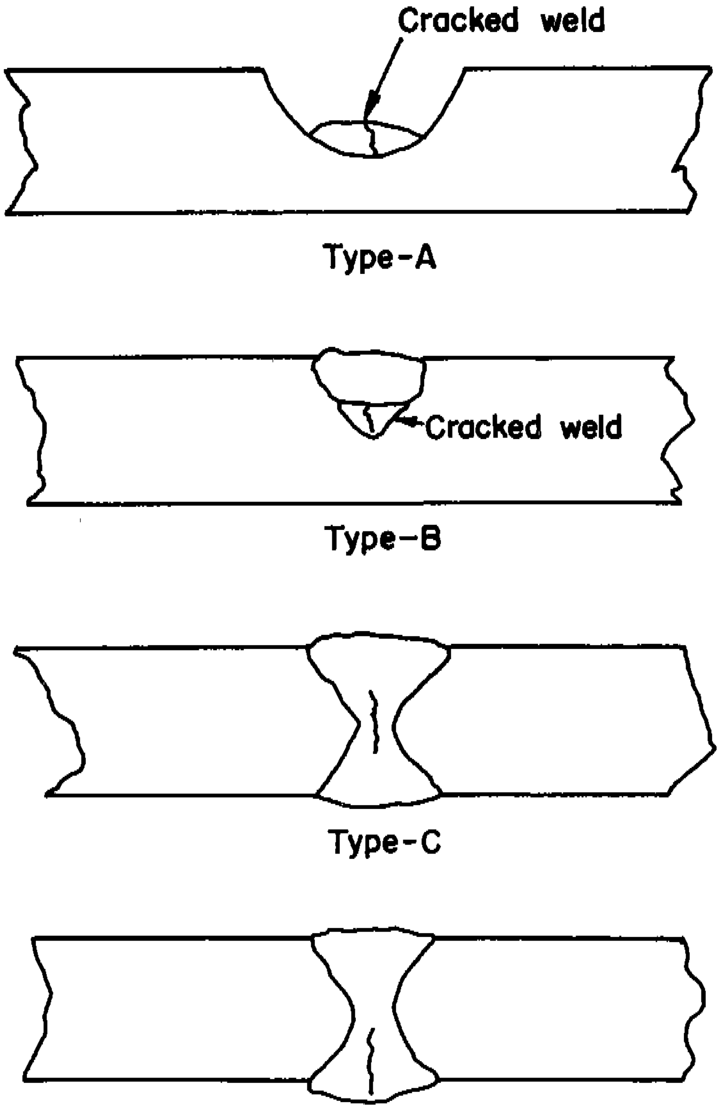

FIGURE 5. TYPES OF CRACKED WELDS USED

controlled with any degree of assurance.

Early in the work, it was decided that in general the cracks being used as flaws should not end in weld metal. This decision was based on the known low Charpy V-notch transition temperature for the weld metals used in the flaws. It was hoped that the cast iron used to crack the welds would raise the brittle transition temperature, but consistent behavior could not be counted on. The crack end being in the base plate assured that material of comparable brittleness was involved in fracture initiation in each test. Some of the anomalous test results discussed later are believed to have been caused by the crack end not being in the base plate.

Effect of Test Temperature. When test work was started, it was decided that tests should be made at temperatures between the 5 ft-lb and 10 ft-lb Charpy V-notch temperature for the base plate. This decision was made to try to insure that the test plates would act as "start" plates. In the course of the investigation, a number of tests were made on specimens containing an 8-in. Type A crack in E and modified ABS-B steels at temperatures from 12 F to 34 F. Brittle fractures initiated in all of these tests. Over the temperature range tested, there seems to have been only a slight increase in the nominal fracture stress as the temperature was increased. This is shown in Fig. 6. In the 10 F to 40 F temperature range, the Charpy V-notch value for these steels varies from 3 ft-lb (10 F) to 7 ft-lb (40 F).

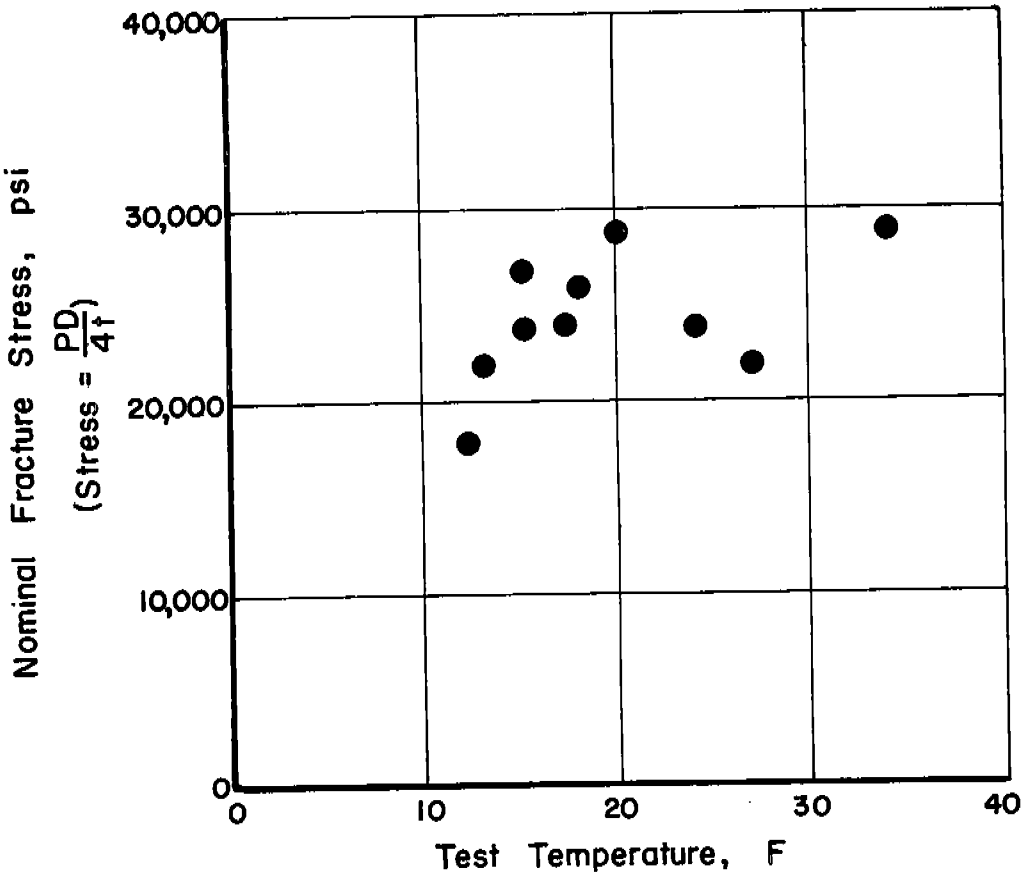

FIGURE 6. RELATION BETWEEN STRESS REQUIRED TO INITIATE A BRITTLE FRACTURE AND TEST TEMPERATURE FOR CRACKS 8 INCHES LONG. TYPE A CRACK IN E STEEL AND MODIFIED ABS-B STEEL. CHARPY VEE-NOTCH VALUES RANGE FROM 3 FT-LB AT 10 F TO 7 FT-LB AT 40 F FOR BOTH TYPES OF STEEL.

When tests are made on both sides of the Charpy V-notch 15 ft-lb temperature, different results are obtained. Using a Type D notch, ABS-B steel, and temperatures at, below, and above the Charpy V-notch 15 ft-lb temperature, the results shown in Fig. 7 were obtained. The results of all of the tests made indicated that, as long as testing was done in the Charpy V-notch 5 to 10 ft-lb temperature range, variations in temperature would not affect results appreciably. However, the results of tests at 15 ft-lb Charpy V-notch temperatures and higher could not be compared with those made at the lower temperatures.

Effect of Crack Length. Length is the dimension of a weld crack that can vary most widely in a structure. Therefore, it seemed important to determine the effect of crack length on the initiation of brittle fracture. Initial tests were made on specimens containing what were thought to be serious flaws. They were Type A cracks (Fig. 5) 8 in. long. Brittle fractures initiated from these flaws at nominal shell stresses well below the 33,000 psi yield strength of the test plate. The results of these tests indicated that the test method worked and a study of the effect of crack length was undertaken. At first, tests were made on rather short cracks, and then during the course of the project, the range of crack lengths was expanded until a range of 1 in. to 16 in. was covered.

Fig. 8 is based on tests made with Type A and Type D cracks. Data obtained from these tests are used since they represent the majority of the tests made. Only three tests were made with

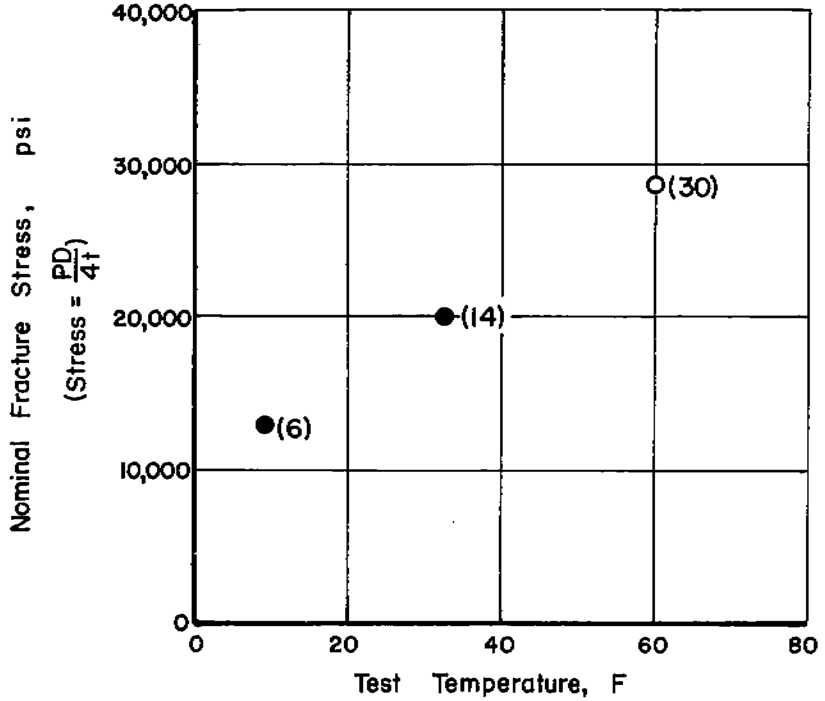

FIGURE 7. RELATION BETWEEN NOMINAL STRESS REQUIRED TO INITIATE FRACTURE AND TEST TEMPERATURE FOR TYPE D CRACKS 12 INCHES LONG, $\frac{3}{4}$ INCH DEEP, IN ABS-B STEEL. FRACTURE AT 60 F WAS DUCTILE, OTHERS WERE BRITTLE. FIGURES IN PARENTHESES ARE CHARPY VEE-NOTCH VALUES FOR THE PLATE AT THE TEMPERATURE OF TEST.

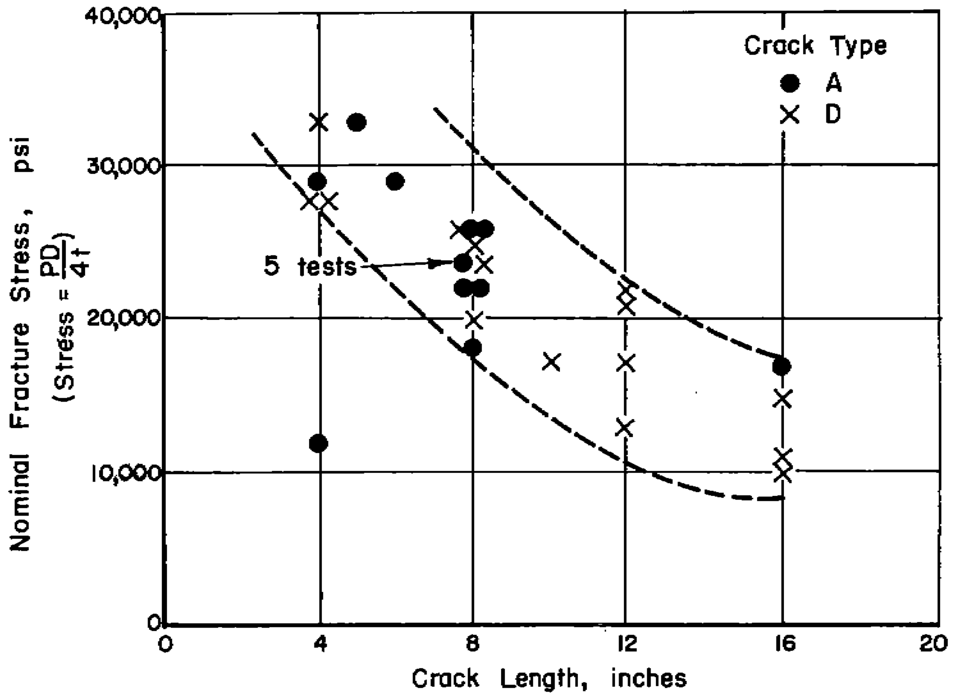

FIGURE 8. RELATION BETWEEN LENGTH OF CRACK AND NOMINAL STRESS REQUIRED TO INITIATE BRITTLE FRACTURE. IN STRESS FORMULA, P = PRESSURE, D = DIAMETER OF SPHERE, AND t = THICKNESS OF PLATE.

Type B cracks. The results of tests made with Type C cracks will be discussed later.

It was mentioned earlier that it was decided to end all cracks in base plate. Some tests were made to determine the effect of having the crack end in sound weld metal. For these tests the test plate was cut in two and welded back together using a double-V weld. Cracks of desired depth and length were made in this double-V weld. Tests were made on disks containing cracks from 8 in. long to 16 in. No brittle fractures initiated in any of these specimens. In tests with 12-in. and 16-in. cracks, a fracture ran across the weld to the heat-affected zone, propagated a short distance along the heat-affected zone of the weld and stopped. In all of these, there was evidence of considerable necking along the path of the fracture.

Only one test shown in Fig. 8 falls outside the band. This is the test with a 4-in. crack which failed at a nominal stress of 12,000 psi. No reason for this result has been discovered. With the exception of this test, the relationship between crack length and nominal fracture stress seems fairly consistent, although the scatter band is rather wide. The reason for this wide band may be that crack depth, test temperature, and type of base plate were ignored in drawing the figure. It is believed that of these, crack depth is most important in causing scatter since all tests were made at temperatures which were well below the 15 ft-lb Charpy V-notch temperature.

Effect of Crack Depth. The effect of crack depth is shown in Fig. 9. This figure shows that apparently crack depth does have some effect, although much less than crack length.

It will be noted that there are no points shown on either Fig. 7 or Fig. 8 for cracks less than 4 in. in length, although tests were made on plates which contained shorter cracks. However, none of these plates failed in test. In fact, two tests were made on specimens containing 4 in. long cracks in which brittle fractures did not initiate at 33,000 psi. It appears that for this test 4 in. is about the limiting length of cracks which will initiate fractures at nominal stresses below the yield strength of the test plate.

