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OPERATION HARDTACK—PROJECT 3.5

Loading and Response of Submarine Hulls from Underwater Bursts

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This project involved the measurement of the loading, strain, deformation, and damage to the hull of a submarine-like target resulting from planned near lethal attack during Shot Umbrella. It also involved the measurement of hull strains in an operating submarine in simulated attack positions during Shots Wahoo and Umbrella.

The objectives established for this project were:(1) to determine the range for lethal hull damage to a submarine-like target under attack in shallow water by an antisubmarine nuclear weapon; (2) to study the process of hull damage to a submerged target for correlation with observed pressure and existing approximate theories and empirical formulas; and (3) to determine the response of the hull of a submarine in simulated attack position in both deep and shallow water.

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FOREWORD

Classified material has been removed in order to make the information available on an unclassified, open publication basis, to any interested parties. The effort to declassify this report has been accomplished specifically to support the Department of Defense Nuclear Test Personnel Review (NTPR) Program. The objective is to facilitate studies of the low levels of radiation received by some individuals during the atmospheric nuclear test program by making as much information as possible available to all interested parties.

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OPERATION HARDTACK—PROJECT 3.5

LOADING and RESPONSE of SUBMARINE HULLS from UNDERWATER BURSTS

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FOREWORD

This report presents the final results of one of the projects participating in the military-effect programs of Operation Hardtack. Overall information about this and the other military-effect projects can be obtained from ITR-1660, the "Summary Report of the Commander, Task Unit 3." This technical summary includes: (1) tables listing each detonation with its yield, type, environment, meteorological conditions, etc.; (2) maps showing shot locations; (3) discussions of results by programs; (4) summaries of objectives, procedures, results, etc., for all projects; and (5) a listing of project reports for the military-effect programs.

ABSTRACT

Project 3.5 participated during Shots Wahoo and Umbrella in order to: (1) determine the hull lethal range for nuclear weapon attack on submarines in shallow water, (2) study the process of hull damage to a submerged target for correlation with observed pressure and theory, and (3) determine the hull response of an operating submarine in simulated attack position.

The only submerged target in the ship array for Shot Wahoo was the USS Bonita, SSK 3, which was manned at 18,000 feet. The maximum hull strain observed during the test was 0.23 per thousand compressive; i.e., well below the elastic limit. It was produced by the pressure wave reflected from the ocean bottom.

For Shot Umbrella, the USS Bonita was not manned and was located bow-on at 2,880 feet. The maximum compressional hull strain was 0.36 per thousand. No permanent hull deformations occurred.

The principal submerged target for Shot Umbrella was Squaw 29, a four-fifths-scale short model of SS 567, placed at 1,680 feet. This target was instrumented with 23 strain gages, 10 pressure gages, 4 deflection gages, 9 high-speed cameras, and roll, pitch, depth, and flooding indicators.

The maximum hull strain observed was 13.8 per thousand in compression. The peak pressure measured in the tanks was 1,340 psi. Pressures associated with the closure of cavitation were also observed in the tanks and caused additional permanent set.

The operations of Project 3.5 were successful. The data combined with the observed damage allow some refinement of estimates for safe delivery and damaging ranges. One of the main objectives was not realized in that Squaw 29 was not severely damaged. The data allows correlation of load and response for conditions of small damage, rather than for the more-useful case of large damage.

The following conclusions are based on the Operation Hardtack data. (It should be understood that the terms "Wahoo conditions" and "Umbrella conditions" include the yield, shot geometries, the bottom-reflection characteristics, and water-temperature gradients for these tests. Furthermore the damage ranges throughout this report are only for hull damage. Damage to equipment would occur at other ranges as discussed in the report of Project 3.3.)

Under Shot Umbrella conditions, a target such as Squaw 29 would survive

The hull lethal range is estimated   to the nearest portion of the hull. At close ranges, the pressure produced by cavitation closure could supply the killing load to a substantially damaged target. The small degree of damage sustained is in agreement with predictions based on Crossroads Baker results and Snay's pressure estimates. It also agrees with estimates based on the observed pressures and excess impulse and shock factor concepts.

Under Shot Umbrella conditions, the USS Bonita could deliver, without sustaining hull damage,

It is estimated that USS Bonita would not have sustained hull damage   from surface zero under Shot Wahoo conditions.

The hull damaging radii for nuclear weapons in shallow water are small relative to the radii for deeply submerged detonations. The lethal radius in shallow water probably increases only slowly with yield.

