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

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

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ABSTRACT

This report describes a study made of the conditions needed for initiation of a brittle fracture from flaws 4 in. or less in length. Experiments performed have demonstrated that residual and reaction stresses (local stresses) join with applied stresses to make up the total stress that is involved in the initiation of many brittle fractures. If local stresses are high in the vicinity of a flaw, then the applied stress may be low when brittle fracture initiates from that flaw provided that the steel is at or near the nil ductility temperature (NDT). Stress conditions that are expected to exist in ship structures were incorporated in the test specimen. Various techniques were employed to determine the magnitude of the stresses in the area of the flaw front. Some brittle fractures were initiated from flaws 4 in. or less in length at an applied stress of less than 6000 psi. Thus the results provided some insight concerning the state of stress that probably existed in structures that have failed in service at low applied stress.

Service failures and the results obtained on this project show that flaws, (especially cracks), of almost any size are potential initiation points of brittle fracture. On the other hand, these results have shown that a total stress of yield-point value or higher, in conjunction with some stress-raising condition, is necessary to initiate brittle fracture under service conditions from flaws of various sizes and types (such as a crack or lack of fusion in a weld joint). In other words, it takes a combination of conditions to initiate a brittle fracture.

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INTRODUCTION

Numerous investigations of the causes of brittle fracture in ships have been undertaken in the past ten years. Attention has recently been given to the part that weld flaws have played in the initiation of brittle fractures in welded structures. The lack of knowledge concerning the types and sizes of flaws that may be dangerous in a ship structure prompted this investigation, which has been advised by the Ship Structure Subcommittee and sponsored by the Ship Structure Committee.

The principal objective was to investigate the conditions required to initiate brittle fractures from flaws 4 in. or less in length. The information obtained from flaws greater than 4 in. in length has been reported and published.[1] It was believed that the information gained would aid in establishing production, inspection, and repair procedures for use in ship construction. The work described in this report is the concluding phase of this investigation.

REVIEW OF PREVIOUS WORK ON FLAW EVALUATION

The literature covering the broad subject of brittle fracture has been carefully surveyed. This survey was necessary to determine (1) what was required of a laboratory test specimen, and (2) what the design of specimen should be if service conditions were to be simulated. After an extensive study of the subject of brittle fracture, it was decided to use a sphere approximately 9 ft in diameter as the testing apparatus. The test specimen that contained the weld flaw was welded in place as an integral part of the sphere wall. The stress condition in the sphere wall at some remote distance from the flaw front was essentially biaxial. It was intended that the stress field in the sphere wall would simulate stress conditions in the deck or hull of a ship where a biaxial stress field is known to exist. Details of the design and fabrication of the testing apparatus are described in Appendix A.

The most serious types of defects in welds are believed to be cracks and lack of fusion, and of these, weld cracks seem to be most dangerous on the basis of past experience. Perhaps the reason for this is the very sharp radius at the flaw or crack front, which produces high stress concentration. In view of this, the first studies were confined to weld cracks and lack-of-fusion-type flaws, and more specifically, to the effect of size of flaw on the applied stress required to initiate a brittle fracture under static loading. From the studies, the following conclusions were drawn:

(1) Brittle fractures were initiated at applied 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 applied fracture stress decreased. An increase in crack depth decreased the applied fracture stress only slightly. These data are shown in Fig. 1.

(3) When weld cracks ended in sound E6010 weld metals, brittle fractures did not initiate. In some tests, ductile fractures occurred even though the Charpy V-notch 15-ft-lb transition temperature of the base plate was above the test temperature.

(4) In general, the applied fracture stresses were lowered by the addition of residual or reaction stresses to the stress system. However, the magnitudes of residual or reaction stresses were not known in these tests.

(5) Brittle fractures were initiated from lack-of-fusion flaws in welds. The applied fracture stress decreased somewhat with increase in length of flaw, or slightly with increase of depth of flaw.

The important finding that the flaw had to be 4 in. long or longer in order to give a failure at applied stresses lower than the yield strength of the A3S-B steel base material does not agree with the reports from service failures. Apparently the state of stress in the area of the flaw front was not the same for the

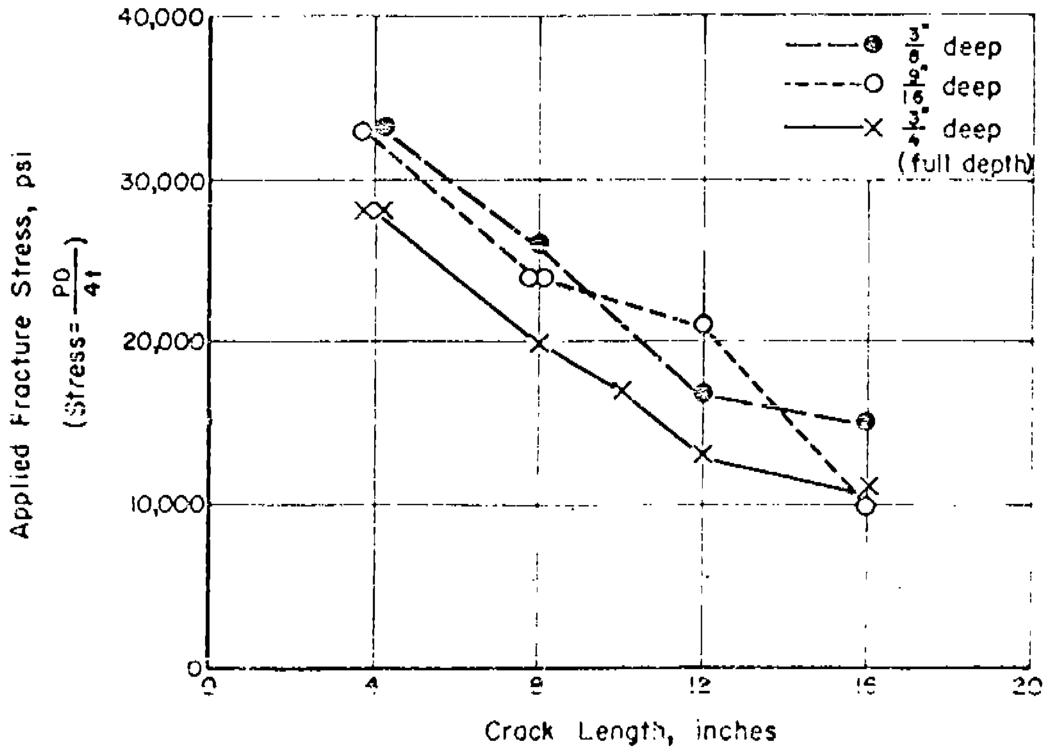

FIGURE I. RELATION BETWEEN CRACK LENGTH, CRACK DEPTH, AND APPLIED STRESS REQUIRED TO INITIATE BRITTLE FRACTURE

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laboratory tests and the service failures It appeared that stresses, other than those calculated to be present in a ship deck, might be playing a part in initiating brittle fracture. The phase of the investigation reported here was thus directed toward a study of the effect of residual and reaction stresses on the magnitude of applied stress required for the initiation of a brittle fracture; it is hoped that a knowledge of the effects of residual stress might help to explain the discrepancies between service failures and laboratory studies.

TEST PROCEDURE

The sphere that was designed and built during the initial study of weld flaws was used in the final phase of the investigation Briefly, the test apparatus was a 9-ft-diameter sphere made of 3/4-in. high-yield-strength low-alloy steel with good notch toughness Mechanical properties of the low-alloy steel, fabrication details and other pertinent data of the sphere are given in Appendix A. The test plate was a 3/4-in.-thick by 23-in.-diameter circular curved disk, which was welded into the wall of the sphere. The flaw to be evaluated was fabricated into the central area of the 23-in.-diameter test specimen before the specimen was welded into the sphere In effect, this made the entire sphere the test specimen. The test disk was fabricated from the base material being studied. The chemical composition and mechanical propertie of the ABS-B steel used in this phase of the program are given in Table 1 A sketch of the testing apparatus is shown in Fig 2.

Since it was desirable to study the effect of residual and reaction stress on the applied fracture stress, it was necessary to apply a load of some type across the flaw front to simulate the residual stresses found in service. The load was applied so that the maximum stress was normal to the flaw The residual and reaction stresses were applied by either a hydraulic ram, circular-patch-type specimen, or weld deposits made on each side of and parallel to the

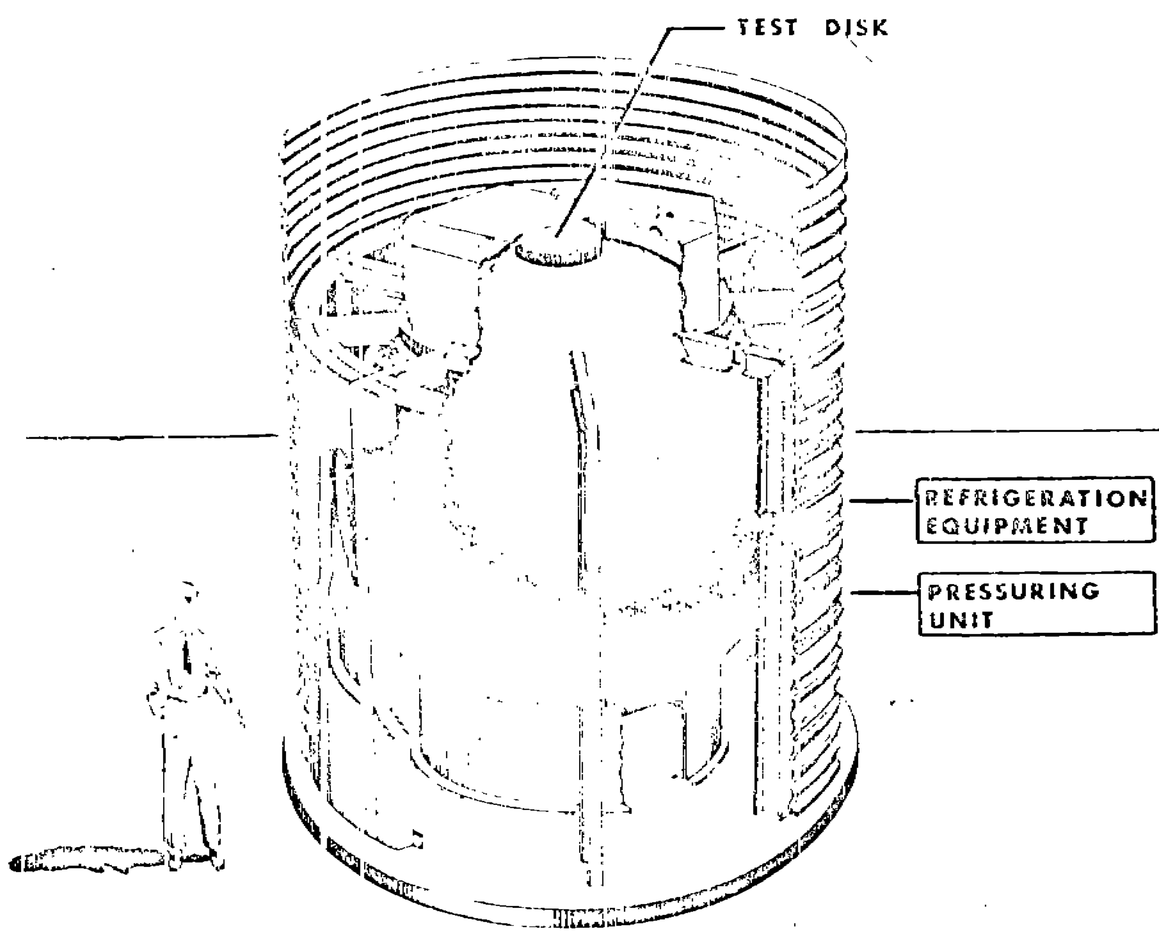

FIGURE 2. CUTAWAY DRAWING SHOWING TESTING APPARATUS AND SUPPLEMENTARY EQUIPMENT

TABLE 1. CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF ABS-B STEEL(2)

Chemical Composition, per cent		Mechanical Properties	
Carbon	0.21	Yield strength, psi	30,700
Manganese	0.80	Ultimate strength, psi	59,400
Phosphorus	0.019	Thickness, in.	3/4
Sulfur	0.034	Elongation in 2 in., per cent	55.3
Silicon	0.04	Elongation in 8 in., per cent	31.7
Aluminum	0.003		
Nickel	0.10	15 ft-lb Charpy V-notch transition temperature, F	40*
Copper	0.05	Tear-test transition temperature, F.	100
Chromium	0.04		
Molybdenum	0.01		
Nitrogen	0.005		
Vanadium	0.01		
Titanium	0.004		

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

test flaw The individual methods used for applying the residua' and reaction stresses are discussed later After the application of the residual stress, the strain measurements were recorded and the sphere prepared for testing The objective was to apply a known amount of residual stress that was below the fracture stress, then load the sphere by hydrostatic pressure until the crack initiated and propagated in a brittle manner.