Even at 4 in. the crack had to be open to one surface or the other of the weld in the test plate for fracture to initiate at nominal stresses below 33,000 psi. A number of tests were made on plates containing Type C flaws which in general contained sound weld metal over both top and bottom of the crack. Cracks from 4 to 16 in. in length were used in these tests. In only two tests did brittle fractures initiate from Type C cracks. In one of these tests a groove was ground 1/8 in. deep in the weld over the 10-in. long crack after the test plate had been taken to 33,000 psi nominal stress without failing. On reloading, a brittle fracture initiated at 31,000 psi nominal stress. In the second test the 4-in. long crack opened up during loading to the top surface of the weld. It thus became a Type D crack of unknown length. The brittle fracture initiated at 18,000 psi nominal stress.

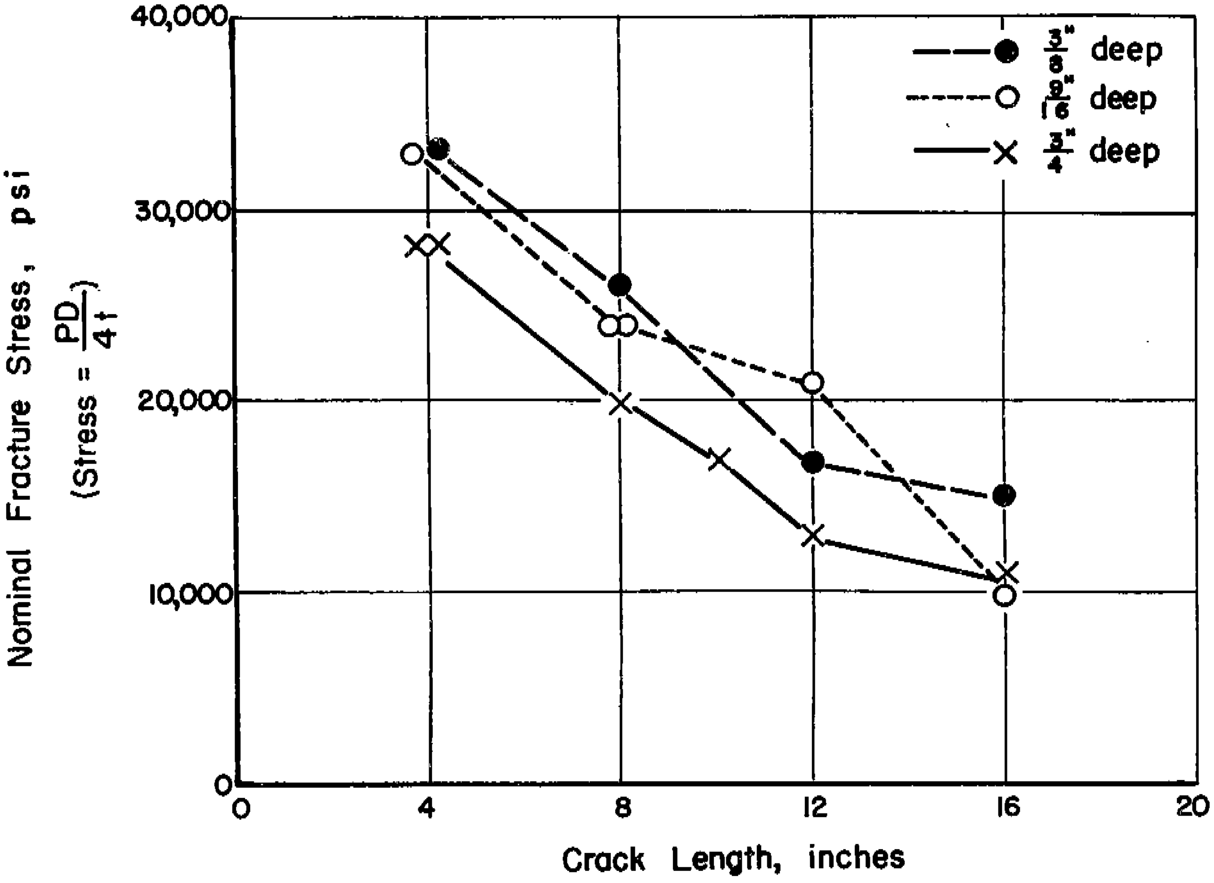

FIGURE 9. RELATION BETWEEN CRACK LENGTH, CRACK DEPTH AND NOMINAL STRESS REQUIRED TO INITIATE BRITTLE FRACTURE

A number of the plates containing Type C flaws started to leak through the flaw at nominal stresses between 25,000 and 31,000 psi. This, of course, stopped the test.

Effect of Cyclic Loading. Early in the experimental work on this project it was suggested by the Project Advisory Committee that the stresses required to initiate brittle fractures were too high. That is, they were higher than the apparent service experiences of various types of welded structures would have predicted. Changes were made in the test procedure to attempt to reduce the magnitude of the nominal stresses required to initiate fracture. One of the changes was to use cyclic loading rather than uniform loading during the test. The results of tests made with cyclic loading are shown in Table 2. In one test the crack opened up during cycling, and the test had to be stopped because pressure could not be held. In the other tests after cycling, the test plates were loaded to a higher stress than had been used in cycling. In two tests the higher nominal stress used was in the range that should have initiated a brittle fracture from the type and length of crack used. Fractures did not occur in these tests. This indicated that cyclic loading did not reduce the nominal stress required for fracture. Consequently, no further tests were made using cyclic loading.

Effect of Residual Stresses. A second change that was introduced into the test procedure to try to reduce the nominal stress required to initiate brittle fracture was to try to supplement the

TABLE 2. SUMMARY OF CYCLIC-LOADED TESTS

Flaw			Nominal Stress, psi		Number of Cycles	Results
Type	Length	Depth	Cycling Range	Maximum		
A	8	9/16	11,000--20,000	20,000	200	Crack opened up
A	8	9/16	11,000--22,000	27,500	50	No failure
A	8	9/16	3,700--20,000	25,700	1000	No failure
C	8	9/16	9,000--20,000	24,000	1000	No failure

pressure stress. In most of the tests made, the supplementary stresses were residual or reaction stresses imposed on the weld containing the flaw by other welds. Fig. 10 shows a test plate which contained residual or reaction stress prior to testing. The two curved welds were used to produce these stresses. They were put in after the test disk was welded into the sphere.

One problem with such test plates was the difficulty of measuring the stresses imposed by the supplementary welding. The temperatures developed by the welding generally put the strain gages used out of commission. Consequently, in most of the tests the magnitude of the residual or reaction stresses was not known. The results of the tests are plotted in Fig. 11. These results show that residual or reaction stresses of varying amounts were produced. These stresses were high enough in three cases to initiate brittle fractures from 8-in. cracks without pressure stresses being added.

FIGURE 10. Test Plate which was designed to contain residual or reaction stresses prior to testing

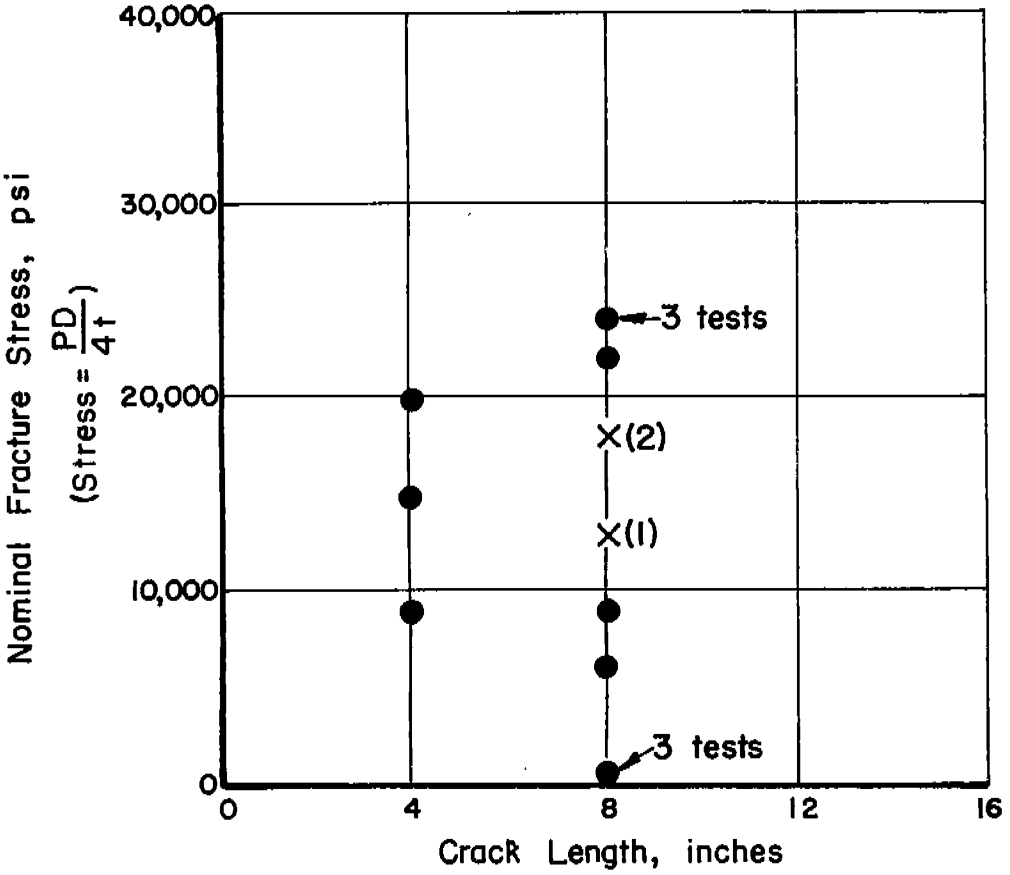

FIGURE 11. COMPARISON OF RESULTS OF TESTS IN WHICH AN ATTEMPT WAS MADE TO INTRODUCE RESIDUAL STRESSES AT THE FLAW. NORMAL STRESSES REQUIRED TO INITIATE BRITTLE FRACTURE WITH 8-INCH CRACK WAS 24,000 PSI, WITH 4-INCH CRACK 30,000 PSI OR HIGHER

(1) Measured residual stress = 13,000 psi

(2) Measured residual stress = 11,000 psi

Influence of Lack of Fusion in Welds on Initiation of Brittle Fracture. In a number of structural failures, lack-of-penetration flaws have been found to be the apparent cause of brittle fracture initiation. In this investigation lack of fusion was substituted for lack of penetration. This was done because the size (length and depth) of a lack-of-fusion flaw could be controlled more easily than could lack of penetration. A sketch showing the method of making a lack-of-fusion flaw is shown in Fig. 12.

The results of tests made with lack-of-fusion flaws are shown in Fig. 13. There does not appear to be a definite relation between nominal brittle fracture stress and length of flaw. This is in contrast to what was found for cracks. There does, however, appear to be a relation between depth of flaw and nominal brittle-fracture stress.

At least there is a definite tendency for brittle fractures to initiate from the deeper flaws at lower nominal stresses than from the shallow flaws. Also there were three tests made with 3/8-in. flaws in which a fracture did not initiate, even though two of these flaws were 12 in. long.

DISCUSSION

It has been pointed out in the past that the evidence obtained from ship failures and other structural failures indicated that in numerous cases failures had started from small weld flaws at low nominal stresses. Stresses of 15,000 psi and lower have been mentioned. The most striking feature of the results obtained during

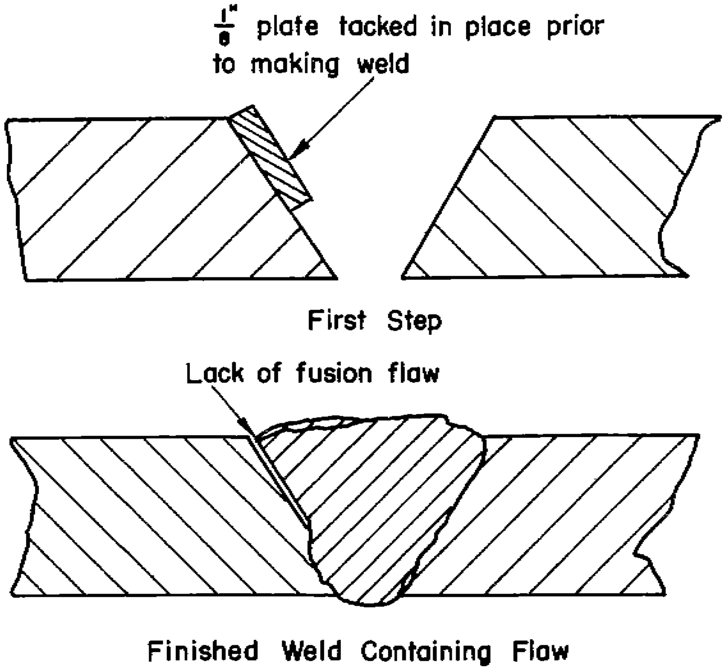

FIGURE 12. METHOD OF MAKING LACK-OF-FUSION FLAW

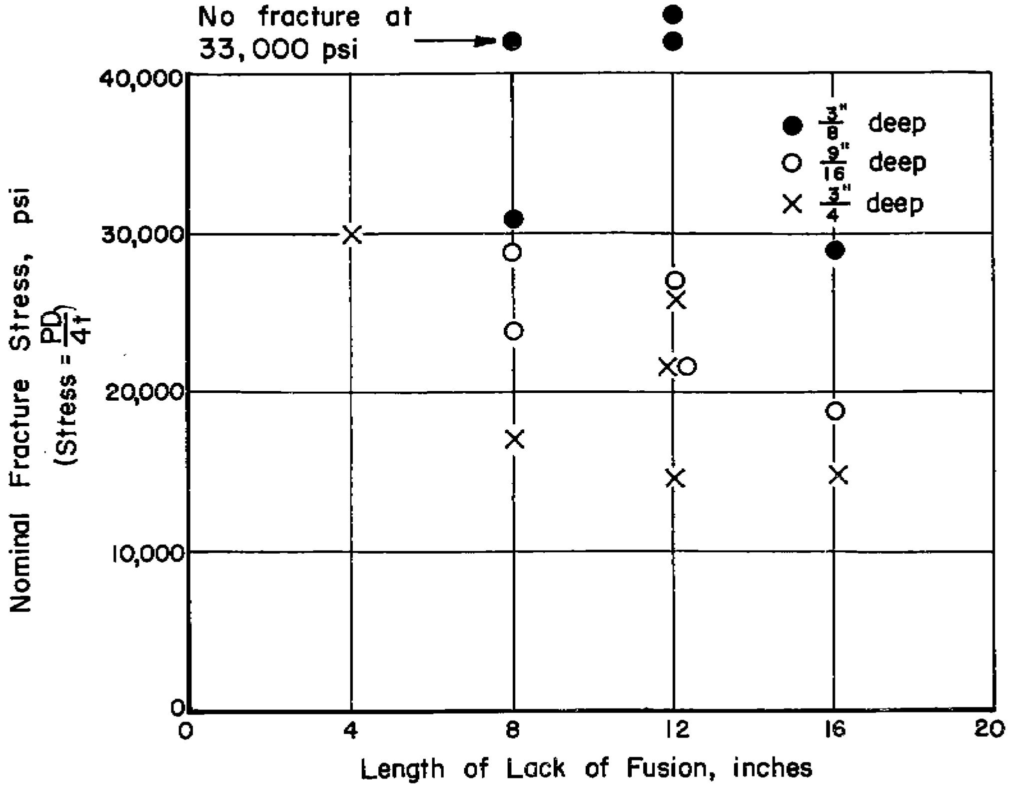

FIGURE 13. RELATION BETWEEN LENGTH OF LACK-OF-FUSION FLAW AND NOMINAL BRITTLE FRACTURE STRESS

the course of this project is that they do not correlate with this previous experience. If it can be assumed that a 4-in. crack qualifies as a small flaw, the data presented in previous sections show that a nominal stress of 30,000 psi or more is required to initiate a brittle fracture from such a flaw. In a number of cases fractures were not initiated at stresses equal to the yield strength of the plate. Even with an 8-in. crack, nominal stresses of 20,000 to 25,000 psi were required to initiate brittle fractures.