PREFACE

This project was executed by personnel from the Structural Mechanics Laboratory of the David Taylor Model Basin assisted by F. B. Miller and B. F. von Bernewitz. Important contributions during the operations were made by K. T. Cornelius.

The damage survey of Squaw 29 was made under the direction of C. M. Atchison of the Model Basin, by personnel of the Pearl Harbor Naval Shipyard, which also provided photographic coverage.

The staff of the Naval Repair Facility at San Diego, California, where the targets were outfitted, gave splendid cooperation. Lt T. L. Moore, USN, of the Planning Department, and LTJG H. T. Howard, USN, Ship's Superintendent, deserve particular notice for their assistance.

The cooperation of the officers and crew of USS Bonita (SSK 3) and the commanding officer and crew of YFNB 12 is gratefully acknowledged.

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Chapter 1
INTRODUCTION

Project 3.5 involved the measurement of the loading, strain, deformation, and damage to the hull of a submarine-like target, Squaw 29, resulting from planned near-lethal attack during Shot Umbrella. It also involved the measurement of hull strains in an operating submarine in simulated attack positions during Shots Wahoo and Umbrella. The Squaw 29 was a $^4/_5$-scale hull, cross-section short model of SS 563, class submarine, which had been built for Operation Wigwam. The operating submarine was the USS Bonita, SSK 3; it was manned during Shot Wahoo, the deep-water shot, and unmanned during Shot Umbrella.

1.1 OBJECTIVES

The objectives established for Project 3.5 were to: (1) determine the range for lethal hull damage to a submarine-like (Squaw) target under attack in shallow water by an antisubmarine nuclear weapon; (2) study the process of hull damage to a submerged target for correlation with observed pressure and existing approximate theories and empirical formulas; and (3) determine the response of the hull of a submarine in simulated attack position in both deep and shallow water.

The first of the above objectives was one of the principal aims of Shot Umbrella. In effect, successful attainment of this objective would result in evaluation of a nuclear weapon as an antisubmarine device in shallow water. The information obtained should also be valuable for planning tactics in antisubmarine warfare.

The second objective was probably as important as the first: understanding of the process of hull damage, correlation of damage with observed pressures, and proof or disproof of hypotheses are necessary for obtaining lethal radius estimates for generalized submerged targets under generalized nuclear attack.

The third objective resulted from the inclusion in the ship array of the USS Bonita for both Shots Wahoo and Umbrella. This submarine was included primarily to demonstrate shock-safe delivery ranges for a nuclear weapon. Although it was thought that shock damage to equipment would control the safe range, it seemed desirable to study the response of the hull also. A few strain measurements were made on the pressure-hull plating in a typical bay and at a previously determined weak spot in the forward torpedo room (Reference 1). These measurements were intended to provide data for a comparison of the effects of dynamic and static pressure loading of the hull.

1.2 BACKGROUND

Shot Baker, Operation Crossroads, was the first test involving underwater nuclear attack against submerged submarines. In this test there were submarines of both the SS 212 class and the SS 285 class (Reference 2). Valuable information on lethal radii was obtained. The information, however, was not complete, but was suggestive of what might be expected for nuclear attack in shallow water. The test data did not include definitive pressure-time measurements in the water nor hull response as a function of time. The data on damage furnished reference points, but extrapolation to other targets, other sizes of charge, other depths of water and charge, and other types of bottom could not be made with assurance.

The data from Operation Wigwam is of value, because of its indications concerning submarine damage in deep water from relatively deep bursts (Reference 3). Environmental effects during Operation Wigwam were much less complicated, and the pressure from the bomb was much less subject to erosion by free surface effects than during the shallow-water test of Operation Crossroads. Accordingly, the pressure in the deep-water test was that expected in a free field, except for linear surface cutoff and refraction. Wigwam results are therefore not directly applicable to the Operation Hardtack, Shot Umbrella geometry. In fact, the peak pressure for hull crushing during Shot Umbrella, estimated prior to the shot, was about twice that considered to be lethal during Operation Wigwam.

Shot Umbrella differed from Crossroads Baker in that for Umbrella the nuclear device was on the bottom, rather than at middepth, the rated yield was rather than 20 kt, and the water depth was 140 feet, rather than 180 feet.

Other experimental and analytical studies have been made to predict the lethal range of submarines under nuclear attack (Reference 3). The theories and results are not conclusive and, in general, apply to deeply submerged targets and relatively deep bomb bursts, where free-field conditions and linear cutoff theory can be applied. For shallow burst and shallow target submergence, there are nonlinear propagation and cutoff effects. The loads are of brief duration. The theory for hull collapse under these conditions is tentative, and the experimental results are not definitive.