The temperature of the entire sphere was lowered below the Charpy V notch 15-ft-lb transition temperature o. the ABS-B steel After the desired test temperature was reached, the sphere was loaded hydrostatically During the loading cycle, the pressure was held constant at each 100-psi increment for approximately 30 seconds to record strain gage readings This procedure was repeated until a brittle fracture was initiated. None of the fractures initiated during the 30-second interval. If the fracture did not initiate before the applied stress reached 33,000 psi, the test was discontinued After failure, the test specimen was removed from the sphere for examination of the fracture face.

Various types of flaws were used to determine the effects of residual and reaction stresses on the applied stress required to initiate brittle fractures To reduce the variables that might exist in the non-uniformity of a weld-metal crack, a simulated weld flaw prepared with a band saw was employed The flaw front was then extended an additional 1/8 in at each end with a 0 007-in.-thick jeweler's b[illegible] as shown in Specimen A. Fig 3. This type of flaw was used in the first test of each flaw length studied Specimen B in Fig. 3 is an illustration of a typical buried flaw The flaw was created from a full-depth saw-cut flaw (illustrated in Specimen A) by depositing an E6010 weld metal over the saw cut. The depth of the flaw was controlled by varying the depth of penetration during welding.

Specimen C of Fig 3 is a full-depth weld-metal flaw The flaw was made by placing cast iron chips in the weld groove and welding over them with an E6010 electrode Upon completion, the weld deposit was radiographed to determine the

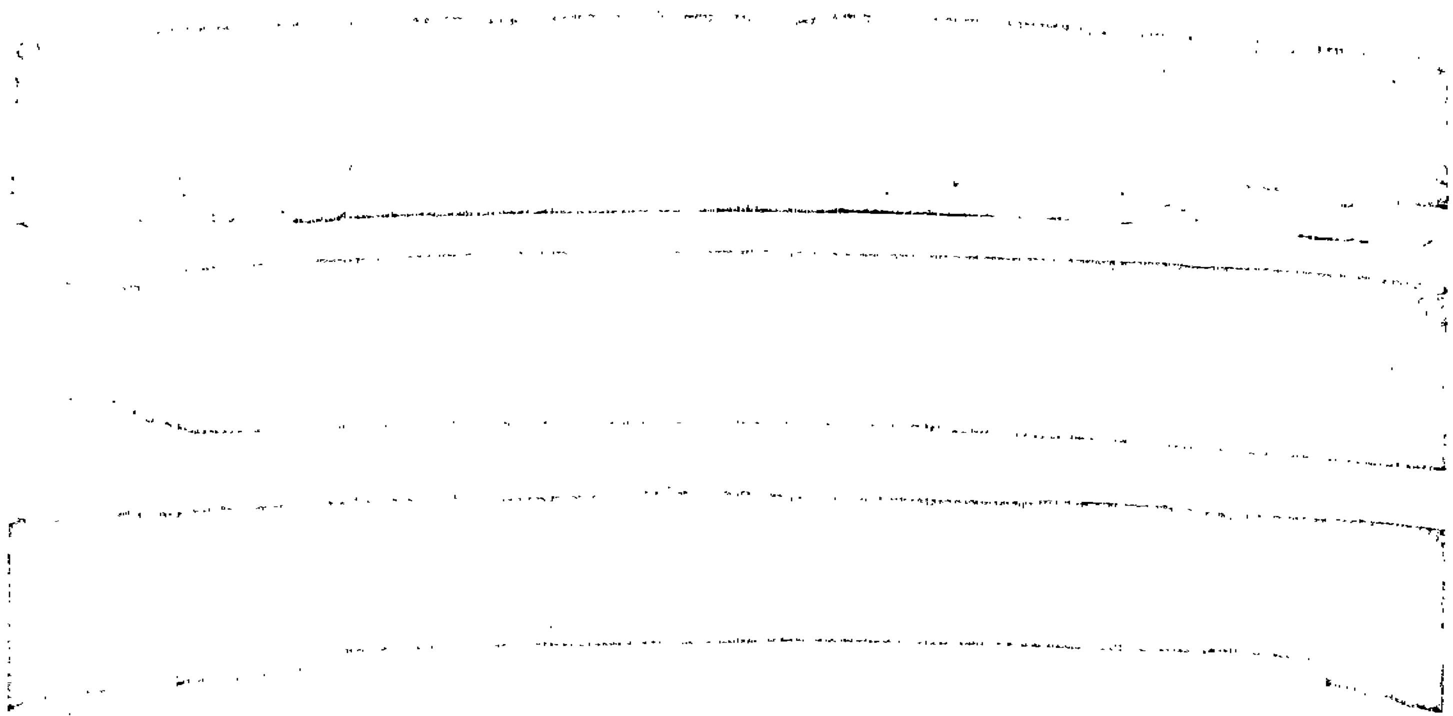

FIGURE 3. THREE TYPES OF FLAWS STUDIED: A. FULL-DEPTH JEWELER'S SAW CUT. B. BURIED FLAW. C. FULL-DEPTH WELD-METAL CRACK.

exact length and configuration of the flaw A metallurgical bond existed between the weld metal and base metal; consequently, the crack front was in the heat-affected base metal.

In several tests, the fractures propagated outside the ABS-B steel test specimen and into the notch-tough steel. These tears were repaired with low-hydrogen E10016-type electrodes To reduce the number of repairs, a method was devised to deflect the propagating crack into the weld joint between the test specimen and the notch-tough steel sphere. The deflection of the crack was accomplished by welding notch-tough steel wedges near the weld joining the test specimen and the sphere and opposite the flaw fronts but a sufficient distance from the flaw front so that the state of stress at the flaw front was not effected by their presence. A specimen in which the notch-tough wedges deflected the propagating crack is shown in Fig. 4 After the idea was conceived, these wedges were used in all tests and were successful in preventing damage to the sphere.

Strain gages and an optical comparator were used to determine the strain during testing Standard SR-4 type strain gages were used to measure the strain resulting from the hydrostatic loading of the sphere These gages were used at or below room temperature and were satisfactory as long as they were properly waterproofed However, they were not satisfactory in areas where a weld had to be made. The high temperatures encountered during welding ruined those gages in the vicinity of the welds. High-temperature strain gages were used and found satisfactory provided the gage was properly bonded to the base material However, the proper application of the gages consumed a lot of time

To reduce the amount of time required for each test, an optical comparator was used instead of the high-temperature gages The distance between scribe marks was measured with the optical comparator before and after welding to determine the residual strains produced by welding Although the use of the optical comparator did not permit a continuous check of the strains, it did give very good

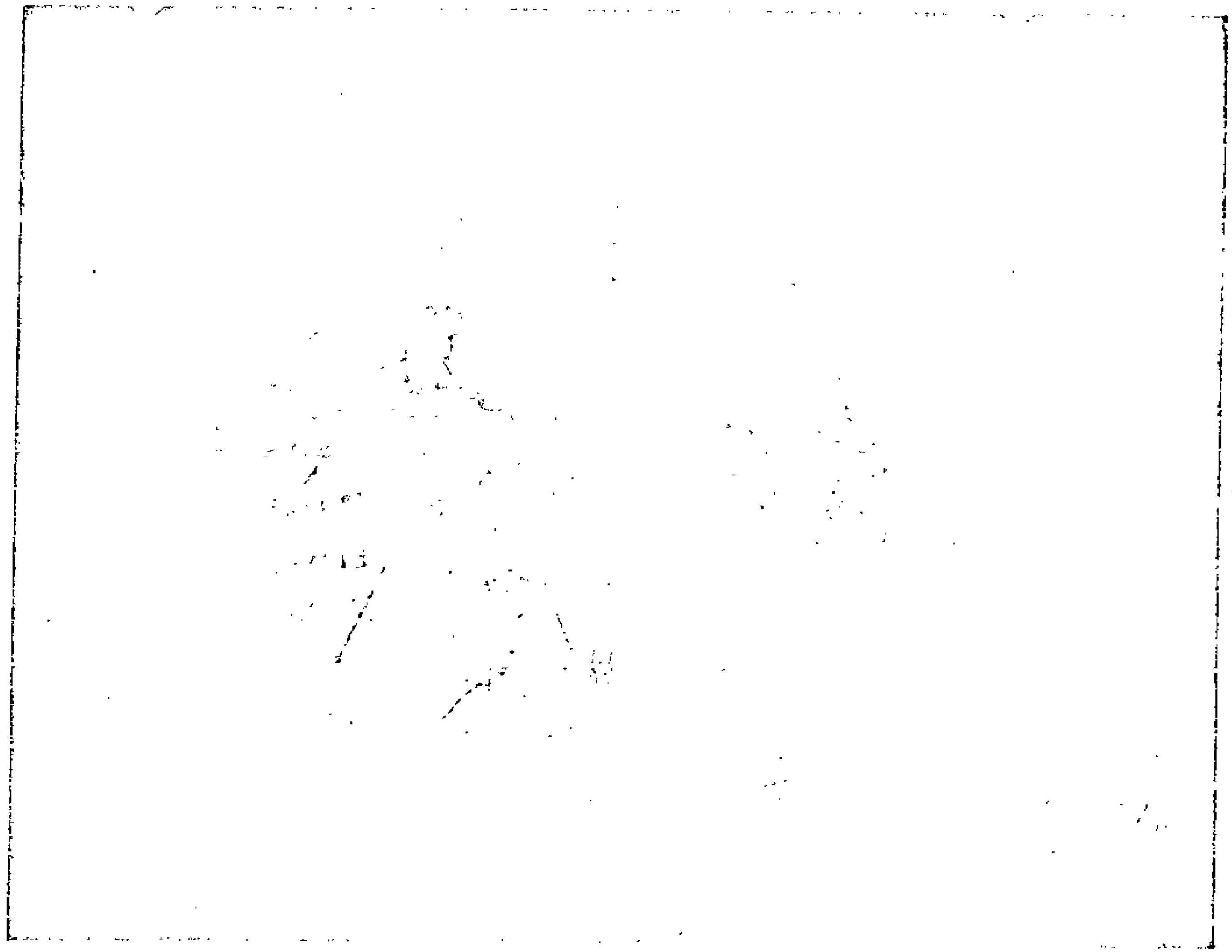

FIGURE 1. TEST SPECIMEN IN WHICH NOTCH-TOUGH STEEL WEDGES WELDED INTO THE SPECIMEN PREVENTED THE BRITTLE FRACTURE FROM PROPAGATING INTO THE SPHERE

results as to the strain produced by welding in the area of the flaw front at the surface of the plate

METHODS USED TO PRODUCE RESIDUAL AND REACTION STRESSES IN TEST SPECIMENS

At the beginning of the study, it was realized that the introduction of a known amount of residual or reaction stress in the area of the flaw front was very important. Consequently considerable effort was expended to find a suitable method of producing these stresses There appeared to be two methods that could be adapted to this particular test specimen: (1) the use of weld deposits, and (2) the use of a mechanical loading system to induce stresses in the material adjacent to the prepared crack front. The methods are described below in detail.