That the specimen in the test used is the whole sphere and not just the 24-in. diameter test plate has already been discussed. It is believed that this specimen is large enough to give a valid indication of what would happen in a large structure containing the same type of flaw. In addition, the nominal stresses in the sphere are biaxial tensile stresses. This simulates the stress pattern present in a ship, particularly in the deck. Consequently, the behavior of the sphere should simulate the behavior of a part of a ship deck.

It should be pointed out that the behavior of the test specimen (the sphere) is similar to that of a ship except for the nominal stress required to initiate fracture. When a test plate containing a flawed weld is welded into the sphere, cooled to some temperature below the brittle transition temperature of the test plate, and loaded to some stress below the yield stress of the test plate, a brittle fracture initiates. This fracture initiates at the end or ends of the flaw (crack) where it enters the base plate. It starts in a material having a high transition temperature and runs as a brittle fracture until it reaches material which has a transition temperature below the test temperature. The fracture then either stops or turns into a ductile fracture which stops in a short distance. If the nominal fracture stresses which have been measured for 4-in. cracks were lower, the correlation with ship behavior would be excellent.

Part of the reason for the discrepancy between the measured values of nominal fracture stress and expected fracture stress may be contained in the data shown in Fig. 11. Here are tests in which fracture initiated at a low nominal stress. In fact, here are tests in which a brittle fracture initiated from an 8-in. crack at zero nominal stress. Even a 4-in. crack initiated a brittle fracture at 9000 psi nominal stress. The reason for these results is, of course, the supplementary stresses (residual or reaction) which were imposed by the additional welding done on these test plates. The results of these tests indicate that initiation of brittle fractures in steel structures at low nominal stress (15,000 psi and below) may be due to the presence of residual or reaction stresses in the structure which are not considered in calculating nominal stress levels. It is possible to conceive of such stresses being equal to the yield strength of the steel. Such stresses would not be serious as long as the structure operates under conditions which permitted the steel to behave in a ductile manner.

But conditions might change and become such that the steel would behave in a brittle manner. Then the residual, reaction, or other stresses, combined with the stresses imposed by normal loading could be high enough to initiate brittle fractures from small flaws in the structure.

One test has been made which indicates the effect of a structural discontinuity. The test plate is shown in Fig. 14. A heavy angle with 4-in. legs was welded through the test disk. Full-penetration welds were used on both sides of the angle. One weld was cracked full-thickness while the angle was being welded in. A brittle fracture initiated from this crack at a nominal stress of 20,000 psi. In other tests nominal stresses of 30,000 psi and higher were required to initiate brittle fractures from 4-in. cracks. The results of this test indicate that stress concentration caused by structural details also can cause brittle fractures to initiate at lower nominal stresses than would be expected from the data shown in Fig. 8.

A factor which has not been studied directly in this investigation but which may influence the initiation of brittle fracture in a structure is the sharpness of the end of the flaw. It may be that the sharpness or condition of the end of the cracks causes the scatter shown in Fig. 8. This factor might also influence the behavior of lack-of-fusion or lack-of-penetration flaws. The lack-of-fusion flaws should be less severe than cracks of the same length and depth since they should tend to be less sharp and therefore

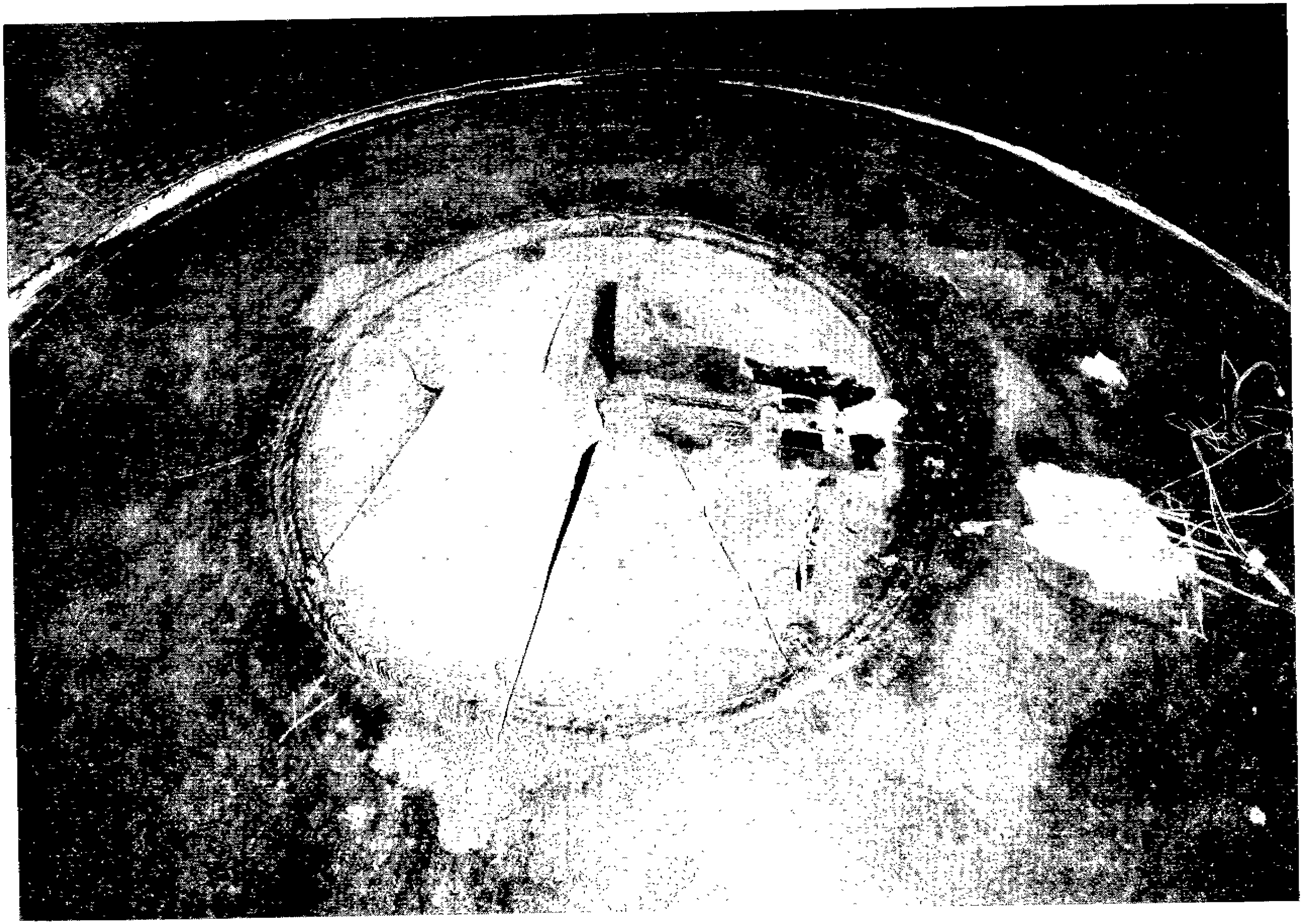

FIGURE 14. Test Plate containing structural detail.
Appearance after test.

less severe. Comparison of Figs. 8 and 13 does not bear this out. In general, some nominal fracture stresses were obtained with lack-of-fusion flaws which were just as low as those obtained for cracks of equivalent length. The important factor for lack-of-fusion flaws appears to be the depth rather than the length of the flaw. There is some relation between flaw length and nominal fracture stress, but increasing depth appears to decrease nominal fracture stress at a relatively faster rate than increasing length.

FUTURE WORK

It was mentioned earlier that no brittle fractures has been produced from crack flaws less than 4 in. long. The reason for this was the decision to stop loading when the nominal stress reached 33,000 psi. However, brittle fractures have initiated from smaller flaws in structures. Therefore, it appears that the next step in the research program is to characterize the conditions required to initiate brittle fractures from flaws smaller than the 4-in. cracks. The work already done with supplementary stresses (residual or reaction) suggests a way to study the influence of small flaws on brittle fracture initiation. Supplementary stresses may be added by welding or by mechanical means. It also may be advisable to investigate the effect of structural details. It will be necessary regardless of the method used to measure the supplementary stresses with a reasonable degree of accuracy.

Lack-of-penetration flaws similar to those found in welded structures also should be investigated. It will be necessary to devise a method of producing this type of flaw with some consistency. The results of such tests can be compared with the results of tests on cracks and lack-of-fusion flaws to determine which are the most serious.

Data are recorded in Battelle Laboratory Record Books No. 7652, pages 1 to 100; No. 8933, pages 7 to 100; No. 9576, pages 1 to 100; No. 10047, pages 1 to 100; and No. 10925, pages 1 to 33.

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APPENDIX A

APPENDIX A

LITERATURE REVIEW OF TEST METHODS AND SPECIMEN USED IN STUDYING BRITTLE FRACTURE

This appendix discusses the laboratory specimen which was chosen in the early part of this investigation and later rejected because it did not meet the specifications as outlined in the section on the Review of Basic Facts Known About Brittle Fracture. The test specimens and testing methods used in various investigations of brittle fracture available in the literature are reviewed briefly in this appendix.

The tension specimen has been used by many investigators in studying various phases of brittle fracture. Tension tests have been conducted at the University of California(1) and the University of Illinois(2) on wide flat-plate specimens with internal notches. Flaw evaluation studies are being made at Swarthmore College(3) with 8-in. wide tension specimens. On the basis of these various studies, a decision was made in the early part of this investigation to use tension specimens.

A beam system was designed to be used as a testing apparatus. Tension specimens 12 in. wide by 3/4 in. thick, containing flaws in welded joints, could be tested with the weld joint at various orientations in relation to the direction of pull. It was thought that the deflection of the beam in the testing apparatus would contribute energy to the propagation of the crack once it was initiated.

However, the reaction time of the beam was too slow to supply energy to a running crack in this size specimen. Investigations(4,5,6) have shown that brittle fractures propagate at about 5000 fps. Theroretically, the fracture can progress with increasing velocity to about 5500 fps. The reason for the accelerated progression of the crack is that as the crack length increases the stress required to keep it growing decreases rapidly. A combination of velocity of the crack propagation, stress-wave velocity in steel, and length of specimens indicated that the specimen would be fractured completely when the stress wave reached the beam. The energy from the deflection of the beam therefore could contribute energy only during the very early phases of the crack or during creep. This system was not developed further for reasons discussed later which indicate the tension specimen did not meet the specifications established on pages 9 and 10.

At this period in the investigation, several members of the Advisory Group suggested that no effort be made to conduct any tests at this time but to review the published material on brittle fracture and discuss the selection of a testing method and specimen with several leading investigators in this field.

A brief review of various test specimens and testing methods covered in the literature survey is presented under the headings: Tension Tests, Bend Tests, Fatigue Tests, Structural Tests of Ships, and Miscellaneous Tests. In most cases the results referred to under these various headings are selected results which are pertinent to this investigation.

TENSION TESTS

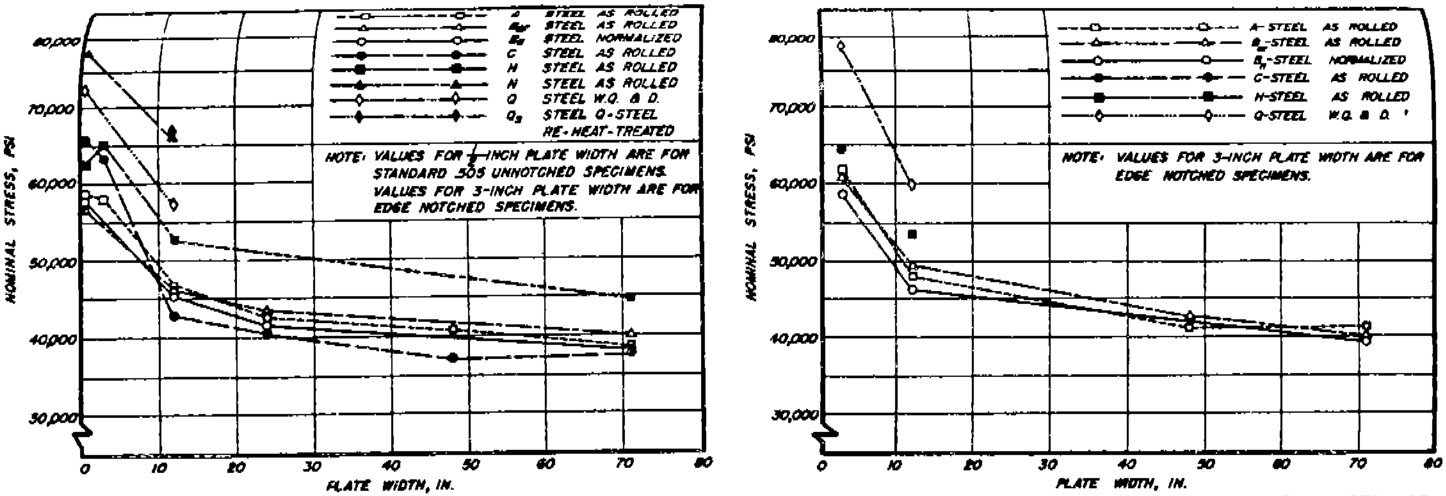
Many investigators studying brittle fractures have used the tension test. Standard tension tests, such as the 0.505-in. diameter specimen with and without a notch, were used in the early attempts to study brittle fracture. An advantage from using this type specimen was that standard equipment could be used in testing, and standards have been well established and generally accepted. However, the results of standard tension tests did not prove adequate because many structures designed to proper specifications failed.

Experience with service failures indicated that "size effect" played an important part in failures. This may be the reason the 0.505-in. diameter specimen did not prove adequate. A correlation between failure and size effect was apparent, since small welded ships seemed to have little trouble with brittle fractures, while larger ones have had a significant incidence of such failures. Small natural-gas lines have not been troubled with brittle fractures, but larger ones have. Brittle fractures were rare in 55,000-barrel oil-storage tanks; but when 100,000-barrel oil-storage tanks were constructed, the incidence of brittle fractures increased alarmingly(7).

Since the small-scale tests had failed to be of much value, a testing program was organized to include large-scale tests along with the small-scale tests. The small-scale tests were designed to attain correlation with the large-scale tests.