1.3 THEORY

When a nuclear weapon or other charge is detonated in relatively shallow water, the generated pressures are subject to effects rising from the air-water interface and the floor of the test area. At depths of the order of Eniwetok Lagoon, the presence of the air-water surface nearby results in erosion of the pressure by a nonlinear process first described by Penney (Reference 2). This phenomenon differs from the ordinary acoustical effects at an air-water surface where linear cutoff occurs. In the linear case, the peak pressure is the same as that in a free field, but the shock wave is cut off as it decays by the reflection of a negative pressure wave from the air-water surface. In the nonlinear case, the reflected wave, in effect, travels within the direct wave so that the peak pressure is reduced. Cutoff occurs, but relatively late so that the duration is longer.

In the Umbrella case, the presence of the bottom also altered the pressures to be expected. Estimates of the expected pressure, including effects of both the bottom and the free surface, were made prior to the test in References 4 and 5. Reference 4 includes an estimate of the time history, but the later calculations of Reference 5 omit time dependency. The calculations were very valuable, as they indicated the decay of pressure with distance. However, their value for estimating lethal ranges was mitigated, because of uncertainty with regard to variation of pressure with time.

In view of the lack of precise knowledge concerning the pressure field, pressure-time measurements were made by other projects in Operation Hardtack (References 6 and 7). Measurements of the load pressures in the tanks were made by Project 3.5 and are reported herein.

It is not sufficient to know pressure-time history in order to arrive at an estimate of lethal range. An additional requirement is a theory relating plastic response of a submarine hull to pressure waves of short duration. There is no adequate theory for the damage process. Several empirical rules have been proposed, but they have not been verified by experiment. A brief discussion of some of these hypotheses follows.

The excess-impulse hypothesis has been proposed by several authors. It may be useful in extrapolating between similar cases. However, the Wigwam data may or may not fit the hypothesis (References 3 and 8). The circumstances under which it applies, means for predicting critical values of excess impulse, and the accuracy of extrapolation have not been established.

The peak-pressure concept used by the Taylor Model Basin in making predictions for Operation Wigwam (Reference 9) was considered not applicable in Operation Hardtack, Shot Umbrella, because of the relatively short duration of the pressure pulse.

An empirical formula has been proposed by Chertock for making predictions for exponential pressure waves not too different from those studied during Operation Wigwam (Reference 3). This formula also has not been verified for pressure waves of such duration as those from Shot Umbrella. For a more complete discussion the reader is referred to Reference 3.

Thus, there were two difficulties which rendered theoretical estimates of lethal range uncertain: (1) the variation of pressure with time was not known; (2) the theories of plastic response had not been confirmed. Accordingly, prior to Shot Umbrella it appeared preferable to estimate the lethal range by extrapolating Crossroads Baker data. Such estimates are derived in Section 1.4.

Measurements of the hull response of Squaw 29 during Shot Umbrella were considered to be most desirable for the insight they might yield concerning the damage process. Strain and deflection measurements give a time history of damage and increased understanding of the damage process. Correlation with pressure-time history casts light on existing theories and possibly permits founding of an improved theory.

1.4 SELECTION OF TARGET RANGES

The ranges for the target ships in the arrays for Shots Wahoo and Umbrella were established mainly by a special positioning panel sponsored by the Armed Forces Special Weapons Project (AFSWP).[1] It is instructive to review some of the considerations entering into selection of the ranges by the panel.

[1] The panel consisted of CAPT C.G. Mendenhall, USN, Chairman; LCDR J.F. Clarke, CEC, USN, Secretary; CDR R.C. Gooding, USN, Lt Col E. Pickering, USA, or his alternate, CDR R. Gonzalez, USN; A.H. Keil; W.J. Sette; and W.J. Thaler.

[2] A better estimate for the Baker yield is 23.5 kt.

Another estimate of range could have been based on the predicted peak pressures. Reference 5 indicated that the desired value should have been expected to occur The Squaw might have been placed at this distance. However, the tentative duration estimates of Reference 4 would suggest that a substantially smaller range would be needed for quasi-lethal damage.

The range of USS Bonita for Shot Umbrella was established by the performance of USS Searaven, SS 196, during Crossroads Baker. This submarine sustained only minor shock damage at 4,200 feet. The peak pressure, at this target during the Crossroads detonation was expected to occur during Shot Umbrella feet, Reference 5. It was accordingly believed that the shock on USS Bonita might be similar to that on USS Searaven at 4,200 feet. The static collapse pressure of USS Searaven was nominally 235 psi, so that hull damage was not expected on the Bonita, which has a static collapse pressure of about 310 psi.