Producing Residual and Reaction Stresses by Welding

The circular-patch specimen was the first configuration used to produce a residual and reaction stress across the flaw front. These tests however were not very successful; their results are discussed in Appendix B

Weld deposits parallel to and on each side of the flaw were also employed as a method of producing residual and reaction stresses at the flaw front A sketch of this type of specimen is shown in Fig 5 This procedure would simulate service conditions where welding might produce or influence the reaction stresses in a welded structure

A preliminary study was made to determine the welding procedures necessary to produce high residual or reaction stresses at the flaw front These studies showed that yield-point stresses could be produced in the base plate between two parallel welds provided high-yield-strength weld metals were deposited.

The parallel weld technique was used by preparing a groove on each side of the flaw before welding the circular test disk into the sphere. The weld containing the flaw was then deposited in the center of the test specimen, and the test specimen was welded into the sphere Gage marks were made on the site of the SR-4

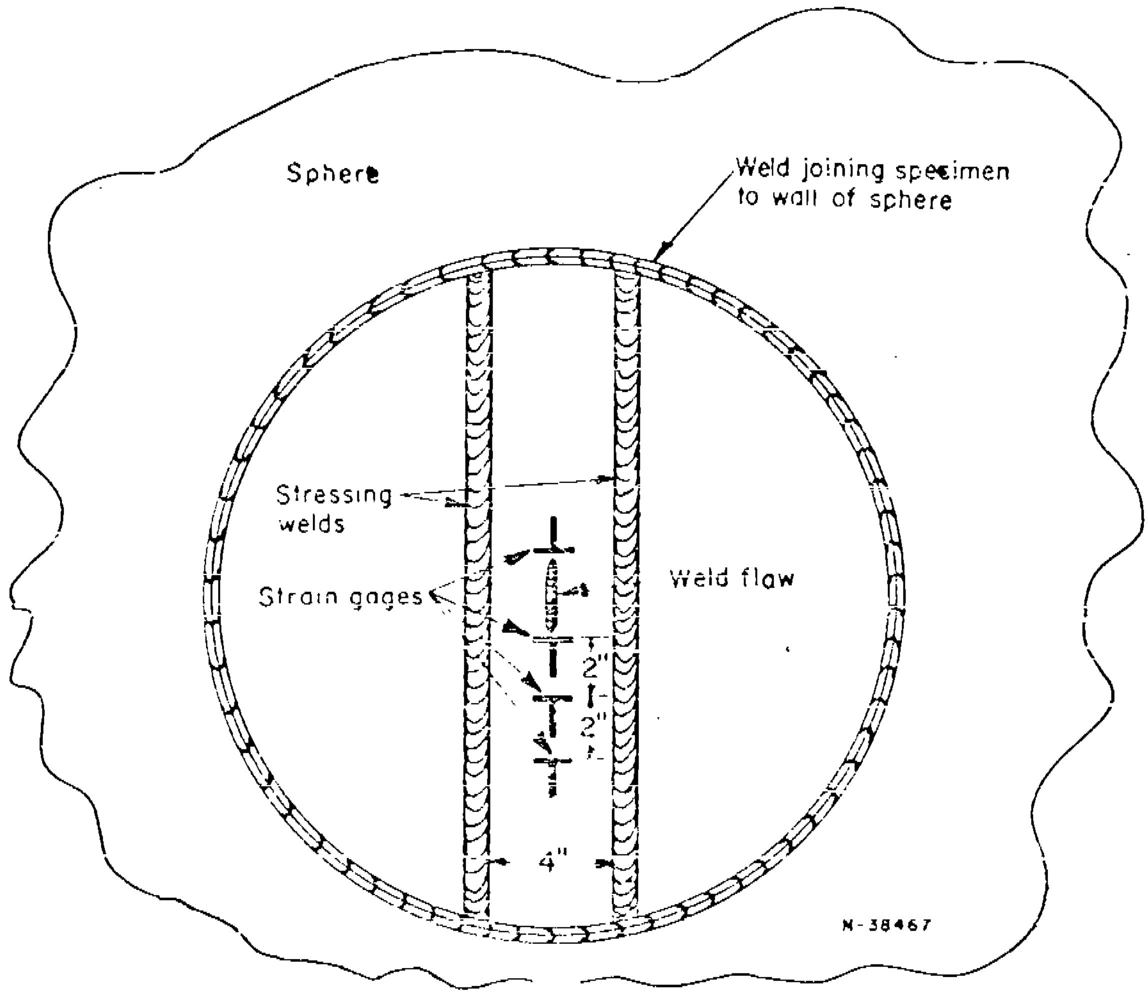

FIGURE 5 SKETCH SHOWING USE OF WELDING TO PRODUCE RESIDUAL AND REACTION STRESSES IN AREA OF FLAW

strain-gage locations (shown in Fig. 5), and measurements were recorded Weld metal was then deposited in the parallel grooves. After the specimen was cooled to room temperature, the strain between the gage marks was measured

The residual stress was obtained from the difference between the strain measurements made before and after the parallel welds were completed The residual stresses in the area of the flaw varied from the yield point of the base steel to a low value of 2000 psi

Producing Reaction Stresses by Mechanical Means

Quite often during the construction of ships, the plates to be joined by welding are jacked into position to give proper fit In these instances, various degrees of reaction stresses remain in the structure after welding Butt welds that contain flaws may possibly be stressed in this manner. Therefore, in an attempt to simulate this condition on a laboratory scale, a mechanical device was used to introduce these stresses in the area of the flaw front of the test specimen. This condition was accomplished by welding two chocks on opposite sides of the flaw, as shown in Fig. 6. These chocks were welded to the test disk before the flaw was prepared This procedure eliminated any stresses in the area of the flaw front resulting from welding the chocks to the disk. The load across the flaw front was supplied by a hydraulic ram placed between the chocks The strain introduced from the load of the ram was measured by SR-4 strain gages placed at selected locations in the area of the flaw front A constant pressure was maintained on the hydraulic ram during the loading of the sphere

STUDY OF INFLUENCE ... LENGTH AND DEPTH OF FLAW AND TRIAXIALITY ON THE APPLIED STRESS REQUIRED TO INITIATE BRITTLE FRACTURE

Effect of Flaw Length on Fracture Initiation

The jeweler's saw-cut notch and weld-metal flaw were employed in these tests to study the effect of flaw length ... the stress required to initiate brittle

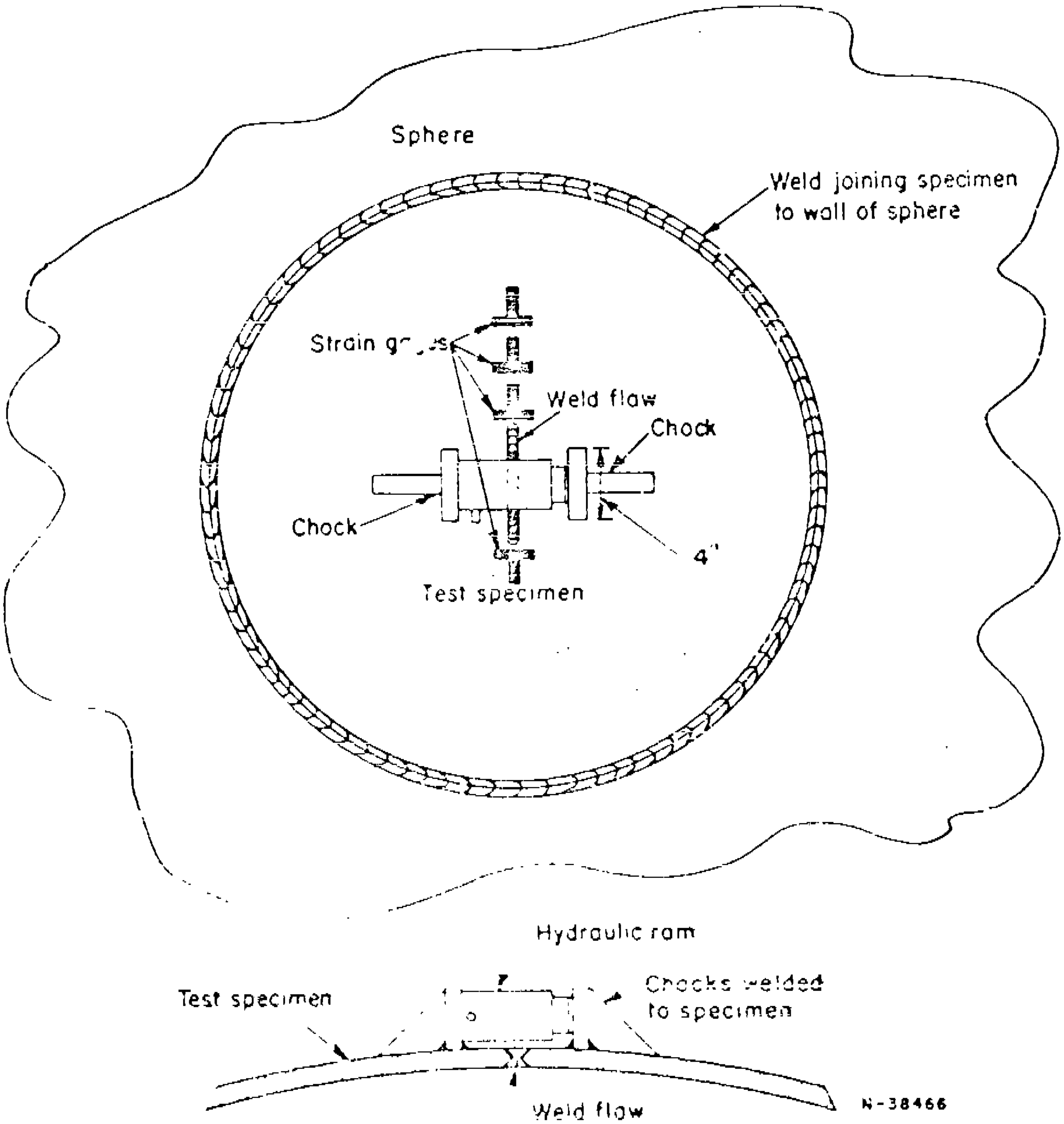

FIGURE 6 SKETCH SHOWING THE USE OF A HYDRAULIC RAM TO PRODUCE REACTION STRESSES AT THE FLAW FRONTS

fractures These flaws ranged in length from 4 in. to 1 in The reaction stress was applied across the fronts of the flaws by means of the hydraulic ram The test results indicated that: (1) the length or the type of flaw had little influence on the average fracture stress required to initiate failure, as shown in Fig 7; (2) reaction stresses reduced the applied stress required for fracture, (3) it made little, if any, difference how the stress was applied, whether by loading the sphere by hydrostatic pressure or by applying reaction stresses by various means and then loading the sphere until fracture occurred.

The strain measurements from which the stress was computed were taken on the surface of the plate at the flaw front. The test data are tabulated in Appendix C The average fracture stress was obtained from the true stress-strain curve of the base material, as shown in Fig. 8. Although this curve was obtained from a specimen tested in uniaxial tension and the specimen in the sphere was stressed biaxially, the stress-strain curve was believed to be useful in obtaining an estimate of the stress that existed in the area of the flaw front Furthermore, the amount of strain that occurred normal to the flaw front was much greater than the strain parallel to the flaw front The average fracture stress, computed from strain measured on the plate's surface at the flaw front, was approximately the same for all the specimens. Any differences that existed in these stress values might be the result of non-uniform placement of the strain gages with respect to the crack front.