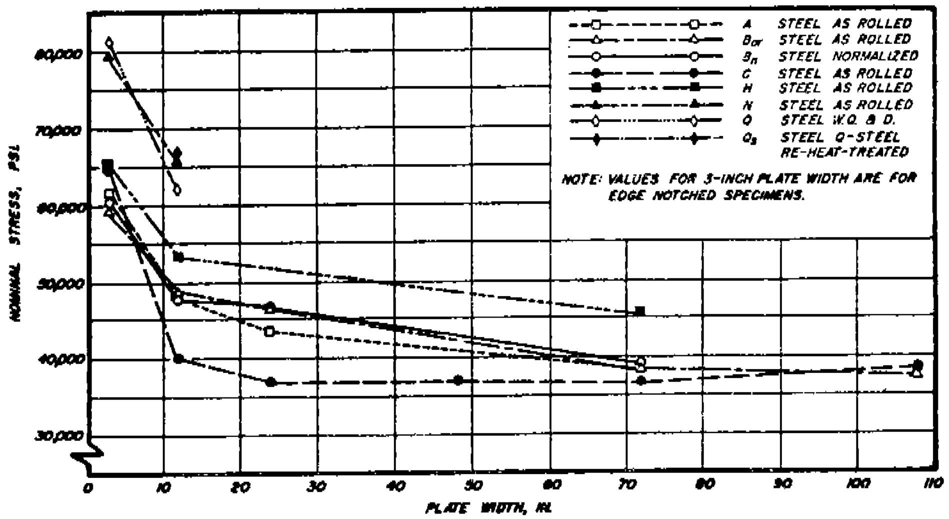
The most notable large-scale laboratory tests were conducted at the University of California(1) and the University of Illinois(2). The exploratory work for these large-scale tests was done at the David Taylor Model Basin(8). This preliminary work was done to become familiar with the specimen and to determine necessary details including notch geometry for establishing the large-scale tests. These results indicated that the jeweler's saw cut was the most severe of the notches studied. Failures were produced in a maximum section at a minimum energy absorption when the ratio of notch length to plate width was equal to 1/4 (L/W = 1/4). The large-scale tests were made with 12-, 24-, 48-, 72-, and 108-in. wide internally notched flat plates. The data obtained from these investigations indicated that the 12-in. wide specimen, on the basis of transition temperature, could rate the steels studied better than could the wider specimens. Fractures obtained were identical in appearance and reduction in thickness to those found in sections of fractured ships. As shown in Fig. A-1, fractures occurred at high nominal strengths and low temperatures. As the width and thickness of the plate increased, the transition temperature increased and its strength decreased. Considerable experience has been gained with additional investigations(9,10,11,12,13) of 12-in. wide flat internally notched plate. The results of these investigations indicate approximately the same as the large-scale tests.

In reviewing the tension test, the small-scale tests were not satisfactory, perhaps because of size effect and also strength.



VARIATION IN NOMINAL STRESS WITH WIDTH OF PLATE — TESTS AT ROOM TEMPERATURE.

VARIATION IN NOMINAL STRESS WITH WIDTH OF PLATE — TESTS AT 50 °F



VARIATION IN NOMINAL STRESS WITH WIDTH OF PLATE-TESTS AT 32°F.

FIGURE A-1. TEST RESULTS OF WIDE FLAT PLATE WITH INTERNAL NOTCH(1)

The small-scale tests rated steels on the basis of strength and ductility, but brittle fracture involves something besides strength. The general conclusion was that these specimens were not large enough.

The large-scale tests made an attempt to simulate the restraint from the edges similar to that on the deck of a ship. However, fractures from the large-scale tests occurred at high nominal stresses and/or temperatures below 0°F. In most cases elongation was much greater than service failures. Except in the very large specimens, there is not sufficient energy available to propagate fracture under conditions which simulate those encountered in service.

The hatch corner tests(14) were developed from the large-scale test because of various results which could not be applied directly to the problem of ship failures. A design similar to hatch corners on Liberty ships was used as a basis for comparing the effectiveness of various modifications(15), as shown in Fig. A-2. The results, as shown in Fig. A-3, indicate that failure still occurred at relatively high nominal strengths but lower than the strength obtained in a large-scale flat plate test. Brittle fracture also occurred at higher temperatures.

One important thing learned in the hatch corner test was that of stress concentrations at structural discontinuities. These stress concentrations are shown in Fig. A-3. Stress-concentration factors have been measured in other tests, such as structural tests

HATCH CORNER TESTS

MAXIMUM NOMINAL STRESS AND ENERGY ABSORPTION

(All tests at 70°F.)

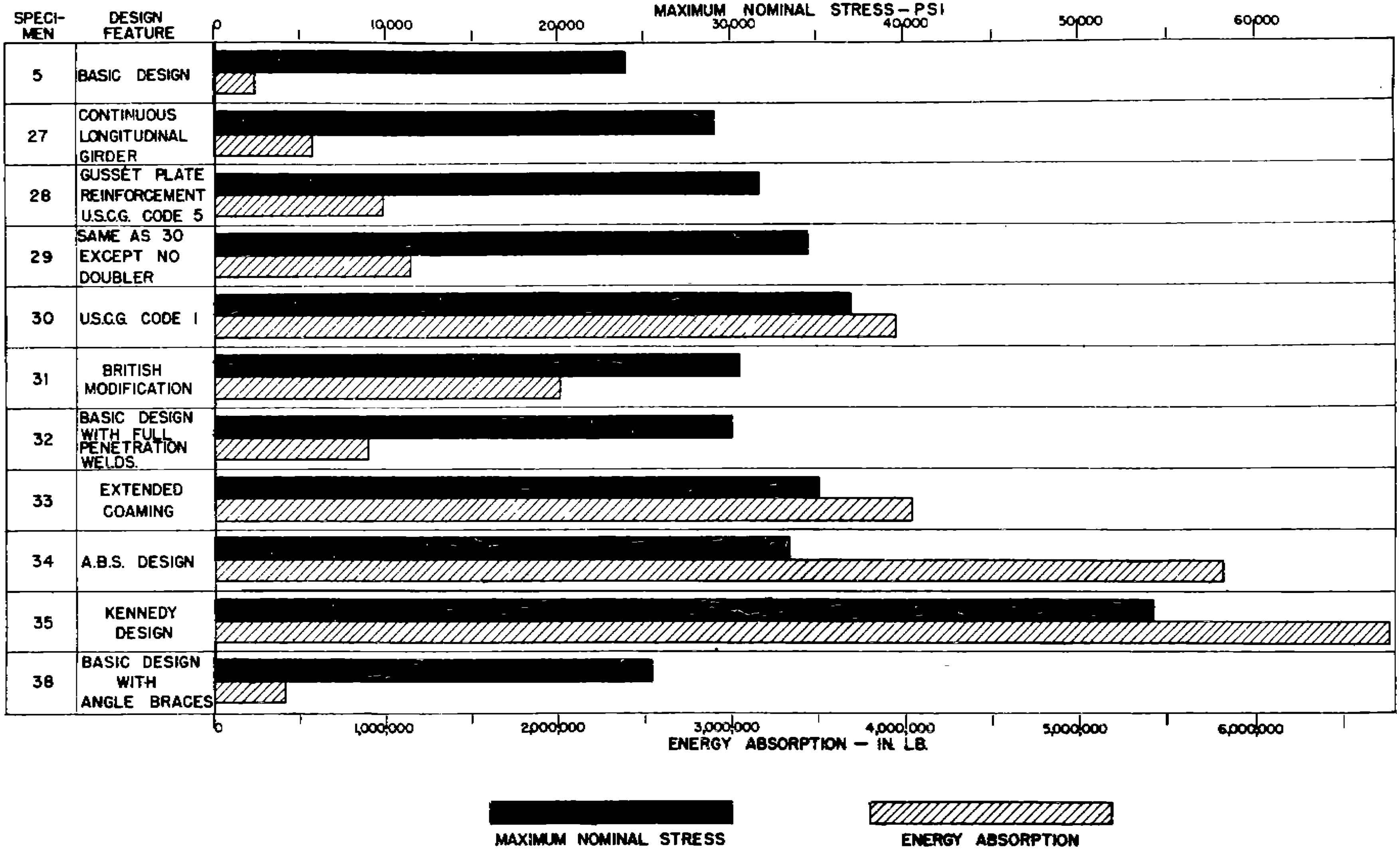


FIGURE A-2. COMPARISON OF VARIOUS DESIGNS OF HATCH CORNERS(14)

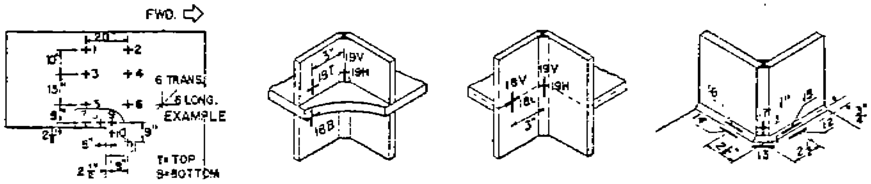
FIGURE A-3. STRESS CONCENTRATION, ELONGATION, AND ENERGY ABSORPTION OF HATCH-CORNER TESTS (12)

SPECIMEN NO.	NOMINAL LOAD AT FAILURE LBS MAXIMUM FAILURE	NOMINAL STRESS AT (1) FAILURE LB/IN² MAXIMUM FAILURE	LONGITUDINAL STRESS CONCENTRATION BASED ON 200,000 LB. LOAD(2) GAGES								
			5	6	7	8	9	10	17	T 18L B	H 19 V
5	1,450,000	24,000	1.6	2.0	1.2	2.1	2.3	1.5	-1.9	2.6	10.4
											3.4
27	1,745,000	28,900	1.7	1.9	1.3	1.6	2.1	1.0	-1.3	2.0	11.7
											2.6
28	2,125,000	31,500	1.3	1.5	1.3	1.5	1.6	1.2	-.3	1.2	2.1
	2,120,000	31,400								1.5	-.7
29	1,950,000	34,400	2.0	2.1	2.9	3.0	2.8	3.1	2.4	2.6	2.9
	1,920,000	33,800								N.G.	2.6
30	2,550,000	36,800	1.3	1.4	2.2	2.2	2.2	1.8	-.3	2.4	2.0
	2,370,000	34,200								2.6	1.1
31	1,920,000	30,400	1.8	1.0	1.7	2.7	2.3	1.5	.1	3.2	6.9
											.8
32	1,815,000	30,000	1.4	1.8	1.5	1.8	1.7	1.2	-1.0	2.8	6.6
	1,755,000	29,000									-.4
33	2,610,000	34,900	.8	1.1	.9	1.1	1.0	.4	—	1.0	2.8
	2,250,000	30,100									-.2
34	2,880,000	33,200	1.1	1.4	1.5	1.3	1.4	1.2	—	—	.2
											-.4
35	3,265,000	54,100	1.4	1.2	1.5	1.4	1.4	1.4	—	—	—
36	1,460,000	23,700									
	1,380,000	22,400									
37	2,470,000	33,600									
38	1,550,000	25,500	1.9	2.1	1.8	3.2	2.6	1.4	-1.5	4.2	5.7
	1,400,000	23,000									0.1
39	2,240,000	37,700									

SPECIMEN NO.	STRAIN CONCENTRATIONS(3) FOR 200,000 LB. LOAD 1,200,000 LB. LOAD GAGES													TOTAL ENERGY ABSORBED PIN TO PIN IN. LB. MAXIMUM FAILURE
	L 5	L 6	L 7	L 8	L 9	T 12 B	13	T 14 B	T 15 B	T 16 B	H 17 V	T 18L B	H 19 V	
5	1.6	2.0	1.3	2.0	2.2	4.5 3.0	3.0	.9 .3	4.7 3.9	3.2 1.5	-2.1 .9	2.8	9.9 .5	230,000
	2.0	2.0	1.1	2.0	2.9	2.0 4.4	1.9	-.5 -.3	2.3 6.5	— 2.5	-4.5 .4	2.1	10.6 -8.2	
27	1.7	1.9	1.4	1.2	2.1	3.9 3.2	3.4	1.4 .7	5.1 4.0	1.7 1.0	-4.6 1.3	2.3	11.4 -.8	552,000
	2.1	2.5	1.3	1.6	2.4	6.1 11.8	9.4	.7 1.6	7.3 12.8	3.5 1.0	-1.3 .5	5.1	10.8 -11	
28	1.3	1.6	1.3	1.5	1.7	1.8 1.9	1.6	-.3 -.3	2.2 1.8	.2 -.2	-.7 1.6	1.4 1.5	2.4 -1.4	868,000
	1.5	2.0	1.4	1.6	1.5	2.1 2.2	3.0	0 -.3	2.5 2.4	.4 .1	-.6 1.7	1.9 1.9	2.6 -1.5	974,000
29	2.0	2.2	2.8	2.7	2.8	3.8 3.2	1.8	.3 -.6	4.0 3.2	1.1 .2	2.5 -.6	2.7 N.G.	2.2 1.8	1,042,000
	2.6	2.4	5.8	4.0	4.8	5.6 10.9	3.6	-1.3 -3.7	4.9 8.1	.3 -1.8	2.1 -.1	5.9 N.G.	.8 —	1,132,000
30	1.3	1.5	2.1	2.0	2.3	2.0 2.2	2.0	-.2 -.5	1.1 2.0	0 -2.5	-.1 -.8	2.2 2.4	1.8 .5	3,316,000
	1.2	1.3	2.6	2.3	1.8	2.2 2.3	3.3	.5 -.3	2.2 2.2	.4 0	0 -.9	1.8 2.4	1.5 .4	3,938,000
31	1.7	1.0	1.7	2.4	2.1	4.2 3.2	2.7	1.7 1.1	4.9 3.9	1.8 2.0	-.7 2.8	3.3	6.6 -1.2	1,990,000
	3.7	.9	1.8	9.6	2.2	13 9.3	0	3.1 4.0	15 11	3.6 .5	.3 .6	6.1	4.7 3.4	
32	1.4	1.8	1.5	1.7	1.7	2.4 3.0	1.1	.5 .7	2.7 3.0	1.4 .9	-1.1 .8	3.0	6.9 -2.4	793,000
	2.2	2.4	1.5	3.9	2.2	6.5 9.5	3.4	.8 3.2	6.6 9.5	5.3 3.7	-1.9 .3	4.6	6.0 -5.0	882,000
33	.9	1.3	1.0	1.1	1.0	1.7 2.4	—	.7 .7	2.1 2.4	.7 .9	— -.3	1.8	4.5 -1.2	3,772,000
	1.4	1.6	1.0	1.3	1.0	3.2 3.1	—	1.3 .9	4.4 3.5	1.4 1.3	— -.4	1.8	2.5 -1.7	4,024,000
34	1.0	1.4	1.4	1.2	1.4	.9 1.7	—	-.2 -.2	1.1 1.3	0 -.1	— -.3	1.4 1.3	.3 -.4	5,800,000
	1.3	1.5	1.6	1.3	1.4	.9 1.6	—	-.2 -.1	.7 1.5	-.1 -.1	— -.3	1.7 1.4	.4 -.5	
35	1.4	1.2	1.5	1.4	1.5	—	—	—	—	—	—	—	—	6,786,000
	2.1	1.6	3.2	1.4	4.5	—	—	—	—	—	—	—	—	
36														146,000
														221,800
37														2,017,000
38	1.9	2.3	2.0	3.1	2.6	6.0 5.0	1.7	.8 .7	7.8 5.4	2.2 .5	-2.0 2.0	3.6	6.0 -1.7	277,000
	2.4	2.3	1.6	4.3	2.8	8.2 11	5.7	-.3 .3	9.5 13	6.2 1.0	-2.4 2.3	6.2	7.1 -2.3	417,600
39														1,570,000