The range of USS Bonita, with a crew aboard, during Shot Wahoo was 18,000 feet. This figure greatly exceeded the range considered safe. In the preliminary planning of the test, the test range was established at 10,500 feet and the crew was not to be aboard. Difficulties during the test led to a change of plan. At 10,500 feet the peak pressure in the direct shock wave (assuming isovelocity water) was expected to be Because cutoff would occur in about there was little question of hull damage. The pressure in any waves reflected from the bottom was not expected to exceed so that hull damage from this source was unlikely.

Chapter 2
PROCEDURE

2.1 OPERATIONS

Measurements were made on Squaw 29 during Shot Umbrella only and on USS Bonita during both Operation Hardtack underwater shots. Both targets were submerged approximately to periscope depth.

The Squaw was submerged remotely from its associated instrument barge, the YFNB 12. Submergence was accomplished by venting ballast tanks on the Squaw through air hoses connected to a manifold on the barge. With all ballast tanks completely flooded and trim tanks partially flooded, the Squaw, with its external keel (weight 105 tons) had a positive buoyancy of approximately 5 tons. Additional clumps of weights were attached to chains and hung from the Squaw at the bow and stern, 5 tons at each end. These additional weights made the Squaw negatively buoyant and pulled her down. When the clumps rested on the bottom, the Squaw was suspended at the proper depth. The YFNB was 2,300 feet upwind from surface zero.

For Shot Umbrella, USS Bonita was unmanned and submerged in a manner somewhat similar to the Squaw. Concrete clumps were suspended from chains at the bow and stern, and the ship was trimmed by the crew so that it would descend until the clumps rested on the bottom. The ship was then brought to the surface by blowing two main ballast tanks. The crew departed after opening valves, which allowed the ballast tanks to reflood slowly. After the test, divers blew two main ballast tanks by opening two external valves. These valves were part of a specially installed system connecting high pressure air within the Bonita to the main ballast tanks.

During Shot Wahoo, USS Bonita was operated by its crew at 18,000 feet from surface zero. This was a change from the original plan, which had it moored at 10,500 feet. This change was necessitated by the loss of mooring cables, due to unexpected rough sea conditions.

2.2 TARGETS

2.2.1 Squaw. The Squaw 29 is the only remaining one of the three submarine-like targets built for the Wigwam test by the Long Beach Naval Shipyard (Reference 13). It consists of two cylindrical compartments and two conical end sections. The former are similar in design to the SS 563 class of submarine on 0.8 scale, except that the Squaw is internally framed. Internal and external views of a Squaw are shown in Figures 2.1 and 2.2. Figure 2.3 illustrates the general arrangement. Internal measurements were made mainly in the cylindrical ("test") compartments.

Significant design features are: diameter of pressure hull (inside), 14 feet $4\frac{3}{4}$ inches; length of pressure hull, 121.5 feet; hull plating, 1 inch HTS with a yield strength of 56,000 psi; frame spacing, test sections, 29 inches; frames, as shown in Figure 2.4; length of each compartment, 29 feet.

Ten ballast tanks outside the pressure hull extend the length of the Squaw. They cover the pressure hull up to 32 degrees, port and starboard, from the crown.

Special efforts were made to achieve circularity of the pressure hull. Measurements made during the construction and upon the completion of Squaw 29 (Reference 13) showed that the eccentricity did not exceed the specification of $\pm \frac{1}{2}$ inch; i.e. $\pm \frac{1}{2}$ the shell thickness. A typical measurement of circularity for the finished Squaw is shown in Figure 2.5.

The static collapse pressure of the circular sections was computed to be 655 psi (Reference 3). This figure is a weighted average of values obtained by several methods.

Inside the Squaw, major items of the propulsion machinery of the SS 567 (of later type than those on SS 563) were simulated on four-fifths scale by cast-steel weights. Items simulated were