Since there was considerable plastic deformation at the flaw front prior to fracture, any differences in performance between the specimens are illustrated by variations in strain more clearly than by variations in stress The strain plot is shown in Fig. 9 The total strain of the specimens containing the 4- and 3-in. weld flaws was considerably lower than the strain recorded for the other specimens The specimen containing the 4-in. flaw may not be too representative because the test was originally planned to study a buried flaw. A fracture could not be initiated from the buried flaw, therefore the specimen was modified to give a full-depth flaw. Because of this modification, it is possible that some residual stresses that were not

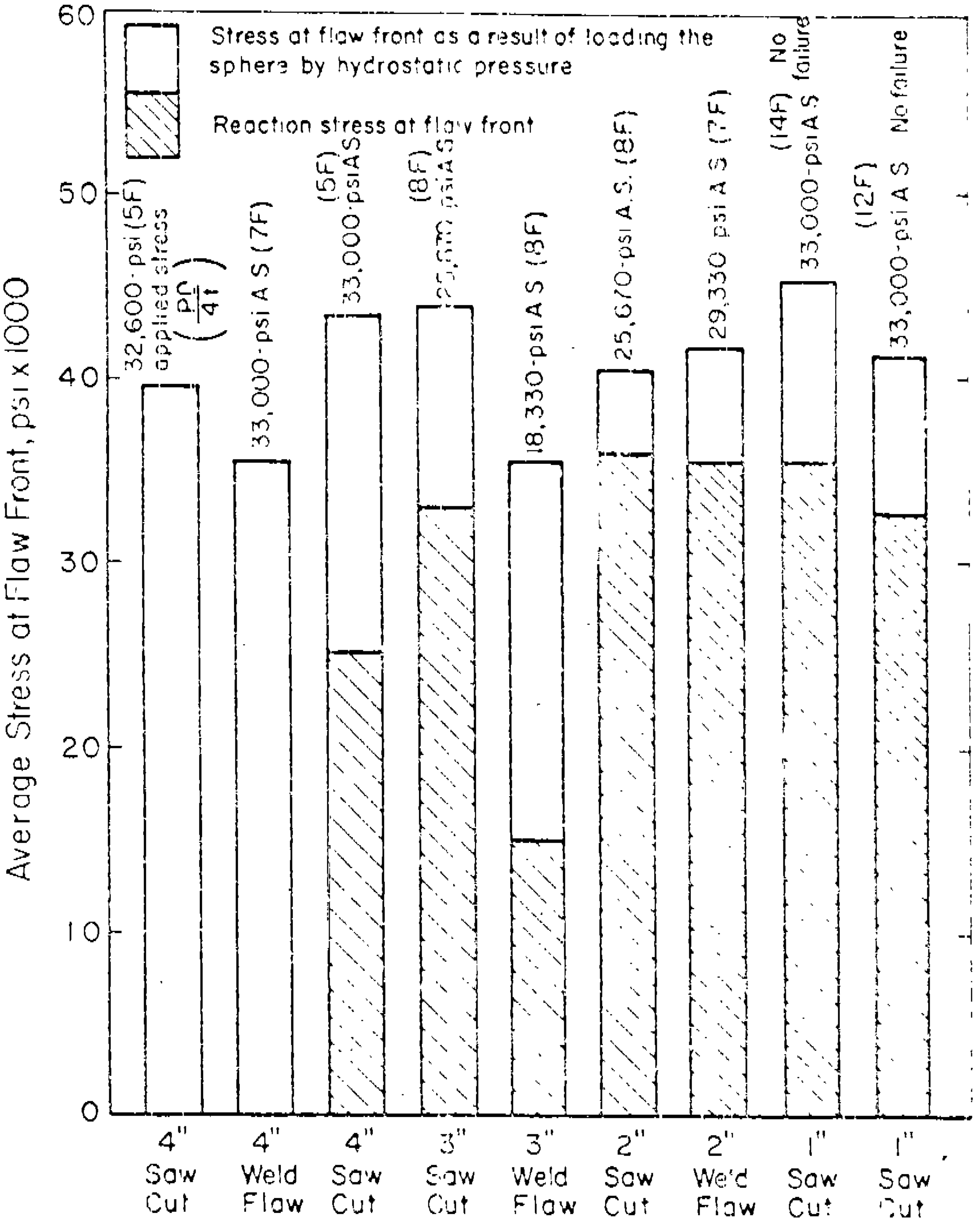

FIGURE 7. EFFECT OF REACTION STRESS ON THE INITIATION OF BRITTLE FRACTURES FROM SIMULATED WELD FLAWS

Reaction stresses introduced by hydraulic ram. All plotted stresses were calculated from strain measurements at the flaw front and the uniaxial stress-strain curve.

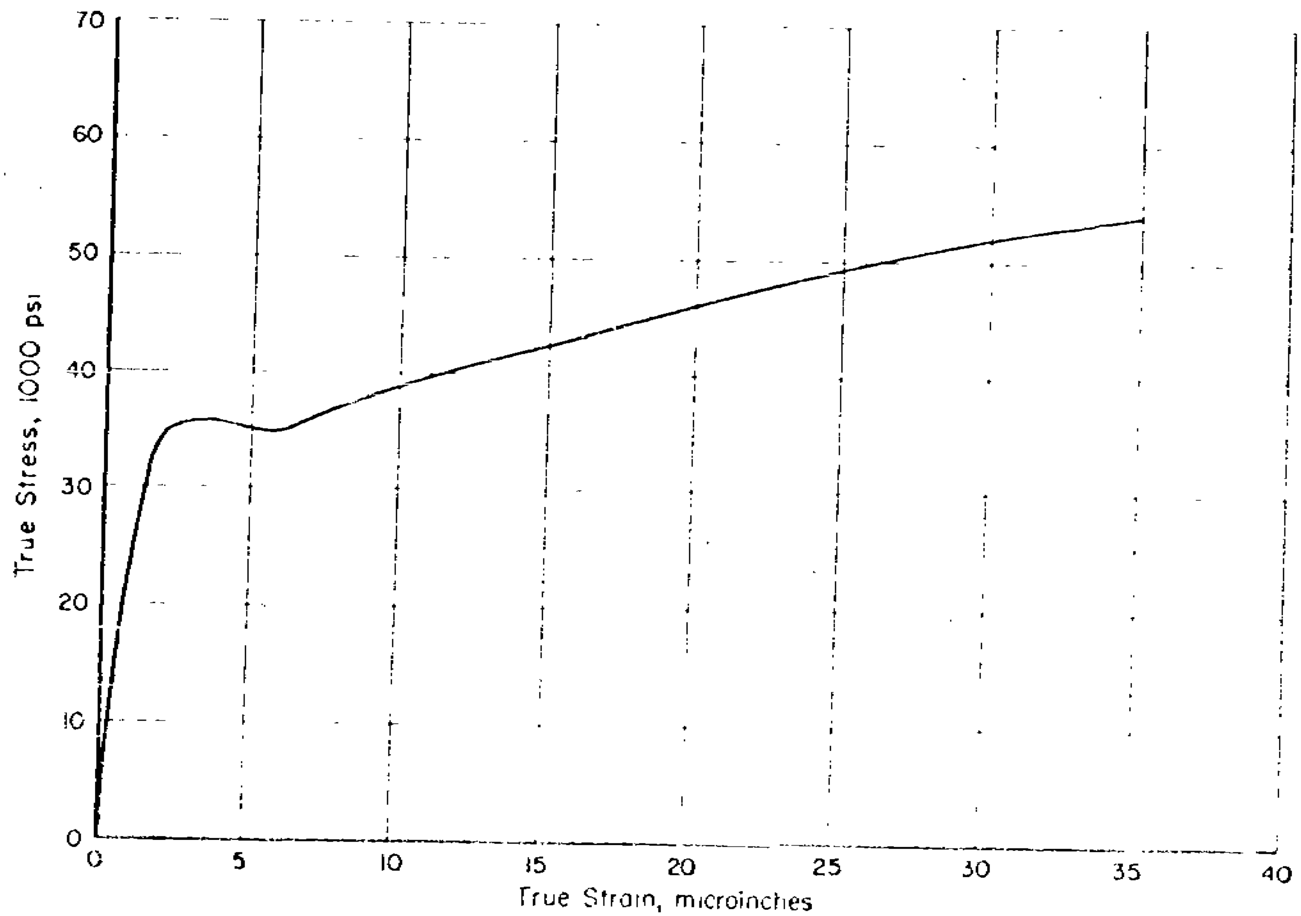

FIGURE 8 TRUE STRESS - STRAIN CURVE FOR ABS - GRADE B SHIP STEEL

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recorded remained at the flaw front from the original loading of the full-depth flaw. There is no apparent reason why less strain was required to initiate fracture from the 3-in. weld flaw than from the other flaws. There was considerable difference in the amount of strain recorded from the two specimens containing the 4-in. saw-cut flaws. In these two specimens, the strain gages were accurately oriented in the same geometric arrangement with respect to the saw-cut front. With this accuracy, there was a difference of 5000 microinches of strain between the specimens prior to fracture. Since this amount of scatter existed between these two tests, the differences in strain for the other specimens might be considered as normal scatter, except for the 3-in. weld-flaw specimen.

No fractures were initiated from either the 1-in. saw cuts or the 1-in. weld flaws. In the one specimen containing a 1-in. saw-cut flaw, more strain occurred than for any other length of flaw. A fracture would be expected to initiate from the 1-in. flaw if the amount of plastic deformation (strain) at fracture is relatively constant regardless of flaw length. The strain recorded from the specimen containing the other 1-in. saw-cut flaw and two 1-in. weld flaws was in the order of 10,000 to 15,000 microinches, which is approximately the amount recorded from the longer flaws. The testing conditions and apparatus did not permit loading the 1-in. flaws to failure.

A series of tests was made in which the weld flaws were stressed by depositing welds on each side of and parallel to the flaw. As mentioned previously, yield-point stresses were recorded in the base material when reaction stresses were produced in this manner. The test results are shown in Fig. 10. In all of the test specimens, a high residual stress across the flaw front resulted in brittle fracture initiating at rather low applied stresses. The second 4-in.-long weld flaw tested is of particular interest in this series of tests. The residual stress at the flaw front at the start of the test was [illegible]8,200 psi (considerable deformation had occurred) and after [illegible] an additional stress of approximately 1800 psi, a brit-

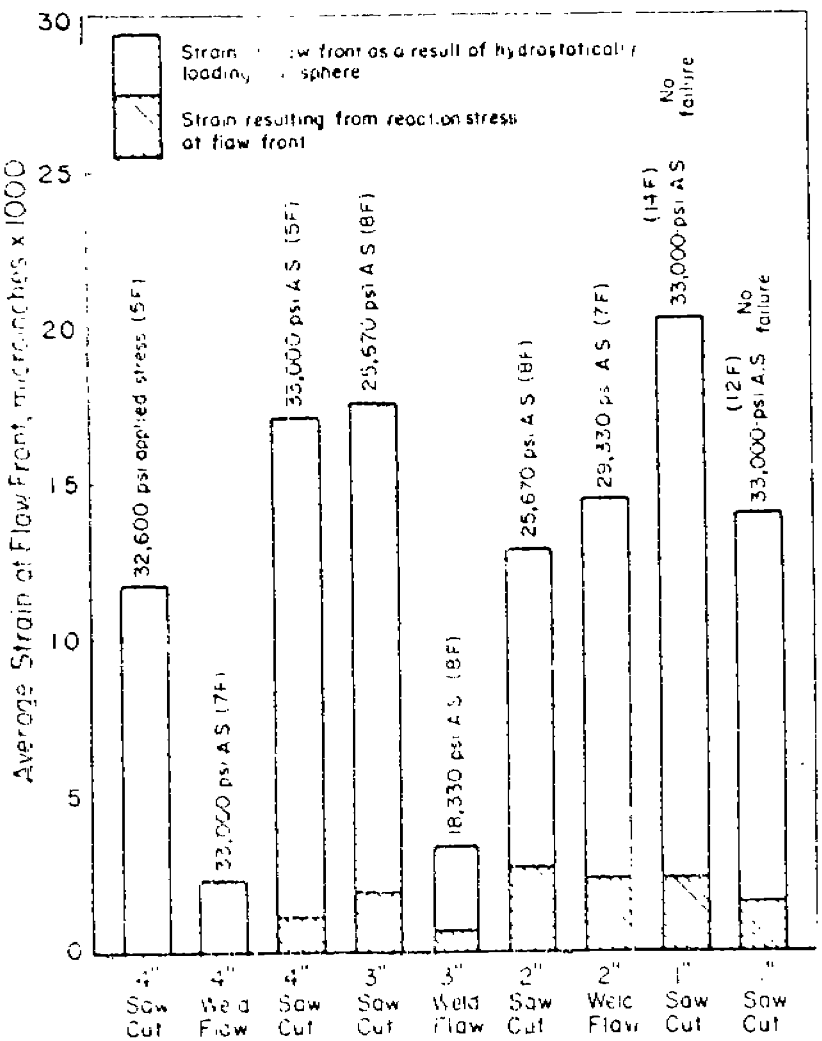

FIGURE 9. EFFECT OF REACTION STRAIN ON THE TOTAL STRAIN REQUIRED TO INITIATE BRITTLE FRACTURES FROM SIMULATED WELD FLAWS (JEWELER S SAW CUT)