SPECIMEN NO.	STRAIN RATIOS 200,000 LB. LOAD 1,200,000 LB. LOAD GAGES									MAXIMUM STRAIN AT OR NEAR FAILURE MICRO IN/IN GAGES				THICKNESS REDUCTION AT FRACTURE % DISTANCE FROM FRACTURE EDGE IN.						REMARKS
	5	6	7	8	9	10	(4) 11	19H / 19V	17H / 17V	B 12	B 15	T 18L B	H 19							
5	-8.1	-4.2	-2.6	12	-11	4.7	-7.2	21.7	-2.3	3,600	5,000	—	7,000	19	1.9	1.0	.3	0	0	BASIC DESIGN ENERGY VALUE OBTAINED FROM TEMPERATURE-ENERGY CURVE FOR C STEEL.
	-7.4	-7.5	-4.3	10.8	-17.1	—	7.9	-1.3	-3.5					34	2.3	.9	.1	0	0	
27	-6.0	-3.8	-4.0	1.1	-7.2	—	-7.7	-14	-13	14,100	11,600	8,200	11,100	19	1.9	1.2	.8	.5	.3	CONTINUOUS LONGITUDINAL GIRDER, (HATCH END BEAM INTERCOSTAL). CLEAVAGE FAILURE AT CORNER.
	-2.8	-3.3	-3.0	.7	-4.2	-1.3	3.0	-10	-2.8					34	2.1	1.9	1.5	.6	.3	
28	—	-3.1	-6.5	-7.3	-4.7	—	-4.8	-1.7	-.5	5,600	3,600	1,700	2,500	19	1.8	1.4	1.0	.7	.5	GUSSET PLATE REINFORCEMENT. (U.S.C.G. CODE 5)
	-6.8	-5.8	-4.8	-13	-3.9	-2.4	-12	-1.8	-.4					34	.7	.6	.5	.4	.3	
29	-6.8	-3.7	-12	5.8	-4.8	-5.8	-7.0	1.3	-3.8	9,900 at 1,350,000 lb load	11,200 at 1,600,000 lb load	9,300	N.G.	19	1.1	.8	.5	.4	.3	SAME AS 30 EXCEPT NO DOUBLER.
	-17.5	-4.5	-4.9	5.4	-5.5	-2.6	—	N.G.	-2.2					34	1.6	1.1	.7	.4	.3	
30	—	-4.0	—	8.0	-6.0	-3.8	-3.5	3.5	-.1	5,600	3,000	4,800	N.G.	20	1.5	1.2	.9	.7	.5	U.S.C.G. CODE I END TAB FAILURE AT 2,180,000 LBS. ON FIRST LOADING. SPECIMEN RELOADED TO FAILURE NO GAGE READINGS TAKEN ON SECOND LOADING
	-11	-3.1	-2.0	3.5	-8.0	-1.5	-3.2	4.3	0			6,100		34	3.1	1.8	.9	.4	.1	
31	-4.7	-3.2	-3.5	9.7	-17	3.4	-5.2	-5.4	-.2	16,000	17,300	13,100	14,600	19	2.3	1.6	.8	.2	0	BRITISH MODIFICATION.
	-2.7	-1.9	-4.2	3.0	4.9	6	-4.6	1.4	-.4					34	.7	.5	.3	.2	.1	
32	-6.7	-4.5	-3.2	9.3	-4.7	6.0	-8.3	-2.9	-1.4	16,000	16,000	11,500	9,900	19	.9	.7	.8	.4	.3	BASIC DESIGN WITH FULL PENETRATION WELDS.
	-3.7	-7.7	-2.9	4.0	—	-5.1	2.3	-1.6	-6.8					34	2.8	2.5	2.0	1.6	1.2	
33	-5.3	-3.3	-4.5	3.9	5.1	-1.4	-8.0	-2.7	—	16,000	18,000	11,000	16,000	19	.9	.7	.6	.5	.3	EXTENDED COAMING.
	-4.3	-3.7	-3.2	15	4.9	-.8	-6.0	-1.5	—					34	2.8	1.9	1.0	.5	.2	
34	—	-2.9	—	—	-4.3	-4.4	-3.4	-.8	—	11,000	11,000	11,000	5,000	19	.7	.5	.3	.2	.1	A B S. DESIGN.
	-2.4	-3.1	-3.6	-14	-4.5	-3.5	-3.1	-.8	—			11,000		34	2.0	1.1	.6	.3	.1	
35	-7.3	-2.7	-6.5	-3.1	-2.9	-2.3	-2.9	—	—	—	—	—	—	19	1.9	1.1	.5	.3	.2	KENNEDY DESIGN. SPECIMEN LOADED TO 3,000,000 LBS. SPECIMEN RELOADED TO FAILURE. NO GAGE READINGS TAKEN ON SECOND LOADING
	-6.1	-3.9	-5.7	-16	-11	3.9	3.3	—	—					34	1.7	1.1	.7	.4	.3	
36																				BASIC DESIGN WITH ANGLE BRACES. INVALID, LAMINATED PLATE. NO GAGE READINGS TAKEN.
37																				REPEAT OF 33 — INVALID, LAMINATED PLATE. NO GAGE READINGS TAKEN.
38	-6.4	-3.2	-2.5	—	-8.5	4.3	-3.7	-3.6	-1.0	10,000	11,200	5,300	12,900							REPEAT OF 36. HATCH END BEAM OF COMMERCIAL STEEL.
	-3.0	-7.0	-2.6	—	-7.0	-2.4	—	-3.1	-1.0											
39																				U.C. DESIGN NO GAGE READINGS TAKEN.

NOTES
1. BASED ON LOAD CARRYING SECTION OF DECK, DOUBLER, LONGITUDINAL COAMING BELOW DECK. (ACTUAL PLATE THICKNESS)
2. BASED ON AVERAGE OF LONGITUDINAL STRESSES FOR GAGES 1-2-3-4 TOP AND BOTTOM.
3. BASED ON AVERAGE OF LONGITUDINAL STRAINS FOR GAGES 1-2-3-4 TOP AND BOTTOM.
4. READINGS QUESTIONABLE. GAGE 11 VERY CLOSE TO DOUBLER WELD.
5. TEST TEMPERATURE 70° ± 4°F.



of ships(16), and found to be 4.6 at the bulwark plating attachment at the front of the deckhouse. Strain concentrations as high as 9.7 were recorded in another structural test(17).

An investigation has been conducted at the University of Washington(18) to determine the properties of selected types of welded reinforcements for openings in plain-carbon structural steel plates. These results indicate about the same as those previously quoted in which failures occurred at high nominal strength and at a low temperature. Ultimate strengths for tension-type tests are higher at -40 F than at room temperature. The general conclusion from this is that cleavage fractures with high energy absorption and high ultimate strength are possible in welded structures, that is, if all stress-raising effects are sufficiently reduced and that the operating temperature is not too far below the fracture transition temperature for the steel as determined by the Navy tear test(19).

An investigation with tension specimens that simulate certain types of welded details has been performed at Swarthmore(20). The results indicate that structural discontinuities reduce load capacity, energy absorption, and raise transition temperature.

In another investigation at Swarthmore(3), 10-in. wide tension specimens containing transverse butt welds with varying degrees of penetration were used. In tests at 0°F and 75 F, the maximum stress on a net section of specimens with a flaw which simulated incomplete penetration was in most cases equal to, or greater than, the maximum stress sustained by specimens with no welds or those with completely penetrated welds. Recent tests have been made on tension specimens containing an internal flaw, 2 1/2 in. long by 3/8 in. wide, which simulates a crack made with a jeweler's hack saw cut. This flaw was located in the center of a transverse butt weld or at the intersection of a longitudinal butt weld and a transverse butt weld at a length equal to half of the specimen width. The flaw terminated in weld material. The specimen was tested at a low temperature and failed in a cleavage mode with fracture propagating across the unwelded plate as well as across the transverse weld. The average unit stress at fracture was 63,000 psi(21). In all previous tests on transverse butt-welded specimens, the fracture propagated completely in the weld joint. This new specimen was devised to make the fracture propagate in plate material.

Eccentric notch-bar tension specimens(22) have been used to determine zones of low ductility in commercially welded ship plate. Comparisons(23) have been made with the notched (eccentric and concentric) and unnotched tension properties at the midthickness level of a semikilled steel weldment.

Unique-type tension tests which involve impact loading are the Robertson test(24) and the Standard Oil test(25). The work described previously has been conducted with the assumption that the factors involved in the initiation of the brittle fracture are the important consideration. These two tests assume the initiating condition is already present and it is necessary only to consider the factors in propagating the fracture.

The Robertson specimen is subjected to a uniform tensile stress of 10,000 psi, and a temperature gradient is established by means of liquid nitrogen at one end and a gas flame at the other. The usual temperature values for normal mild steel is -94 F at the end which contains the notch and 140 F at the other end. The temperature gradient is about 18 F per in. at the middle. The results show that there is a strength transition which in most of the materials tested occurs at a low stress value of about 10,000 psi. The temperature at which the crack is arrested varies little with increased stress above the transition.

The Standard Oil test is an adaptation of the Robertson specimen. The Standard Oil specimen is shown in Fig. A-4. It contains a notch composed of a brittle crack on one edge and a saw cut of equal depth on the opposite edge. The brittle crack is introduced at liquid nitrogen temperature, as shown in Fig. A-4. The shaded area is cooled by liquid nitrogen. When this area reaches the temperature of liquid nitrogen, a wedge is driven into the saw cut by impact from a small slug shot at high velocity. This produces a sharp crack at the root of the notch. The specimen is allowed to warm up, then placed in a tension machine, and a uniform load is applied, as shown in Fig. A-5. A length of the specimen is cooled to the desired temperature. Another wedge is driven into the saw cut to determine the condition which propagates the crack.

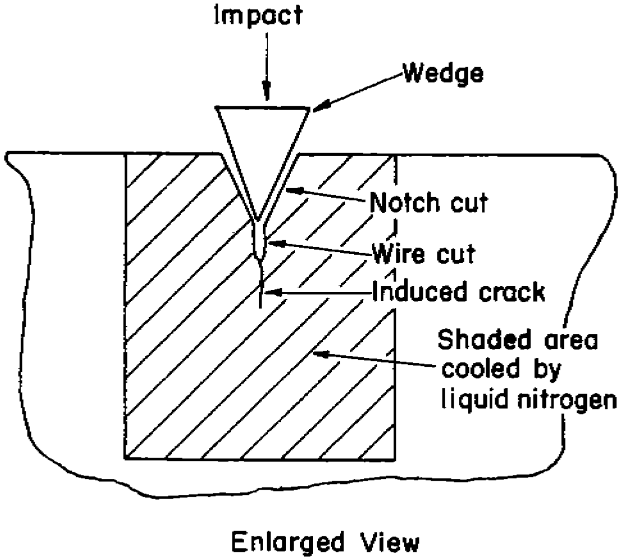


FIGURE A4. TENSION IMPACT SPECIMEN SHOWING METHOD OF INTRODUCING CRACK (25)

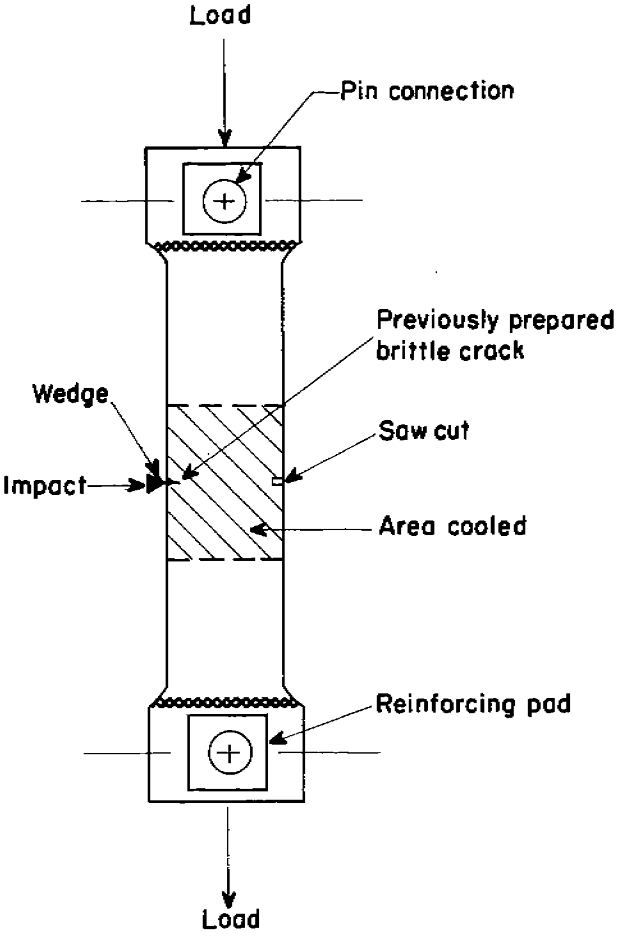


FIGURE A-5. TENSION IMPACT SPECIMEN SHOWING DETAILS OF SPECIMEN DURING TESTING (25)

The results show that if the stress is below a certain critical value the notch is only slightly extended and no failure occurs. If the stress is above this critical value, however, the specimen fails completely with a brittle fracture. Below a certain temperature, the brittle breaking stress is constant, while above this temperature the brittle breaking stress increases markedly. An example of the correlation between the service conditions and laboratory specimens is shown in a test made in steel which was removed from a storage tank. Failure of a tank occurred at a calculated stress of 15,800 psi at 40 F. Some of this material was tested in the laboratory using the procedure just described, and it failed between 12,000 and 14,000 psi applied stress at 40 F.

This is the first tension-type specimen that has been successful in reproducing brittle fracture at a nominal stress below 20,000 psi. The Standard Oil test is being used to study fundamentals of propagation in brittle fractures at various temperatures.

BEND TESTS

Specimens involving bending or a combination of tension and bending have been used more frequently in brittle fracture studies than any other method of testing. Of the smaller specimens in this group the Charpy and Izod are the most notable. Specimens containing a Charpy V-notch, a keyhole-notch, or a saw cut notch, and Navy tear-test, slow-bend, and Schnadt specimens are examples of the smaller specimen. The transition temperature of steels has been determined by these various smaller specimens. The trend in this country is toward increasing use of the V-notch Charpy specimens for evaluating the relative brittleness of steels, for the V-notch, being sharper, yields a higher transition temperature than does the rounded keyhole type. Furthermore, it is believed that the V-notch represents structural discontinuities better than the keyhole. A good correlation has been found between V-notch Charpy properties and service failures of ships(26). Kahn has conducted many investigations with these smaller specimens and on the basis of this experience has developed the Navy tear test(27). The Schnadt(28) specimen is a recent addition to the small-bar group. It is similar to the Charpy, but it has a variable notch geometry and contains a hardened steel pin inserted in a cylindrical hole on the compression side of the specimen. The slow-bend test(29) has given results which correlate with large-scale tests. Vanderbeck and Gensamer(30) have shown that there is a direct correlation between transition temperatures as determined by the V-notch Charpy specimen and the keyhole Charpy. The evidence produced by many investigators shows that regardless of the specimen or criterion selected steels are rated in the same general order of brittleness.