Reaction strain introduced by hydraulic ram

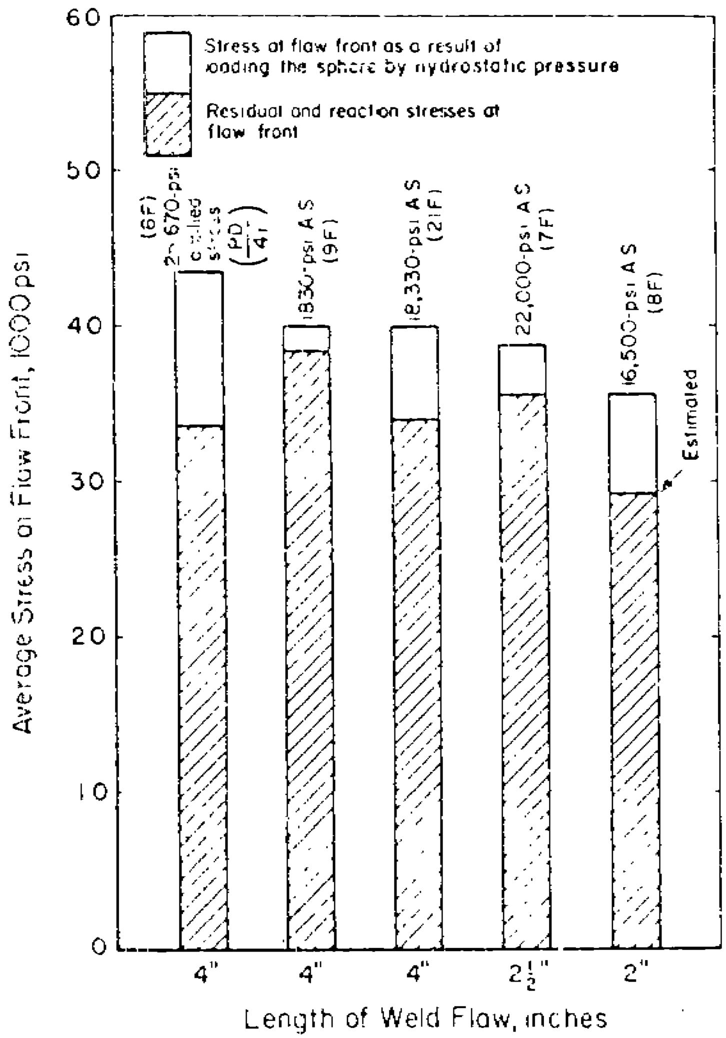

FIGURE 10. EFFECT OF RESIDUAL AND REACTION STRESSES INTRODUCED BY WELDING ON THE INITIATION OF BRITTLE FRACTURES FROM WELD FLAWS

the fracture initiated from the weld flaw. These test results illustrate the magnitude to which residual and reaction stresses can be built up within a structure. With such high residual stresses present, little additional stress is required to initiate fracture if the temperature is low enough.

The average strain at the flaw front of each specimen containing only a weld flaw is plotted in Fig. 11. These measurements were used to determine the stress shown in Fig. 10. A plot of the strain illustrates differences in the amount of plastic flow in the area of flaw front more clearly than a plot of the stress, because considerable plastic strain occurs without any appreciable increase in stress

Most of the deformation occurred in the pre-stressing (residual) stage of the loading cycle for the one 4-in. flaw In another flaw of equal length, most of the strain occurred from loading the sphere by hydrostatic pressure The total strains were approximately the same. Consequently, it appears that the majority of the strain can be produced at any stage of stressing without influencing the total strain at fracture The total strain recorded for the 2 1/2-in flaw is also of the same magnitude as for the 4-in flaws The amount of strain recorded for the specimen containing the 2-in. flaw may not be very accurate, because the specimen was originally stressed as a buried flaw. Because a fracture did not initiate from the buried flaw, the flaw was modified to give a full-depth [illegible] In the course of this modification, it is believed that residual stresses were introduced and were not recorded This chain of events may be the reason for the low strain measurements prior to fracture. However, these strain recordings are approximately the same as those shown in Fig. 9 for the 3- and 4-in weld flaws. The wide range of strain recorded prior to the initiation of the weld flaws may be the result of variations in the location of the crack front Although great care was exercised in preparing the weld flaw, there was always the possibility of lack of fusion near the crack front. In some of the specimens, the crack front may have been in the high-carbon weld metal, while in others it may have been in the heat-

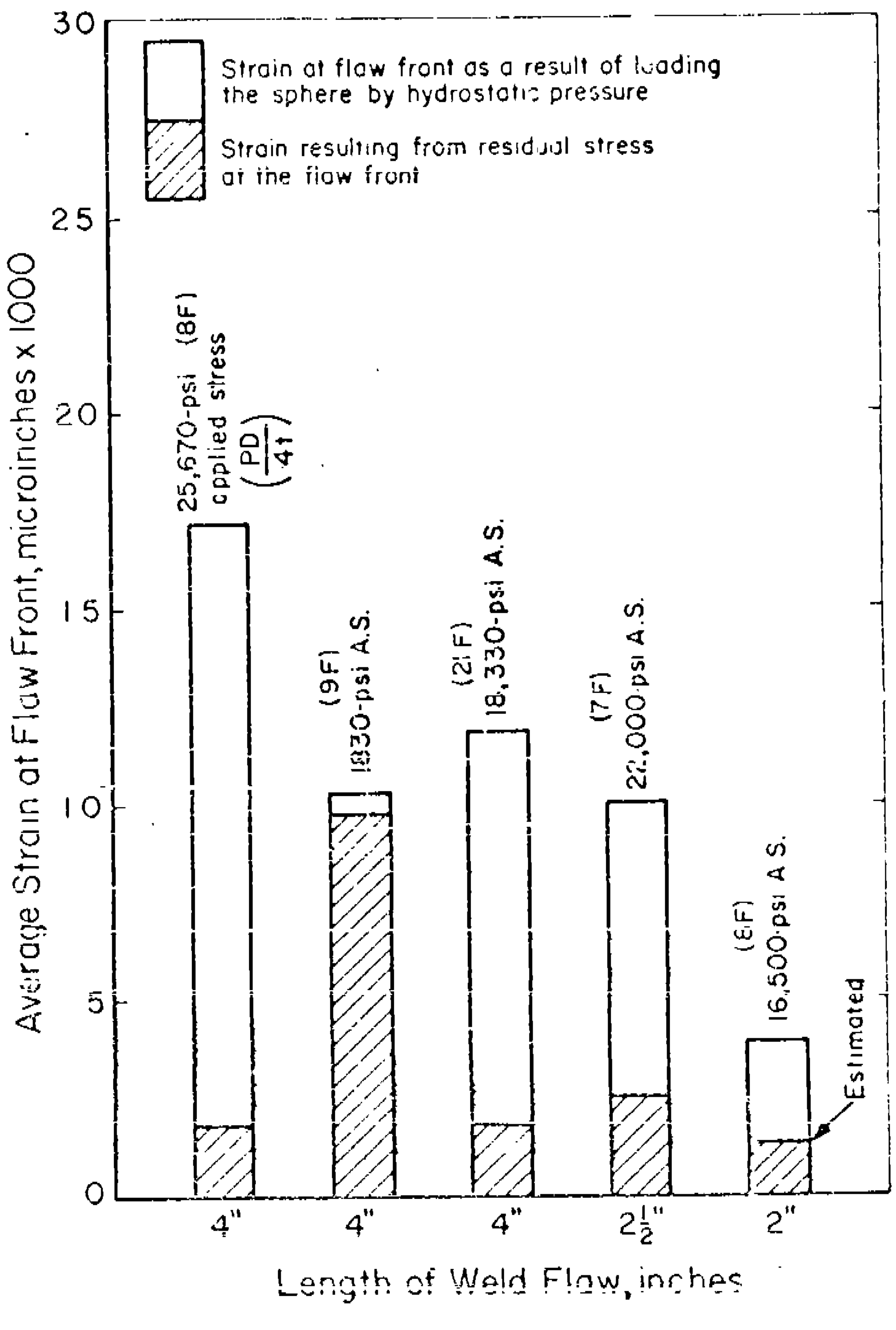

FIGURE 11 EFFECT OF RESIDUAL AND REACTION STRAIN FROM WELDING ON THE AVERAGE STRAIN REQUIRED TO INITIATE BRITTLE FRACTURES FROM WELD FLAWS

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affected zone of the base plate. The scatter in strain measurements also may be attributed to the inability to locate the strain gages at the same location on each specimen with respect to the flaw front.

Effect of Flaw Depth on Fracture Initiation

In the previous work on the project, it was found that flaw depth had little effect on the applied fracture stress. These data are shown in Fig. 1 for flaws 4 in. or greater in length. In order to initiate brittle fracture from the 4-in. flaws, the crack had to first open to at least one surface of the plate. During this past year, a series of tests was made with 4-in. flaws of various depths that were completely buried; that is, sound weld metal was deposited over the flaw on each surface. Specimen B shown in Fig. 3 is a typical flaw of this type.

A plot of the average fracture stress measured in the vicinity of the flaw front is shown in Fig 12 A full-depth flaw was included in this series of tests for comparison purposes. All of the flaw fronts were prepared with the jeweler's saw blade and the reaction stress was applied with the hydraulic ram.

The average fracture stress was somewhat higher for the full-depth flaw than for the buried flaws. There was little difference in the average fracture stress of the specimens containing the buried flaws. Less strain was required to initiate a fracture from buried flaws than from a full-depth flaw, as shown in Fig. 13 As mentioned previously, an E6010 weld metal was deposited on the outer surfaces of the buried flaws. Strain gages were placed at the center and at the ends of the flaws. Because of the geometry of the joint, the maximum strain occurred over the center of the flaw. The limits of the strain gages in the center of the flaw were exceeded first. Since these gages were attached to the ductile E6010 weld metal, considerable strain was recorded before failure In no case were the failures in the weld metal brittle. Although the strain gages in the center of the flaw failed first, this occurence does not necessarily mean that the flaw opened to the surface prior to extending lengthwise. Less strain could occur at the flaw front than over

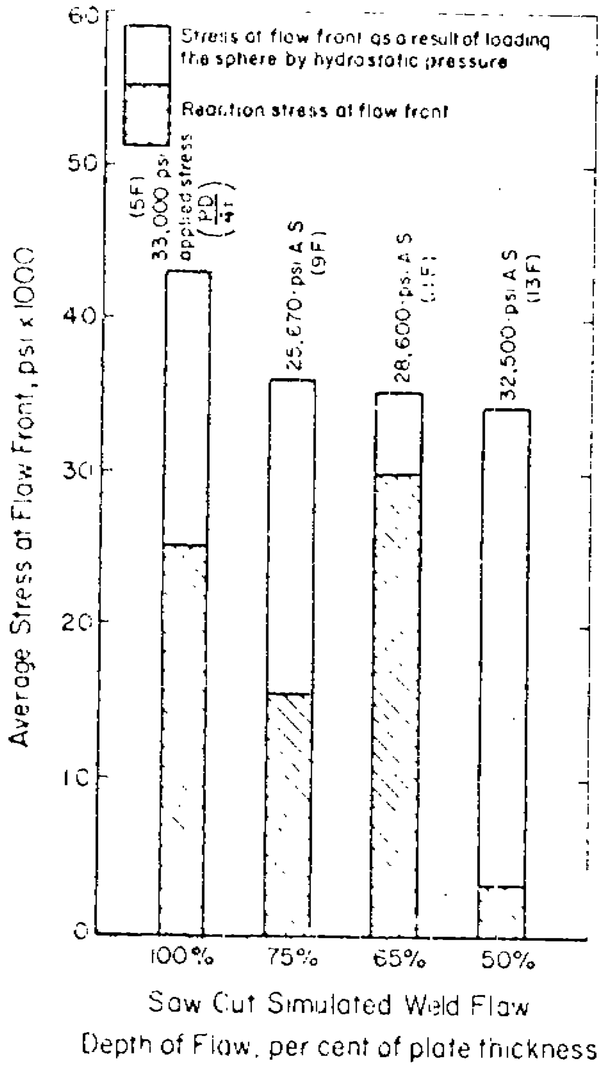

FIGURE 12 EFFECT OF REACTION STRESS ON THE INITATION OF BRITTLE FRACTURE FROM 4-INCH FLAWS OF VARIOUS DEPTHS

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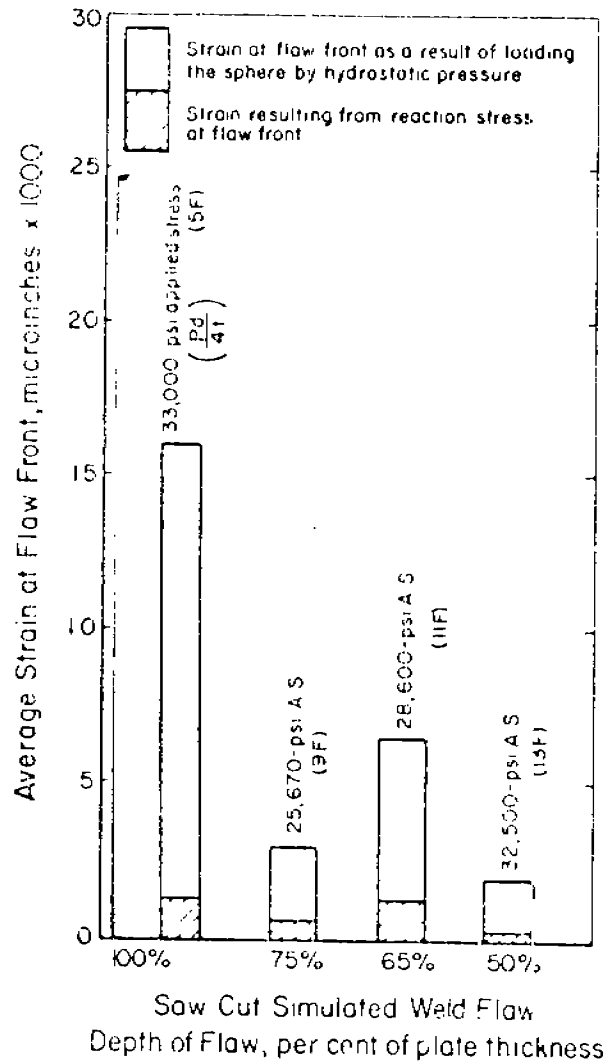

FIGURE 13 EFFECT OF REACTION STRAIN ON THE INITIATION OF BRITTLE FRACTURE FROM 4 INCH FLAWS OF VARIOUS DEPTHS

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the center of the flaw and still have fracture initiate at the flaw front. However, it is of interest that the amount of strain on the plate surface prior to fracture was lower for the buried flaws than for any of the full-depth flaws prepared with the jeweler's saw blade Although the data are quite limited, they are of some significance. It would be interesting to know if the fracture of the buried flaw opens to the surface first or if it extends lengthwise.

Effect of Triaxiality on Fracture Initiation

As the state of initial stress approaches triaxiality, plastic deformation prior to fracture is decreased. In the tests described in the previous sections, the state of stress at a remote distance from the crack front was biaxial Some degree of triaxiality exists at the crack front as a result of constraining the plastically deformed metal from further deformation; even under these conditions considerable plastic deformation occurred on the surface of the plate at the crack front If this material was further constrained, the degree of triaxiality would be increased, and failure would be expected to occur at a lower average applied stress as calculated from the elastic strain measured on the wall of the sphere.

Service failures have been reported that have initiated from small flaws at low applied stresses. In an attempt to reproduce this type of service condition in a laboratory test, an 8-in. square structure was fabricated from 3/4-in.-thick plate and welded into the test specimen, as shown in Fig 14 Two 4-in.-long full-depth weld flaws were made in the test specimen and located at diagonally opposite corners of the box, in such a manner that one flaw lay in the direction of rolling and the other perpendicular to the direction of rolling of the test specimen plate

An applied stress of approximately 6500 psi, caused by loading the sphere by hydrostatic pressure, propagated the flaw that was parallel to the direction of rolling for a distance of approximately 1 1/2 in The test was continued and the flaw perpendicular to the direction of rolling propagated approximately 3 in. at an applied stress of 7400 psi The sphere wall was further stressed to 32,000 psi without any further increase in the length of the cracks.

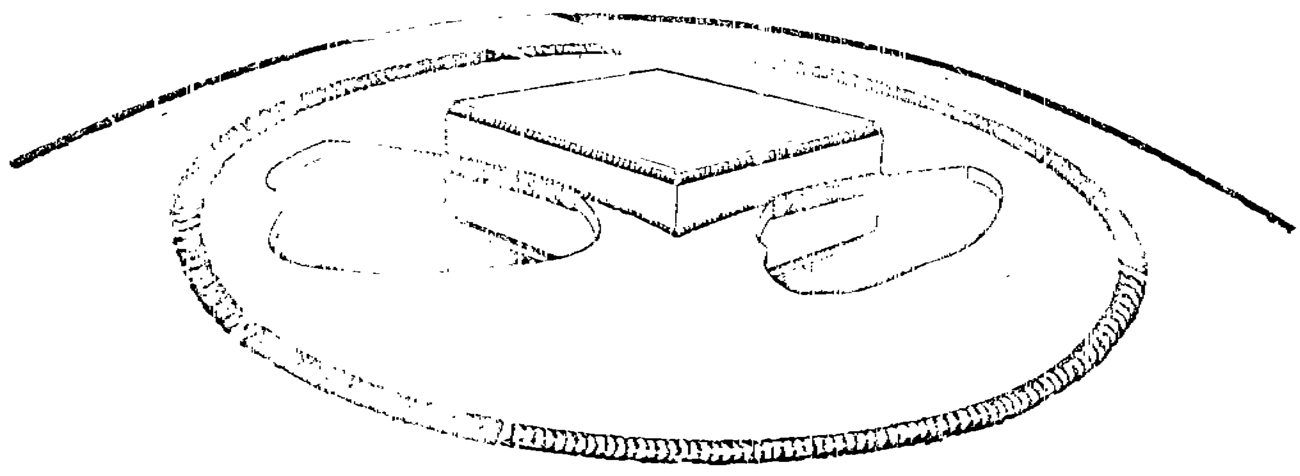

FIGURE 14. SKETCH OF SPECIMEN WITH STRUCTURE USED TO INCREASE THE DEGREE OF TRIAXIALITY NEAR THE FLAW

In previous work, at least a 30,000-psi applied stress was required to initiate fracture from a 4-in. flaw in a specimen highly stressed in only two dimensions. A point of interest to be noted is that the flaw stopped after it propagated for a distance. One explanation for the termination of the fracture was that the flaw entered an area of compression stresses that probably existed from the weld joint between the test disk and sphere wall. The applied tensile stress may not have been high enough to overcome these compressive stresses and propagate fracture in this area.

DISCUSSION

One of the requirements for propagation of a brittle fracture in steel is to have sufficient elastic strain energy in the system to cause continuing separation once the crack is initiated. Another requirement is to ensure that some plastic deformation occurs at the crack front prior to the initiation of the fracture. These required conditions were produced with the laboratory testing apparatus used in this study. Although the primary objective was to study crack initiation, it was necessary to produce brittle fracture to simulate reported service failures. Once the brittle fracture was initiated and propagated in the ABS-B steel, fracture was terminated in a notch-tough steel without serious damage to the test vessel. Brittle fractures were initiated from 2-in. flaws at applied stresses of one-third the yield strength, in addition to the residual and reaction stresses. These data then compare favorably with the reports of service failures that occurred at 15,000 psi applied stress or lower.

Residual and reaction stresses have a very important influence on the stress required to initiate a brittle fracture from actual weld flaws and simulated weld flaws (jeweler's saw cuts). In fact, in one test a brittle fracture was initiated at an applied stress of only 2000 psi after residual and reaction stresses were introduced in the area of the flaw front. However, the total average fracture stress at the flaw front (as measured on the surface of the plate) was about 40,000 psi This suggests that most fractures initiating from small flaws in the deck of ships, which may be considered as a field of biaxial tension stresses, did not fail from the low applied stresses only An auxiliary stress must have been present

All of the laboratory tests in which brittle fracture occurred were conducted below the 15-ft-lb transition temperature of the base steel The test temperatures also were below those encountered during service failures. Since there was considerable plastic deformation at the flaw front of the laboratory specimens, there must have been considerable plastic deformation at the flaw front of the service failures This assumption can be made only if the states of stress at the flaw fronts were the same. It would have been desirable to have initiated brittle fractures from flaws 1 in. or less in length in order to simulate some of the service failures. It has been reported by Williams et al that most of the fractures that initiated from small flaws (1 in or less in length) were not in a stress field of biaxial tension (excluding the triaxiality at the crack front).[3] In most cases, a third structural member was involved. This apparently produced a more complex stress system when residual and reaction stresses were present by providing more constraint. An attempt was made to simulate this condition through use of the test specimen in which a structure was built into the circular disk. A brittle fracture was initiated from a 4-in. flaw at an applied stress of 6600 psi. With sufficient experimentation, it appears possible that brittle fractures could be initiated from small flaws (1 in. or less) at low applied stress levels if sufficient constraint is provided at the flaw front

The data illustrate that as the flaw or crack length is increased, the applied fracture stress decreases. This condition is predictable from the familiar Griffith equation as modified by Irwin and Kies for application to brittle fracture in metals[4] This study provided considerable data that were evaluated, using the modified equation, to ascertain whether any correlation existed between the experimental results and the theoretical values that could be obtained.

As a first approximation, the equation $G = \frac{\pi \sigma 2a}{E}$ was considered. G is the crack extension force, σ is the stress normal to the crack direction, 2a is crack length, and E is Young's Modulus. This approximation may be considered only when the existing plastic deformation is limited to the immediate vicinity of the crack front. Data of some of the laboratory tests are plotted as average stress versus crack length in Fig. 15. Curves for three theoretical values of G are also shown. The average stress for the specimens containing cracks 4 in. and longer was the $(\frac{PD}{4t})$ stress at fracture unless indicated otherwise. All of the G values for cracks longer than 4 in. fell within the band of 200 to 100 in.-lb/sq in.