Bagsar(31) developed a cleavage tear test for determining the tensile breaking loads and the conditions under which failure occurs with edge-notched rectangular steel sections.

Some investigators(32,33,34) have employed explosive charges to provide impulse loading to plates and cylinders. Impulse loading creates high strain rates and with triaxial tensile stresses frequently causes brittle behavior. The initial wave travels into the metal as a triaxial compressive stress which is reflected from the opposite surface as a triaxial tension wave(7).

Pellini(35) has correlated the results of explosion tests with the Charpy V-notch curve and also with ship fracture data. He also has correlated the above results with those of a drop-weight test. This test is conducted with the delivery of an energy blow in a device which acts as a stop after the specimen is deformed a very small amount. Tests are conducted over a series of temperatures.

Many investigations(36,37,38,39) have been conducted using longitudinal and transverse notched-bead bend specimens. The notch induces a behavior approaching that which can be expected in the neighborhood of a structural discontinuity such as a weld crack.

The results of investigations referred to above show that cracks originate in weld metal transverse to the weld joints. It has been said that the weld is stronger than the base material. This may be misleading because many specimens which appear ductile in a transverse weld test are brittle when tested with the weld in the longitudinal direction. When the weld is longitudinal, all elements, the weld, the heat-affected zone, and the base plate are forced to undergo equal strains. When the heat-affected zone is martensitic, for example, it will crack at a very low strain, and this crack may cause the specimen to be brittle. When the weld is transverse to the loading direction, the heat-affected zone need not undergo any plastic strain at all. When the elastic limit of the heat-affected zone is above the maximum stress that the weld or base plate can support, all plastic deformation will be forced to occur in the weaker, but more ductile, material. Thus, a specimen with a hard brittle zone may bend through a large angle and appear ductile when the transverse weld specimen is tested but may be brittle when the weld is longitudinal.

Bend tests have been used to great advantage in many investigations, but in this investigation the flaw will be located midway in the thickness direction. This is a region of minimum stress in a bend specimen. The bend specimen therefore was not given further consideration.

FATIGUE TESTS

Fatigue tests have not been used so extensively in the study of brittle fracture as other tests because there is very little evidence of fatigue failures in ships. However, local cyclic stresses have in some cases contributed to brittle fracture. For this reason and because Williams(40) has found the characteristic markings of a fatigue failure in a weld joint from a ship, this test is being reviewed here.

Fatigue tests have been conducted at Cornell University(41) with tension specimens subjected to a nominal stress range of

0 to 30,000 psi. The results indicate that fatigue cracks appear in longitudinal welds at approximately 1/3 the number of cycles when compared with similar tests of homogeneous plate. The surface folds, or pits, in the weld metal create stress raisers which are incipient points of fatigue failure. Poor root fusion did not always result in fatigue failure. Some small fractures have occurred in welds but were arrested before extending into the parent metal. However, in no case has a crack which extends into plate material been arrested.

Fatigue tests have been conducted by Warren(42) with standard fatigue-type specimens. The loading cycle alternated between the nominal stress range of 16,000 psi tension to 16,000 psi compression. Various weld-metal flaws were included in the specimens. The results indicate that it is possible to correlate performance under fatigue loading of a weld joint containing internal flaws with the appearance of its radiograph, when the flaw has the nature of a crack or lack of penetration. It has not been possible to correlate the performance when the flaw has the nature of a slag inclusion. Cracks and lack of penetration were found to be the most serious of the defects tested.

Fatigue tests are being conducted by Welter(43,44) on model vessels under internal hydraulic pressure. The model vessels are simulated semielliptical thick heads butt welded together. The results indicate after a few thousand cycles of repeated loads that the crack is produced in the circumferential weld which progresses and finally breaks through the plate material or the weld deposit in the circumferential direction. The interesting part of this investigation shows that no fatigue cracks occurred in the longitudinal direction of the shell or in numerous undesirable punch marks, scratches, and welding symbols stamped deeply on the outside surface of the vessel.

An investigation(45) was conducted with notched fatigue specimens that fractured in a slow-bend testing machine at controlled strain rates after being subjected to the various number of cycles of fatigue at various stress levels. The results indicate that, as the number of cycles at a given stress level increase, the brittle transition temperature increased to a broad range of temperatures and the brittle fracture strength decreased greatly.

Weck(46) indicates that, when a ship goes to sea and for the first time experiences fairly severe forces at the hatch corners and similar structural discontinuities, the material flows plastically and there is a certain readjustment of the structure and subsequent applications of reversals of load may cause fatigue failure.

Irwin(47) indicates that fracture origins grow or creep until a point of instability is reached, then the crack will accelerate rapidly. He is of the opinion that strain history is the important factor to be considered in brittle fracture. Klier(26) says that the conditions of loading in a ship's structure are not such that a crack can be initiated and propagated slowly to fracture. The loading cycle can be expected to be quite short with a consequent "impact" type of loading due to the action of the wind and waves. With this type loading, the structure may be overloaded for a relatively short time. The conclusion drawn from the opinions of these investigators is that, generally, fatigue does not cause failure but the low-cycle fatigue and peak loading should be considered in conjunction with the test method.

STRUCTURAL TESTS OF SHIPS

Several full-scale strength investigations have been conducted on ships under various conditions of loading. The structural behavior(48) of similar welded and riveted ships under comparable conditions of loading was tested in still water. The Neverita was the welded 12,000-ton D. W. tanker, and the sister ship Newcombia, was a tanker of practically all-riveted construction. Selected results(49) indicate that welded and riveted construction show no major differences. The stress concentrations observed around large structural discontinuities such as hatch openings are approximately the same for the two forms of construction. It may be presumed, however, that higher concentrations may exist at connections. Transverse stresses were observed to be 20 per cent of the longitudinal stresses. There was considerable fluctuation of these stresses with no apparent explanation. It was felt that the results of these trials in still water did not give a complete answer to the problem. A tremendous undertaking was the investigation(50) of a riveted ship, the Clan Alpine, and a welded ship, the Ocean Vulcan, at sea. The analysis(51) of data from still-water tests will afford a comparison of the behavior at sea.

Vasta(17) has found stress-concentration factors varying from 2.0 to 9.7. During hogging, the main deck plating was in a state of biaxial tension which indicates strong transverse restraint by the deck framing system.

These structural tests on ships provide the ideal testing apparatus. The ideal testing method would be to cut out the section of a ship and weld in a test specimen. The specimen could then be subjected to all conditions of service. This type of large-scale test is conceivable but hardly feasible. The next step might be to have a laboratory testing apparatus that would simulate the conditions of a ship and insert the specimens in this apparatus. This line of reasoning is discussed further in the section on the development of a testing method and specimen.

MISCELLANEOUS TESTS

Various tests which do not rightfully belong in any of the above classifications have been reviewed with interest because of their uniqueness.

Hydrostatic and hammer tests have been performed on pressure vessels for many years. A survey(52) was made to determine the effectiveness of these tests and also to what extent these test procedures may damage a vessel. It was indicated that 160,000 pressure vessel tests were reported; 4000 noticeable defects were found by the hydrostatic test, and 30 crack failures occurred under the hammer test. Of the 4000 defective vessels discovered by the hydrostatic test, only 21 cases could be termed as "serious"; the others were mostly "pinhole" leaks. Of the 30 hammer-test failures, only 9 were serious. Cracks at connections in welded joints and in plate were the most frequent defects.

Tests of large tubes(53) have been conducted over wide controlled limits of temperature, while the hoop stresses in the shell could be varied regularly through prescribed values to fracture. The tests were conducted with 20-in. diameter by 10 ft long welded tubes made of 3/4-in. thick ship plate. The results indicated that these large tubes exhibited strengths and ductilities considerably less than the tensile strengths and ductilities of standard coupons made of the plate material. Under certain combinations of conditions, failures were found to occur with very low ductilities, approaching those observed in fractured ships. This was true even without a mechanical notch. The strengths under such conditions were correspondingly low as compared with the strengths of the most ductile specimens. The tubes tested at 70 F, with few exceptions, exhibited considerable ductility prior to fracture. The tubes tested at 40 F, with one exception, exhibited relatively low plastic strains prior to rupture. The tubes, which developed fracture in the region of a weld, appeared to have cracks which originated in the weld or weld zone. Then the fracture propagated into the plate, sometimes extending for relatively long distances and sometimes inducing shattering. The fractures which started in the weld zone were presumably initiated by cracks which formed in the weld metal. This conclusion was indicated also in the section on bend tests, e.g., all fractures began in the weld metal.

An investigation(54) has been conducted with spherical shells This type specimen was chosen because it provides essentially a biaxial state of stress. The yield, ultimate, and fracture strengths for the combined state of stress used in this investigation were shown to increase with decreasing temperature. The combined stress ductility decreased with decreasing temperature. Although the change in ductility was small, the specimens tested at low temperature fractured into a number of pieces.

The advantage to the large-tube and sphere tests is that it more closely resembles the transverse restraint of the main deck of a ship. Vasta(17) has shown that the main deck plating is subjected to biaxial tension which indicates strong transverse strength. The disadvantage to these two tests is that they are extremely expensive to produce, and the specimens are only good for one test. The large-tube tests depend upon an axial load to produce various ratios of stress, but the expense and equipment necessary to do this make it an impractical test.

APPENDIX B

APPENDIX B

PROPERTIES OF T-1 STEEL, FABRICATION DETAILS, AND OTHER PERTINENT DATA ON THE SPHERE

PHYSICAL PROPERTIES OF THE STEEL

A high yield strength alloy steel was used in the fabrication of the sphere. This steel is a recent development of the United States Steel Corporation and is known as T-1 steel. The chemical and mechanical properties are shown in Table B-1.

TABLE B-1. PROPERTIES OF T-1 STEEL

Chemical Composition, per cent		Mechanical Properties
Carbon	- 0.15	Thickness, 3/4 in.
Manganese	- 0.80	Yield strength, 114,400 psi
Phosphorus	- 0.012	Ultimate tensile strength, 121,600 psi
Silicon	- 0.19	Elongation in 2 in., 20%
Sulfur	- 0.016	Reduction of area, 60%
Copper	- 0.34	15 ft-lb Charpy keyhole transition temperature, 235 F
Nickel	- 0.84	
Molybdenum	- 0.44	
Chromium	- 0.39	
Vanadium	- 0.05	
Boron	- 0.0018	

Notch-bend tests have been made on welded and unwelded plate to determine the effect of welding on the notch toughness of the steel. The results of these tests are shown in Table B-2.

TABLE B-2. SUMMARY OF DUCTILITY AND FRACTURE TRANSITION TEMPERATURES FOR 1/2- AND 1-IN. QUENCHED AND TEMPERED T-1 STEEL*

Plate Thickness, in.	Kinzel-Type Notch-Bend Test			Tee-Bend Test	
	Unwelded	E12015	E6010	E12015	E6010
	Ductility Transition Temperature, F				
1/2	-132±26	-78±4	-84±4	Approx. -180	-128±28
1	Below -143	-72±8	-78±16	Approx. -144	-124±10
	Fracture Transition Temperature, F (50% Shear)				
1/2	-102±6	-84±6	-92±10	Approx. -62	-100±26
1	-76±8	-44±8	-64±12	-40±6	-72±8

*Bibber, L. C., Hodge, J. M., Altman, R. C., and Doty, W. C., "A New High Yield Strength Alloy for Welded Structures", Paper No. 51-PET-5, The American Society of Mechanical Engineers.

This steel is readily weldable with the low-hydrogen type electrodes. Table B-3 shows the effect of manual metal-arc welding on the properties and characteristics of this steel.

TABLE B-3. TENSILE PROPERTIES OF ARC-WELDED T-1 STEEL*

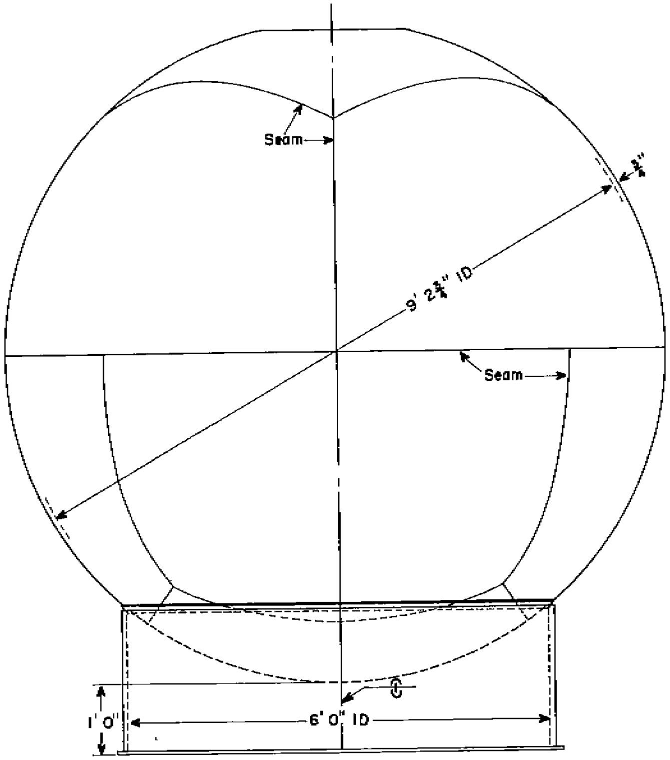
Plate Thickness, in.	Condition	Orientation of Specimen	Yield Strength, psi	Tensile Strength, psi	Elongation, % 2 in.	Elongation, % 8 in.	Reduction in Area, %
1/2	Quenched and tempered	Long.	112,300	119,800	31.3	13.1	56.1
1	Quenched and tempered	Long.	118,000	125,000	39.7	14.8	59.6

*Bibber, L. C., Hodge, J. M., Altman, R. C., and Doty, W. C., "A New High Yield Strength Alloy for Welded Structures", Paper No. 51-PET-5, The American Society of Mechanical Engineers.

FABRICATION DETAILS

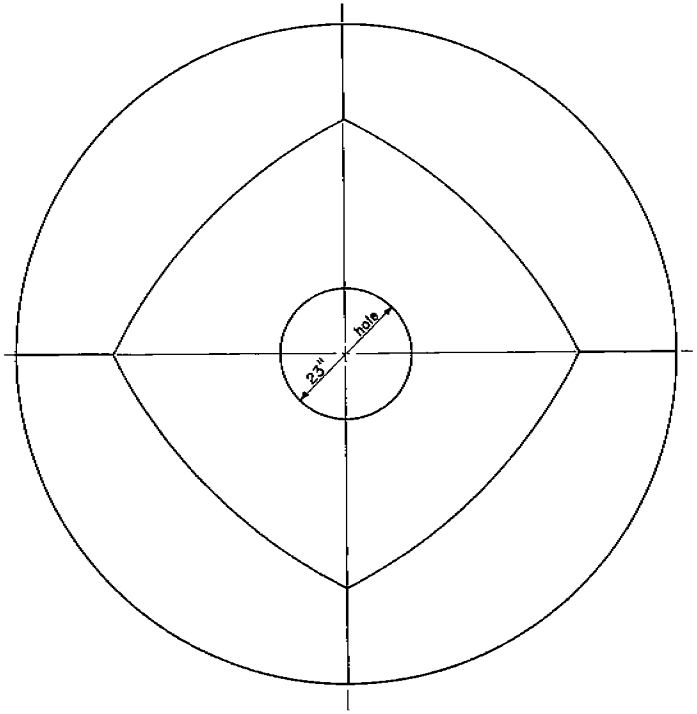
The sphere was fabricated by Chicago Bridge and Iron Company in strict accordance with the ASME Code (1952 Edition). Five plates were welded together with E12015 electrode to form a hemisphere, and the two hemispheres were welded together to make the sphere. The sphere, showing the shape of individual pieces, is shown in Fig. B-1.