Some of the 4-in. flaws and all of those less than 4 in. in length were stressed in a somewhat different manner than the larger flaws. Various degrees of residual or reaction stresses were applied in the area of the flaw front, as well as in the path into which the fracture was to propagate. The lower value plotted in Fig. 15 for each of the specimens containing flaws less than 4 in. long is the $(\frac{PD}{4t})$ stress required to produce fracture after some amount of residual stress was applied. The upper point for each specimen was obtained by adding the residual stress, calculated from strain measurements, to the stress, calculated from the expression $\frac{PD}{4t}$. The difference in stress between the two points for each specimen, therefore, is the residual stress as measured 2 in. from the flaw front. The stress at this location was not affected appreciably by the flaw. Fig. 15 shows that the total applied and residual stresses of several of the specimens (upper point for each specimen) were considerably higher than the stress required to give a G value of 200 in.-lb/sq in. However, the average stress at an area of sufficient distance from the flaw to be virtually unaffected by the geometry of the flaw was less than the sum of the residual and applied stresses. The reason for this was that both the residual and applied stresses when measured separately were in the elastic range. When the two stresses were superimposed, however, the steel behaved plastically. Consequently, the sum of the residual and applied stresses (measured separately) was not equal to but was greater than the actual stress.

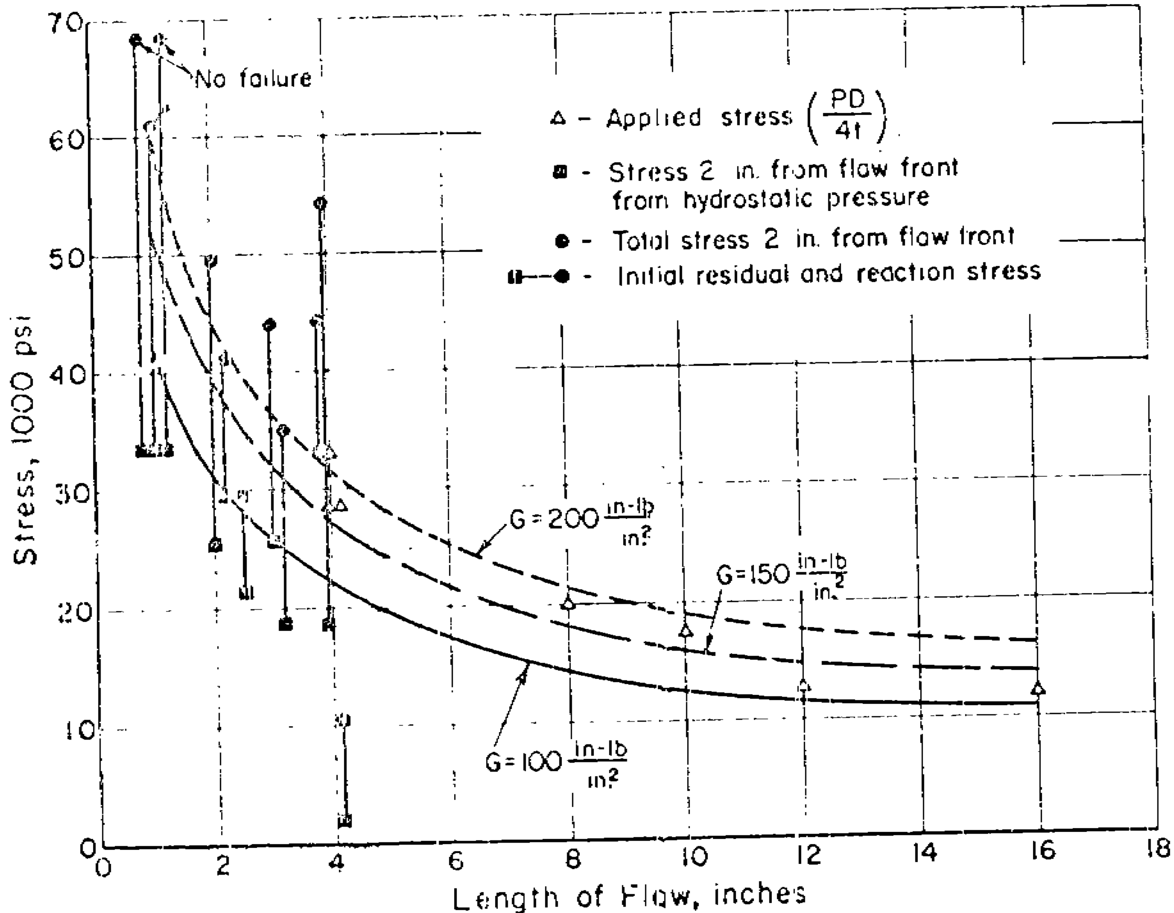

FIGURE 15 RELATIONSHIP OF AVERAGE STRESS FOR INITIATION OF BRITTLE FRACTURE WITH LENGTH OF INITIAL FLAW

The stress computed from the strain measured at a point 2 in. from the flaw front was approximately 36,000 psi for all the specimens containing flaws 4 in. or less in length, although there was considerable strain in the order of 0.005 in./in at this point. However, at this strain level a great difference in strain would not affect the calculated stress appreciably because of the relationship between stress and strain in the plastic range. The applied fracture stress of 36,000 psi gives a G value between 100 and 200 in.-lb/sq in. for most of the tests. One of the specimens containing a 4-in. weld flaw failed at much lower recorded average stress than other specimens of equal flaw lengths. The residual and reaction stresses for this specimen were furnished by the parallel weld technique. Although the amount of strain 2 in. from the front was low, the strain at the flaw front was quite high. It is the strain at the flaw front that determines whether or not fracture initiates. One problem that arose from the introduction of residual and reaction stresses by welding was the difficulty in obtaining a uniform stress pattern between the two parallel welds. Although great care was taken to obtain uniformity in welding, the stopping and starting of an electrode or a difference in size of weld bead affected the magnitude of the residual stress.

No fractures were initiated from the 1-in. flaws. On the basis of the energy force concept, which seemed to correlate with the fractures longer than 1 in., it would be expected that a rather high stress would be required to initiate the fracture from the small 1-in. flaws. The methods used in this study did not produce sufficient stress to initiate fracture at the tips of the 1-in. flaws.

The test results from this study have shown that brittle fractures may initiate from weld flaws at applied stresses much lower than the yield strength of the material. It is very difficult to judge the largest flaw that can be tolerated in a welded structure such as a ship. The state of stress in the area of the flaw front is just as important as the length of the flaw, if not more so. For example, a relatively large flaw of about 16 in. that is contained in a structure so loaded that the tensile stress is parallel to the flaw (a uniaxial stress system) may never be the source of fracture initiation. In another instance, a 1-in. flaw in a ship deck-plate weld that joins a chock or some other attachment to the deck may be potentially dangerous because the state of stress is very complex (constrained in three dimensions). In order to initiate a brittle fracture in each of these cases, the test temperature must be below a certain value, the more complex the state of stress, the higher the temperature at which a brittle fracture might initiate. Of course, the size of the flaw has a direct effect on the state of stress at the flaw front; that is, the elastic stress concentration is increased for a given system with increase in flaw length. This is illustrated in this research by the fact that the applied fracture stress decreased with length of flaw.

In general, the data indicate that very close inspection should be exercised in critical areas (of high stress concentration) and weld flaws greater than 2 in. should be removed. Whereas, in other areas of a structure that are loaded uniaxially, larger weld flaws can be tolerated.

SUMMARY

The studies for the past year concentrated on the initiation of brittle fractures from flaws less than 4 in. in length. It was desirable to determine the effect of residual and reaction stresses on the applied stress required to initiate brittle fractures from various types of flaws.

It is believed that the term "reaction stresses" most clearly defines the stresses that were of most concern in this study. The various techniques, such as the welding and the mechanical devices that were used to give an auxiliary stress in the area of the flaw front, were discussed in detail in the body of the report. Generally, the stresses in the immediate vicinity of a weld deposit that are the result of welding are considered residual stresses, reaction stresses are the stresses resulting from two bodies acting against each other. This reaction

stress may be removed by separating the material between the two acting bodies In this work, weld deposits and a hydraulic ram were used as the acting bodies that produced the reaction stress.

Flaws having different radii at the point of initiation were studied in this investigation. Test specimens were prepared and tested in an attempt to simulate some of the service conditions that could exist and be the source of brittle fracture initiation at a low applied fracture stress

The following are the important findings with regard to the testing technique obtained from this investigation:

(1) Fractures were not initiated from flaws less than 4 in in length from the load (35,000 psi) applied only by hydrostatic pressure on the sphere. However, fractures were initiated from these flaws by superimposing an auxiliary stress in the material at the flaw front in addition to the stress produced from the hydrostatic pressure on the wall of the sphere

(2) Sufficient elastic energy was stored in the wall of the sphere (testing apparatus) to propagate the fracture through the ABS-B steel after it was initiated

(3) The steel of high notch-toughness in the sphere wall was capable of stopping the fracture without serious damage to the sphere

(4) Fast-running brittle fractures were deflected so that the fracture propagated in the weld joint between the test specimen and the sphere; this aided in preventing damage to the sphere wall

With regard to actual weld flaws and simulated weld flaws (jeweler's saw cuts), it may be concluded,

(1) Reaction and residual stresses can be an important part of the total stress required to initiate a fracture. The greater the reaction and residual stresses, the lower the applied stress required to initiate the fracture

(2) Length of flaw appeared to have little influence on the total stress (as measured at the flaw front) required to initiate fracture

(3) Sufficient residual and/or reaction stresses from welding were introduced in the area of flaw front to cause the initiation of brittle fracture at 6000 psi or less applied stress.

(4) Reaction stresses, applied by a mechanical mechanism similar to that used to jack plates in place during the fabrication of ships, contributed to the initiation of brittle fractures at $(\frac{PD}{4t})$ stresses of one-half or less the yield strength of the ABS-B steel.

(5) Considerable plastic strain occurred on the surface of the plate at the flaw front prior to the initiation of fracture In some specimens, the amount of plastic strain decreased with increase in severity of the crack or notch

(6) Less strain was recorded prior to fracture at the flaw front of buried flaws (as measured by strain gages on the plate surface), than for full-depth flaws. The exact sequence and progress of fracture was not determined.

(7) The closer the state of stress at the flaw front approaches triaxiality the lower the applied fracture stress. For example, the applied fracture stress of a "through-plate" welded structure was 6000 psi, as compared with 33,000 psi for a flaw of equal length stressed in biaxial tension only

(8) The data indicate that weld flaws greater than 2 in. may be dangerous and may be the source of fracture initiation, provided the flaw front is in a sufficiently triaxial stress field In a biaxial tension stress field, flaws 4 in. or greater in length may be the source of brittle fracture initiation at applied fracture stresses lower than the yield strength of the ABS-B steel. By introducing a third structural member, thereby decreasing the opportunity for plastic strain, the applied stress required for fracture was as low as 10 to 15 per cent of the yield strength of the ship steel

(9) This study has shown that it is quite difficult to initiate brittle fractures from flaws less than 4 in. in length. In structures that are stressed in biaxial tension, it appears that rather large flaws could be tolerated. Furthermore, there are without doubt areas in a ship structure where the state of stress is even less complicated than biaxial tension, and the total stress is very low at all times. In these areas, rather large flaws may not be harmful. Basically, the information gained in this study illustrates that if the designer has a general idea of the state of stress in a welded structure, he can predict the limitations of the soundness requirements of the weld deposit. In some areas of a structure, it may be virtually impossible to design so that some degree of triaxiality does not exist. In these areas, very close inspection should be exercised, because a very small flaw may be potentially dangerous.

FUTURE WORK

It has been demonstrated that residual or reaction stresses play a very important role in the total stress required to initiate brittle fracture. As the state of stress at the flaw [illegible] approaches triaxial tension, the applied stress level required to initiate fracture decreases. Experiments should be designed where only [illegible] [illegible] stress exist [illegible] applied [illegible] [illegible] [illegible] of pursuing further work in this direction [illegible] seems that [illegible] consideration [illegible] be given to methods of reducing the residual [illegible] stresses that are known to exist in welded structures. Perhaps [illegible] [illegible] redistributed over a greater volume of metal so that [illegible] magnitude [illegible] [illegible].

[illegible] [illegible] [illegible] [illegible] to the [illegible] [illegible] metal being tested. If a [illegible] [illegible] [illegible] the duplication of [illegible] [illegible] [illegible] work [illegible] in this report, the volume of metal under [illegible] [illegible].

stress was relatively small, so that on application of the tensile load, there was probably a redistribution of stresses that permitted the original highly stressed material to strain in a non-linear manner. If a greater amount of material in the region of the flaw front were subjected to residual stress brittle fracture might occur at even lower applied stresses than were recorded in this study.

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REFERENCES

1. Martin, D. C., Ryan, R. S., and Rieppel, P. J., Evaluation of Weld-Joint Flaws as Initiating Points of Brittle Fractures (Ship Structure Committee Report Serial No. SSC-86), Washington: National Academy of Sciences-National Research Council, September 4, 1956.

2. Ginsberg, F., Foster, M. L., and Imbembo, E. A., Notch Toughness Properties and Other Characteristics of Medium Steel Ship Plate, Technical Report on Lab. Project 4936-94, Brooklyn: New York Naval Shipyard, August 31, 1954.

3. Williams, M. L., Meyerson, M. R., Kluge, G. L., and Dale, L. R., Investigation of Fractured Steel Plates Removed from Welded Ships (Ship Structure Committee Report Serial No. NBS-3), June 1, 1951.

4. Irwin, G. R., and Kies, J. A., "Critical Energy Rate Analysis of Fracture Strength," The Welding Journal, 33:4, Research Supplement, 193s-198s (April, 1954).

APPENDIX A

MECHANICAL PROPERTIES OF CARILLOY T-1 STEEL: FABRICATION DETAILS, AND OTHER PERTINENT DATA OF THE SPHERE

Physical Properties of the Steel

A high-yield-strength alloy steel, United States Steel Corporation's T-1, was used in the fabrication of the sphere. The chemical and mechanical properties are shown in Table A-1.

TABLE A-1 PHYSICAL PROPERTIES OF CARILLOY 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 inches, 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 A-2.

TABLE A-2. SUMMARY OF DUCTILITY AND FRACTURE TRANSITION TEMPERATURES FOR 1/2- AND 1-INCH QUENCHED AND TEMPERED CARILLOY T-1 STEEL

Plate Thickness, inches	Kinzel-Type Notch-Bend Test Unwelded	Kinzel-Type Notch-Bend Test E12015	Kinzel-Type Notch-Bend Test E6010	Tee-Bend Test E12015	Tee-Bend Test E6010
	Ductility Transition Temperature, F				
1/2	-132±26	-78±4	-84±4	Approx. -180	-123±28
1	Below -143	-72±8	-76±16	Approx. -141	-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

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

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

Plate Thickness, inches	Condition	Orientation of Specimen	Yield Strength, psi	Tensile Strength, psi	Elongation, % 2"	Elongation, % 8"	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	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.

All joints in the sphere were [illegible] smooth and radiographed. Two connections were welded into the top half 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.

Capacity of Sphere

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

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

where V = volume

r = inside radius

TABLE A-4 VOLUME OF SPHERE

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

Nominal Stress in a Sphere

The stress in the walls of a sphere subjected to internal pressure is:

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

where σ_1, σ_2 = stress

P = internal pressure

D = outside diameter

t = wall thickness

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

Change in Volume Resulting from Internal Pressure

Symbols -

C = circumference

D = outside diameter

E = modulus of elasticity

P = internal pressure

r = radius

t = wall thickness

u = Poisson's ratio

V = volume

ΔV = change in volume

ϵ = strain

σ = stress

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

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

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

$$C_o = 2\pi r_o$$

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

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

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

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

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

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

$$V = 4/3\pi\,(r_c^3 - r_o^3)$$

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

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

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

<u>Change in Volume Owing to Compressibility of Liquid</u>

Since compressibility is the reciprocal of the bulk modulus

$$K = \frac{(V_1 - V_2) / V_1}{P_2 - P_1} = \frac{\Delta V}{V_1 \Delta P}$$

$$\Delta V = K V_1 \Delta P$$

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

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

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

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

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

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

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

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

TABLE A-5 STRESS AND VOLUME INCREASE RESULTING FROM PRESSURE

Pressure psi	Nominal Stress psi	Liquid Volume Increase Compressibility cu in	gal	Sphere Volume Increase Internal Pressure cu in.	gal	Total Increase 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	[illegible]
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, 240	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	[illegible]
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	691	3.0	19.2

Potential Energy in Sphere at Various Pressures

The potential energy was calculated from the following formulas

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

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

Where E = modulus of elasticity, psi

K = bulk modulus

P = internal pressure, psi

u = Poisson's ratio

V = volume, cu in.

σ = stress, psi

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

TABLE A-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	[illegible]
1,500	55,000	1,725,000	2,015,000	3,740,000

Composition of Liquid

Calcium chloride ($CaCl_2$) 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 A-7. The solution was inhibited against corrosion with sodium dichromate and sodium hydroxide. The position of the cooling coils within the sphere is shown in Figure A-1.

TABLE A-7. COMPOSITION, BY WEIGHT, OF LIQUID IN SPHERE

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

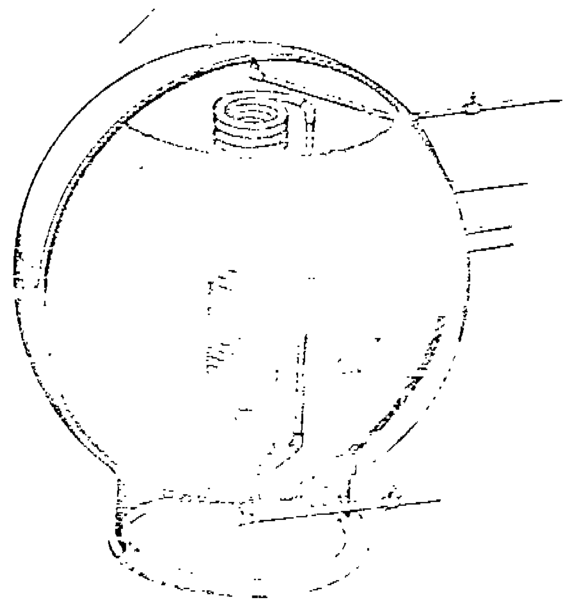

FIGURE A-1. CROSS SECTION [illegible] SPHERE [illegible] LOCATION OF COOLING COIL

APPENDIX B

CIRCULAR-PATCH STUDIES

Miscellaneous Tests

The circular-patch type of configuration was considered as one method of producing residual and reaction stresses in the area of the flaw front. A sketch of the specimen is shown in Fig. B-1. This type of specimen was chosen because the magnitude of residual stresses at the center of the specimen can be varied by changing the diameter of the circular weld.* The smaller the diameter of the circular patch with respect to the over-all size of specimen, the greater the stress at the flaw front in the central area of the patch. High-temperature strain gages were used to measure the strain in this type of specimen.

A test specimen was prepared with a 9-in. diameter circular patch. A 4-in. longitudinal flaw was fabricated into the center of the patch, and the patch was then welded into the 23-in.-diameter disk specimen. High-temperature strain gages were installed to record the strain in the patch. However, these gages failed during the welding of the patch into the specimen. Consequently, the residual stress from welding the circular patch was not known. A stress of 33,000 psi was applied to the specimen by hydrostatic pressure without the initiation of a brittle fracture. The pressure was released on the sphere and additional weld deposits made on the circular patch to increase further the stress at the flaw front. During the retesting of the specimen, a brittle fracture was initiated at approximately 32,000 psi. The fracture propagated for approximately 1 in. and stopped. One possible explanation for stopping of the flaw was that the flaw front encountered a compressive stress field adjacent to the circular weld. A second test was made in which the circular patch diameter was increased to 10 1/2 in. and the maximum applied stress was increased to 36,600 psi. A brittle

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*Levy, Alan V., and Kennedy, Harry E., "Stresses in Circular-Patch Weld-Test Specimens," The Welding Journal, 31 9, Research Supplement, 402s--405s (September, 1952).

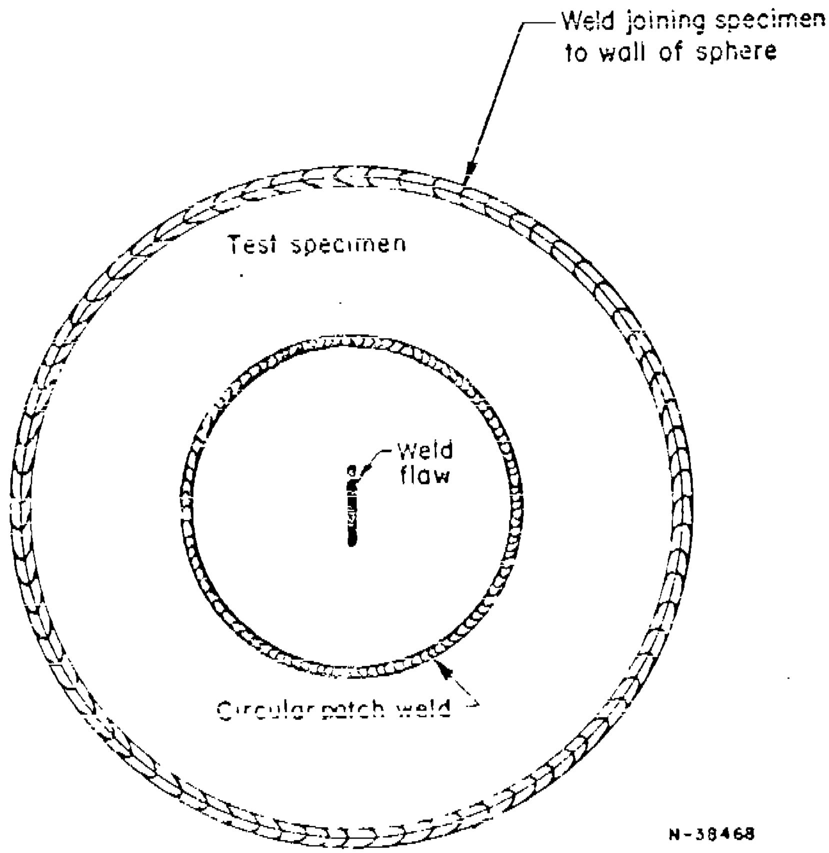

FIGURE B-1. SKETCH SHOWING THE USE OF A CIRCULAR PATCH CONFIGURATION TO PRODUCE RESIDUAL AND REACTION STRESSES AT THE FLAW FRONT fracture failed to initiate from this specimen. The circular patch method of applying a residual stress at the flaw front was abandoned because of the unsatisfactory results obtained from these tests. As has been stated in other sections of this report, welding and a mechanical device were more satisfactory for applying residual and reaction stresses.

In many instances, transverse weld cracks are considered to be very dangerous as sites for the initiation of catastrophic failures. It is well known that the longitudinal residual stresses in a weld deposit approach the yield strength. These stresses are of course responsible for the transverse cracks. It is also believed that very high stresses remain at the tips of a transverse crack and that this crack might thus reinitiate under low applied stress. To explore this condition, a specimen containing two 1-in. transverse weld cracks was prepared and welded to the sphere. The sphere was loaded by hydrostatic pressure to an applied stress of 35,000 psi without initiating a brittle fracture at the weld cracks. The test was repeated after additional residual stress was applied by the hydraulic ram. A fracture failed to initiate from this test also.

APPENDIX C

RESULTS OF TESTS MADE ON ABS CLASS B STEEL
TO INVESTIGATE THE INFLUENCE OF REACTION AND [illegible] ON THE FRE[illegible] SURRO[illegible] LOW STRESS BRITTLE FRACTURE

[illegible]

[illegible]