All joints in the sphere were ground smooth and radiographed. Two connections were welded into the top hole for hydrostatic testing. A hydrostatic pressure test was made at 1300 psi pressure which is equivalent to a nominal biaxial tension stress of 47,620 psi. A hammer test was made at 1100 psi pressure. The connection was cut out and the sphere was delivered to Battelle with one opening. The opening is 23 in. in diameter, as shown in Fig. B-2.



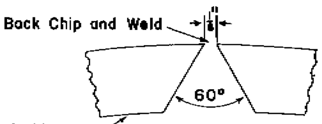
Elevation

FIGURE B-1. DETAILS OF SPHERE AND STAND

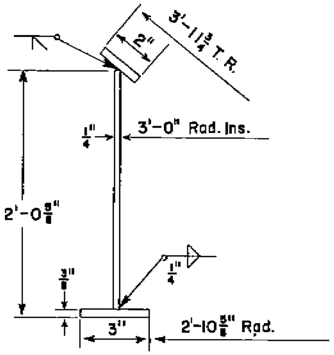


Plan

FIGURE B-2. DETAILS OF SPHERE



TYPICAL SEAM IN SPHERE



SECTION THRU STAND

FIGURE B-3. DETAILS OF SPHERE AND STAND

CAPACITY OF SPHERE

The formula for calculating the volume of the sphere found in Table B-4 is:

$$V = 4/3 \pi r^3$$

where V = volume

r = inside radius

TABLE B-4. VOLUME OF SPHERE

Diameter, in.	Volume	
	cu in.	gal
110 3/4	711,500	3080

NOMINAL STRESS IN A SPHERE

The unit stress in the walls of a thin-walled sphere subjected to internal pressure is:

$$S_1 = S_2 = \frac{PD}{4t}$$

where S_1, S_2 = unit stress

P = internal pressure

D = inside diameter

t = thickness of wall

The unit stress for various pressures calculated from the above formula is shown in Table B-5.

CHANGE IN VOLUME DUE TO INTERNAL PRESSURE

Derivation of volume change due to internal pressure:

Symbols--

V = volume
C = circumference
r = radius
ϵ = strain
σ = stress
ν = Poisson's ratio
E = modulus of elasticity
P = internal pressure
D = outside diameter
t = wall thickness
ΔV = change in volume

Subscripts--

o = initial (zero pressure)
c = with internal pressure

$$\Delta V = V_c - V_o$$

$$V_o = 4/3 \pi r_o^3$$

$$V_c = 4/3 \pi r_c^3$$

Since: $\sigma_1 = \sigma_2 = \frac{PD}{4t}$

and $\epsilon = \frac{1}{E}(\sigma_1 - \nu\sigma_2)$

$$\epsilon = \frac{\sigma}{E}(1 - 0.285)$$

$$\epsilon = \frac{0.715 \, PD}{4 \, Et} = \frac{0.179 \, PD}{Et}$$

$$C_c = 2\pi r_c$$

$$C_c = C_o \; (1 + \epsilon)$$

$$C_c = C_o \; (1 + \frac{0.179 \; PD}{Et})$$

$$r_c = \frac{C_c}{2\pi}$$

$$r_c = \frac{C_o}{2\pi}\left[1 + \frac{0.179 \; PD}{Et}\right]$$

$$r_c{}^3 = \frac{C_o{}^3}{8\pi^3}\left[1 + 3 \; (\frac{0.179 \; PD}{Et}) + (\frac{0.179 \; PD}{Et})^2 + (\frac{0.179 \; PD}{Et})^3\right]$$

$$r_c{}^3 = \frac{8\pi^3 r_o{}^3}{8\pi^3}\left[1 + \frac{0.537 \; PD}{Et}\right]$$

$$V = 4/3\pi \; (r_c{}^3 - r_o{}^3)$$

$$V = r_o{}^3 \; (1 + \frac{0.537 \; PD}{Et}) - r_o{}^3$$

$$V = \frac{0.537 \; PD \; r_o{}^3}{Et}$$

Table B-5 shows the change in volume at various interval pressures based upon the above formula.

CHANGE IN VOLUME DUE TO COMPRESSIBILITY OF LIQUID

Since compressibility is the reciprocal of the bulk modulus

$$K = \frac{\dfrac{V_1 - V_2}{V_1}}{P_2 - P_1} = \frac{\Delta V}{V_1 \Delta P}$$

$$\Delta V = KV_1\Delta P$$

and $K = 52 \times 10^{-6}$ contraction in unit volume per atmosphere

$$K = \frac{52 \times 10^{-6}}{14.7}$$ contraction in unit volume per psi

$$K = 3.5 \times 10^{-6}$$

$$\Delta V = 3.5 \times 10^{-6}\ V_1\Delta P$$

$$\Delta V = 3.5 \times 10^{-6}\ \frac{4\pi r^3}{3}\Delta P$$

$$\Delta V = 3.5 \times 0.811 \times \Delta P$$

$$\Delta V = 2.49\ \Delta P$$

The compressibility of water with various internal pressures is shown in Table B-5 calculated from the formula above.

TABLE B-5. STRESS AND VOLUME INCREASE DUE TO PRESSURE

Pressure, psi	Nominal Stress, psi	Liquid Volume Increase Compressibility		Sphere Volume Increase Internal Pressure		Total Increase, gal
		cu in.	gal	cu in.	gal	
100	3,670	249	1.1	45	0.2	1.3
200	7,330	498	2.2	91	0.4	2.6
300	11,000	747	3.2	136	0.6	3.8
400	14,670	996	4.3	182	0.8	5.1
500	18,330	1,250	5.4	227	1.0	6.4
600	22,000	1,490	6.5	273	1.2	7.7
700	25,670	1,740	7.6	318	1.4	9.0
800	29,330	1,990	8.6	364	1.6	10.2
900	33,000	2,440	9.7	409	1.8	11.5
1,000	36,670	2,490	10.8	455	2.0	12.8
1,100	40,330	2,740	11.9	500	2.2	14.1
1,200	44,000	2,990	12.9	546	2.4	15.3
1,300	47,670	3,240	14.0	591	2.6	16.6
1,400	51,330	3,490	15.1	636	2.8	17.9
1,500	55,000	3,740	16.2	681	3.0	19.2

POTENTIAL ENERGY IN SPHERE AT VARIOUS PRESSURES

The potential energy was calculated from the following formulas:

Potential energy in water $= \frac{P^2V}{2K}$

Potential energy in sphere wall $= \frac{(1 - \nu)\, S^2V}{E}$

where E = modulus of elasticity, psi
P = gage pressure, psi
S = stress, psi
V = volume, cu in.
ν = Poisson's ratio
K = bulk modulus

The potential energy at various internal pressures, calculated from the above formulas, is shown in Table B-6.

COMPOSITION OF LIQUID

$CaCl_2$ was added to the water to reduce the freezing point of the liquid to -15 F. The composition of water and calcium chloride is shown in Table B-7. The solution was inhibited with sodium dichromate and sodium hydroxide.

TABLE B-6. POTENTIAL ENERGY AT VARIOUS PRESSURES

Pressure, psi	Nominal Stress, psi	Energy, in.-lb		
		Water	Sphere	Total
100	3,667	11,550	8,960	20,510
200	7,333	46,200	35,800	82,000
300	11,000	103,950	80,600	184,550
400	14,667	184,800	143,200	328,000
500	18,333	288,750	224,000	512,750
600	22,000	415,800	322,000	737,800
700	25,667	564,000	439,000	1,003,000
800	29,333	736,000	573,000	1,309,000
900	33,000	932,000	726,000	1,658,000
1,000	36,667	1,155,000	896,000	2,051,000
1,100	40,333	1,265,000	1,082,000	2,347,000
1,200	44,000	1,380,000	1,290,000	2,670,000
1,300	47,667	1,496,000	1,508,000	3,004,000
1,400	51,333	1,610,000	1,760,000	3,370,000
1,500	55,000	1,725,000	2,015,000	3,740,000

TABLE B-7. COMPOSITION BY WEIGHT OF LIQUID IN SPHERE

Volume of Sphere		Water, lb	Calcium Chloride, lb	Sodium Dichromate, lb	Sodium Hydroxide, lb
cu ft	gal				
412	3,080	25,700	9,476	50	5

APPENDIX C

TABLE C-1. RESULTS OF TESTS MADE TO INVESTIGATE THE INFLUENCE OF CRACKS AND LACK-OF-FUSION FLAWS IN WELDS OF THE INITIATION ON BRITTLE FRACTURE

Test No.	Type of Flaw	Length of Flaw, in.	Depth of Flaw, in.	Material	Temp. F	Nominal Stress, psi	Type of Failure	Type of Loading	Type Backup Used on Test Plate	Remarks
1	Hard facing	--	--	1/4-in. A283C	-25	51,000	See results	Static	Neoprene	Entire disk blown out and around hole in sphere.
2	A	8	9/16	E	-25	23,800	Brittle	"	"	Frac. stopped at joining weld. Frac. initiated in weld flaw
3	B	5	1/2	E	26	27,500	None	"	None	Crack opened up in weld, which released pressure.
4	D	5	3/8	E	26	38,500	"	"	"	No failure, released pressure.
5	B	5	9/16	E	30	36,670	4-inch cleavage fracture	"	"	Fracture initiated from repaired flaw in Test 4. Fracture stopped in E steel.
6	B	6	1/2	E	20	36,670	Brittle	"	"	Fracture initiated in weld flaw, propagated across diameter of disk and 10 in. into sphere.
7	A	6	1/2	E	22	29,330	"	"	"	Brittle fracture across diameter of disk. Disk blown completely out of sphere.
8	A	1	9/16	E	30	29,330	None	"	"	No failure, released pressure.
9	A	1	9/16	E	27	31,200	"	"	"	Two 3 x 3 x 1/4 angles welded to Test 8. No failure, released pressure.
10	A	5	9/16	E	12	33,000	Brittle	"	"	One half of disk was blown completely out of sphere. The other was blown 1/2 out and hinged up.
11	A	5	9/16	E	27	34,800	None	"	"	Crack opened up, lost pressure.
12	C	5	7/16	E	29	33,000	"	"	"	No failure, released pressure.
13	C	5	7/16	E	18	31,200	"	"	"	No failure, released pressure.
14	C	4	7/16	E	22	31,200	"	"	Neoprene	Poor joining weld. Forced disk out of sphere, but no failure at flaw.
15	C	10	7/16	E	18	31,200	Brittle	"	"	Fracture initiated after grinding down 1/8 into weld. Propagated 4 in. into sphere.
16	C	10	7/16	E	16	31,200	None	"	"	No failure. This disk was similar to Test 16 except the weld went across the diameter of the disk.
17	C	10+10	7/16	E	66	31,200	"	"	None	Crack opened up in weld, lost pressure.
18	A	8	9/16	E	20	22,000	"	"	"	Ditto
19	C	10+4	7/16	E	23	27,500	"	"	Neoprene	Ditto
20	C	6+6	7/16	E	-6	31,200	"	"	"	No failure, released pressure.
21	C	6+6	9/16	E	4	24,800	"	"	None	Crack opened up in weld, lost pressure.
22	A	8	9/16	Annealed ABS-B	15	25,700	Brittle	"	Neoprene	The disk blew out of sphere. Propagated 3 1/4 in. into sphere on one side.
23	A	8	9/16	"	8	25,670	None	Cycled	"	Crack opened up in weld, lost pressure; cycled 200 times between 11,000--20,000 psi.
24	A	8	9/16	"	17	23,500	Brittle	Static	"	Half of disk blown out.
25	A	8	9/16	"	16	27,500	None	Cycled	"	No failure, cycled 50 times between 11,000--22,000 psi
26	A	8	9/16	"	24	23,450	Brittle	Static	"	Propagated across diameter of disk, stopped at joining weld.
27	A	8	9/16	"	18	25,700	"	"	"	Four paths of fracture across diameter of disk.
28	A	8	9/16	"	15	22,000	"	Residual stress Magnitude unknown	"	Propagated across diameter of disk, 3 in. and 2 in. into sphere.
29	A	8	9/16	"	15	23,800	None	"	"	Crack opened up, lost pressure.

TABLE C-1 (Continued)

Test No.	Type of Flaw	Length of Flaw, in.	Depth of Flaw, in.	Material	Temp. F	Nominal Stress, psi	Type of Failure	Type of Loading	Type of Backup Used on Test Plate	Remarks
30	A	8	9/16	Annealed ABS-B	20	11,000	Brittle	Residual stress 13,000 psi	Neoprene	Propagated across diameter of disk, stopped at joining weld.
31	A	8	9/16	ABS-B	30	28,200	None	Static	"	Crack opened up, lost pressure.
32	A	8	9/16	Annealed ABS-B	34	18,350	Brittle	Residual stress 10,942 psi	"	Propagated across diameter of disk, stopped at joining weld.
33	A	8	9/16	"	21	9,530	"	Residual stress Magnitude unknown	"	Ditto
34	A	8	9/16	"	17	25,700	None	Cycled	Neoprene	Cycled 1000 times between 3,700--20,000 psi. No failure when raised to 25,700 psi.
35	C	8	9/16	"	23	24,000	"	"	"	Cycled 1000 times between 9,000--20,000 psi. No failure when raised to 24,000 psi.
36	A	8	9/16	"	15	23,850	Brittle	Static	"	Propagated across diameter of disk, 3 in. into sphere on each side.
37	A	8	9/16	"	8	23,850	None	"	"	No failure released pressure.
38	C	8	3/8	"	23	0	Brittle	Residual stress Magnitude unknown		Propagated 13 in. due to residual stress only.
39	C	8	3/8	"	25	0	--	"	"	Propagated 5 in. due to residual stress only.
40	C	8	3/8	"	23	23,650	Brittle	"	None	Propagated across diameter of disk, stopped at joining weld.
41	A	8	9/16	"	27	22,000	"	Static	Neoprene	Ditto
42	C	8	1/2	"	29	0	"	Residual stress Magnitude unknown	None	Brittle fracture 17 in. long due to residual stress only.
43	C	8	1/2	"	4	5,870	"	"	"	Weld necked prior to static load. Fracture propagated across diameter of disk.
44	C	8	1/2	"	26	23,850	None	"	"	No failure, released pressure.
45	A	16	9/16	"	25	17,400	Brittle	Static	"	Propagated across diameter of disk, stopped at joining weld.
46	C	16	9/16	"	21	33,000	None	"	"	No failure released pressure.
47	A	4	9/16	"	20	16,500	None	"	"	Crack opened up, lost pressure.
47(a)	A	4	9/16	"	20	9,170	Brittle	Residual stress Magnitude unknown	"	Propagated across diameter of disk, stopped at joining weld.
48	A	4	9/16	"	10	12,170	"	Static	"	Ditto
49	D	8	3/4	"	18	Magnitude unknown	"	"	Lead-Neoprene	"
50	C	4	9/16	"	22	18,000	"	"	None	A bang was heard at approx. 8,000 psi. This probably was the crack opening to the surface.
51	A	4	9/16	"	20	29,300	"	"	"	Propagated across diameter of disk, stopped at joining weld.
52	A	8	3/4	"	12	18,300	"	"	14-gage plate	Propagated across diameter of disk and into sphere.
53	A	8	3/4	"	13	21,600	"	"	"	Propagated across diameter of disk, stopped at joining weld.
54	D	8	3/4	ABS-B	8	20,000	"	"	"	Ditto

TABLE C-1 (Continued)

Test No.	Type of Flaw	Length of Flaw, in.	Depth of Flaw, in.	Material	Temp. F	Nominal Stress, psi	Type of Failure	Type of Loading	Type of Backup Used on Test Plate	Remarks
55	D	4	3/4	ABS-B	9	27,500	Brittle	Static	14-gage plate	Half of disk blow out, fracture propagated 2 in. into sphere in two places.
56	D	16	9/16	"	6	10,300	"	"	"	Propagated across diameter of disk, stopped at joining weld.
57	D	8	9/16	"	6	23,850	"	"	"	Ditto
58	D	12	9/16	"	7	21,100	"	"	"	"
										Crack opened to surface at a nominal stress of 18,300 psi.
59	D	12	3/4	"	9	12,800	"	"	"	Propagated across diameter of disk, stopped at joining weld.
60	D	16	3/4	"	10	11,000	"	"	"	Ditto
61	D	12	3/8	"	6	17,400	"	"	"	"
62	D	16	3/8	"	9	22,000	None	"	"	Only taken to 22,000. No failure.
63	D	8	3/8	"	6	25,700	Brittle	"	"	Propagated 8 1/8 in. into sphere on one side and 9 in. on other side.
64	D	16	3/8	"	7	15,200	"	"	"	Propagated across diameter, stopped at joining weld.
65	D	4	3/4	"	10	27,500	"	"	"	Ditto
66	D	4	9/16	"	9	33,000	"	"	"	Propagated 10 in. into sphere on one side and 16 in. on other side.
67	D	12	9/16	"	12	22,000	None	"	"	Only taken to 22,000. No failure.
68	E	8	3/4	"	12	26,300	Brittle	"	"	Propagated across diameter of disk, stopped at joining weld.
69	D	4	3/8	"	12	33,000	None	"	"	No failure.
70	D	8	9/16	"	10	24,600	Brittle	"	"	Propagated across diameter of disk, stopped at joining weld.
71	D	10	3/4	"	8	17,200	"	"	"	Ditto
72	E	8	3/8	"	11	31,200	"	"	"	Propagated 3 in. into sphere on both sides.
73	D	8	3/4	"	11	31,200	None	"	"	No failure. Crack front in weld metal.
74	D	8	3/8							
	E	8	3/8	"	8	16,500	Brittle	"	"	Propagated across diameter of disk, stopped at joining weld.
75	E	12	3/4	"	12	22,000	"	"	"	Ditto
76	E	12	9/16	"	8	22,000	"	"	"	"
77	E	12	3/8	"	11	33,000	None	"	"	No failure.
78	E	16	3/4	"	11	15,400	Brittle	"	"	Propagated across diameter of disk, stopped at joining weld.
79	E	8	9/16	"	12	24,000	"	"	"	Ditto
80	E	16	9/16	"	6	19,000	"	"	"	"
81	E	16	3/8	"	7	29,400	"	"	"	"
82	E	8	3/8	"	8	33,000	None	"	"	No failure, released pressure.
83	E	4	3/4	"	8	30,400	Brittle	"	"	Propagated across diameter of disk, 2 in. into sphere, both sides.
84	E	8	3/4	"	9	16,500	"	"	"	Propagated across diameter of disk, stopped at joining weld.
85	E	12	9/16	"	9	26,800	"	"	"	Propagated across diameter of disk, 2 in. into sphere, both sides.
86	E	12	3/4	"	7	14,500	"	"	"	Propagated across diameter of disk.

TABLE C-1 (Continued)

Test No.	Type of Flaw	Length of Flaw, in.	Depth of Flaw, in.	Material	Temp. F	Nominal Stress, psi	Type of Failure	Type of Loading	Type of Backup Used on Test Plate	Remarks
87	E	12	3/8	ABS-B	9	33,000	None	Static	14-gage plate	No failure, released pressure.
88	E	8	9/16	"	7	29,400	Brittle	"	"	Propagated across diameter of disk, 3 in. into sphere, both sides.
89	D	12	3/4	"	7	33,000	None	"	"	Crack front in weld metal, crack extended but no brittle fracture.
90	D	12	3/4	"	9	29,400	Cleavage	"	"	Crack front in weld metal, crack extended into weld metal, crack propagated along heat-affected zone.
91	D	16	3/4	"	7	33,000	"	"	"	Crack front in weld metal, crack extended into weld metal, both ends.
92	D	16	3/4	"	8	33,000	"	"	"	Ditto
93	D	12	3/4	"	32	20,200	"	"	"	Propagated across diameter of disk from one end of crack only. Some necking.
94	D	12	3/4	"	60	29,000	"	"	"	Crack propagated 3 in. on one and 1 in. on other, considerable necking.
95	Stress concentration	4	3/4	"	9	20,200	Brittle	"	"	Propagated across diameter of disk. Six paths of fracture
96	Circular patch	4	3/4	"	12	15,000	"	"	"	Propagated across diameter of circular patch.

APPENDIX D

APPENDIX D

REPAIR OF SPHERE

The fracture of Test 6, as shown in Fig. D-1, propagated 10 in. into the sphere on each side of the disk.

The disk and sphere were cut along the dotted line shown in Fig. D-1. The sphere was cut out on one side to remove the end of the crack. The other side was beveled to form a single-V butt joint.

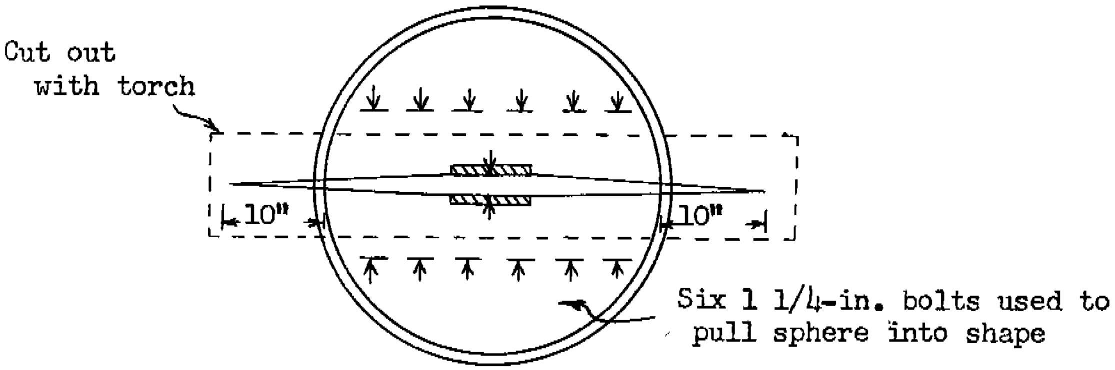


FIGURE D-1. DIAGRAM SHOWING DETAIL OF REPAIR

Six 1-in. steel pads were welded on each side of the disk, as shown in Fig. D-2. Six 1 1/4-in. bolts were placed through the hole in the pad. The bolts were tightened and this brought the sphere back into shape.

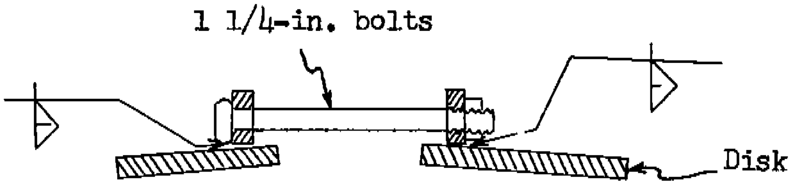


FIGURE D-2. CROSS SECTION OF DISK SHOWING BOLT USED TO PULL SPHERE BACK INTO SHAPE

The grooves were ground smooth and then welded with E10016 electrodes. The repaired section of the sphere is shown in Fig. D-3.

A considerable number of fractures have occurred similar to the one just described except they have not been so extensive. Therefore, after about 60 tests, the area of the sphere around the test hole had become a mass of repaired sections.

The fracture of Test 66, as shown in Fig. D-4, propagated 15 1/2 in. into the sphere on one side of the disk and 12 in. on the other. The fracture turned at the E10016 joining weld to follow an old repair weld in the sphere part of the way down and then stopped after propagating about 5 in. in unrepaired T-1.

The sphere was then repaired by cutting out a 45-in. diameter ring containing the test-plate hole and welding in a new T-1 ring. United States Steel Company furnished the steel, and Chicago Bridge and Iron Company formed the rings at no charge.

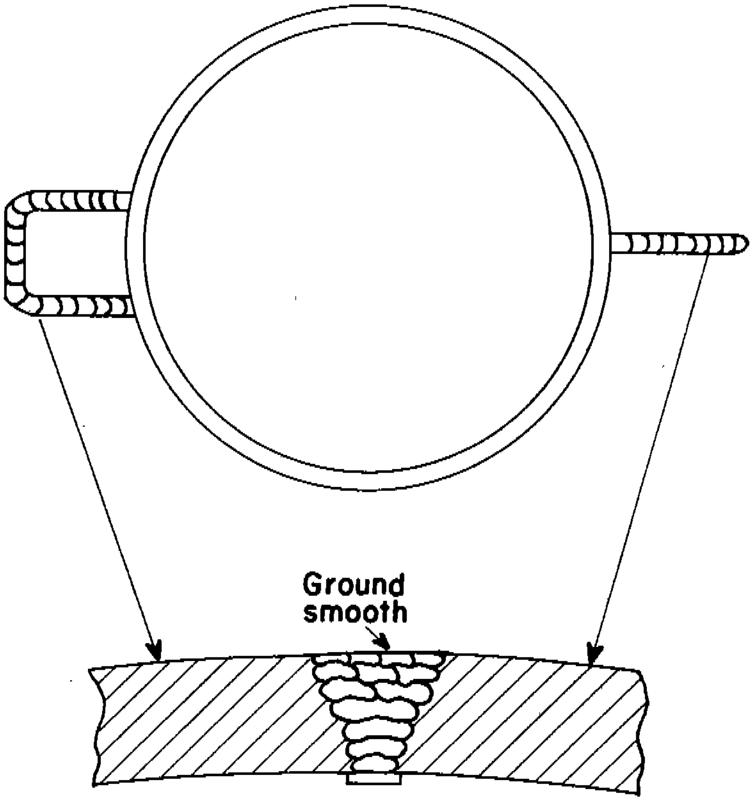


FIGURE D-3. DIAGRAM SHOWING REPAIRED SECTION OF SPHERE

0-22616

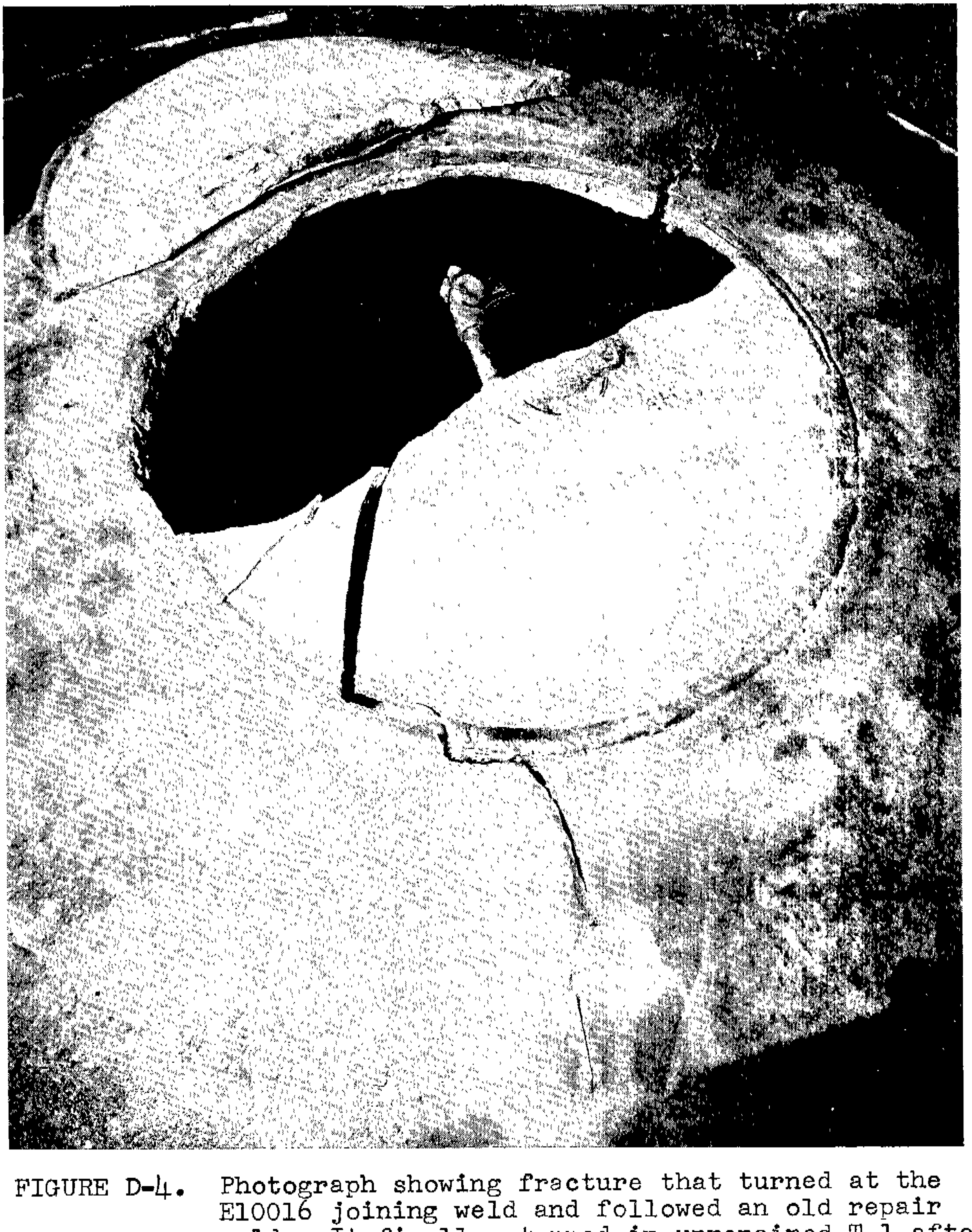


FIGURE D-4. Photograph showing fracture that turned at the E10016 joining weld and followed an old repair weld. It finally stopped in unrepaired T-1 after propagating 15-1/2 in. into the sphere on one side and 12 in. on the other.