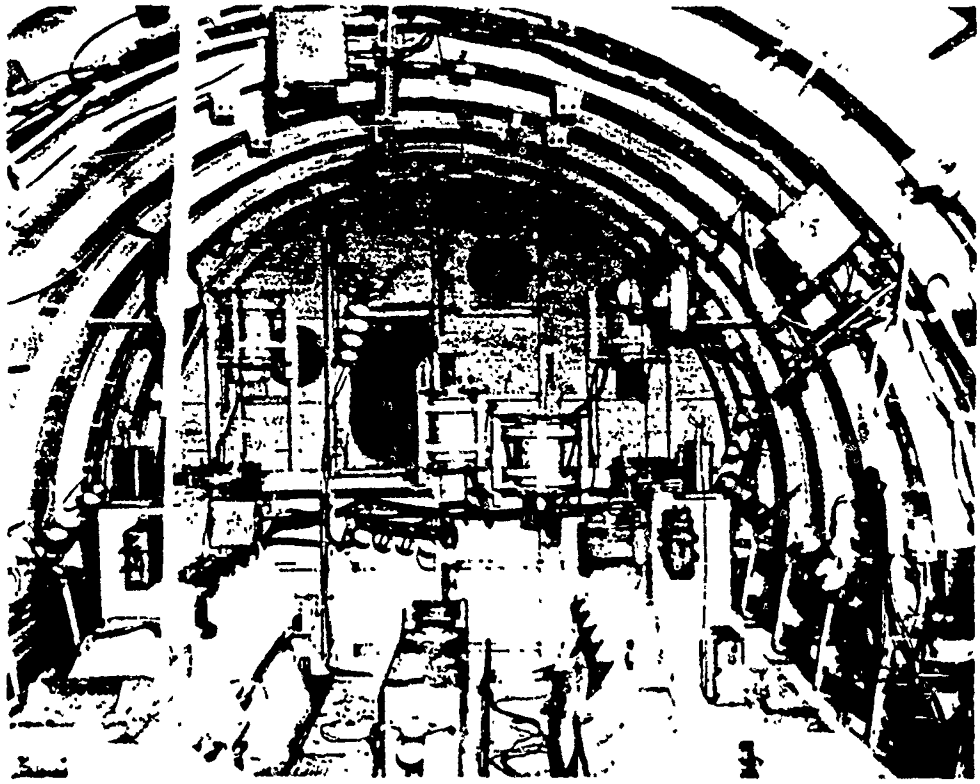


Figure 2.1 View of interior of engine compartment of Squaw 29.

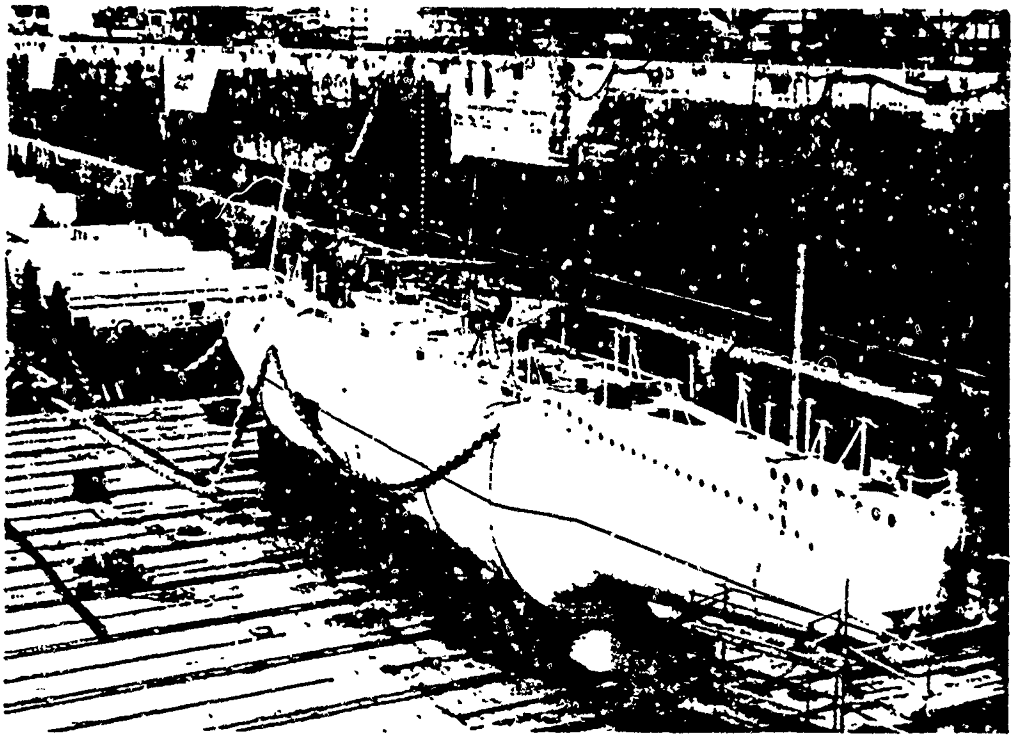


Figure 2.2 View of Squaw in drydock before Operation Wigwam.

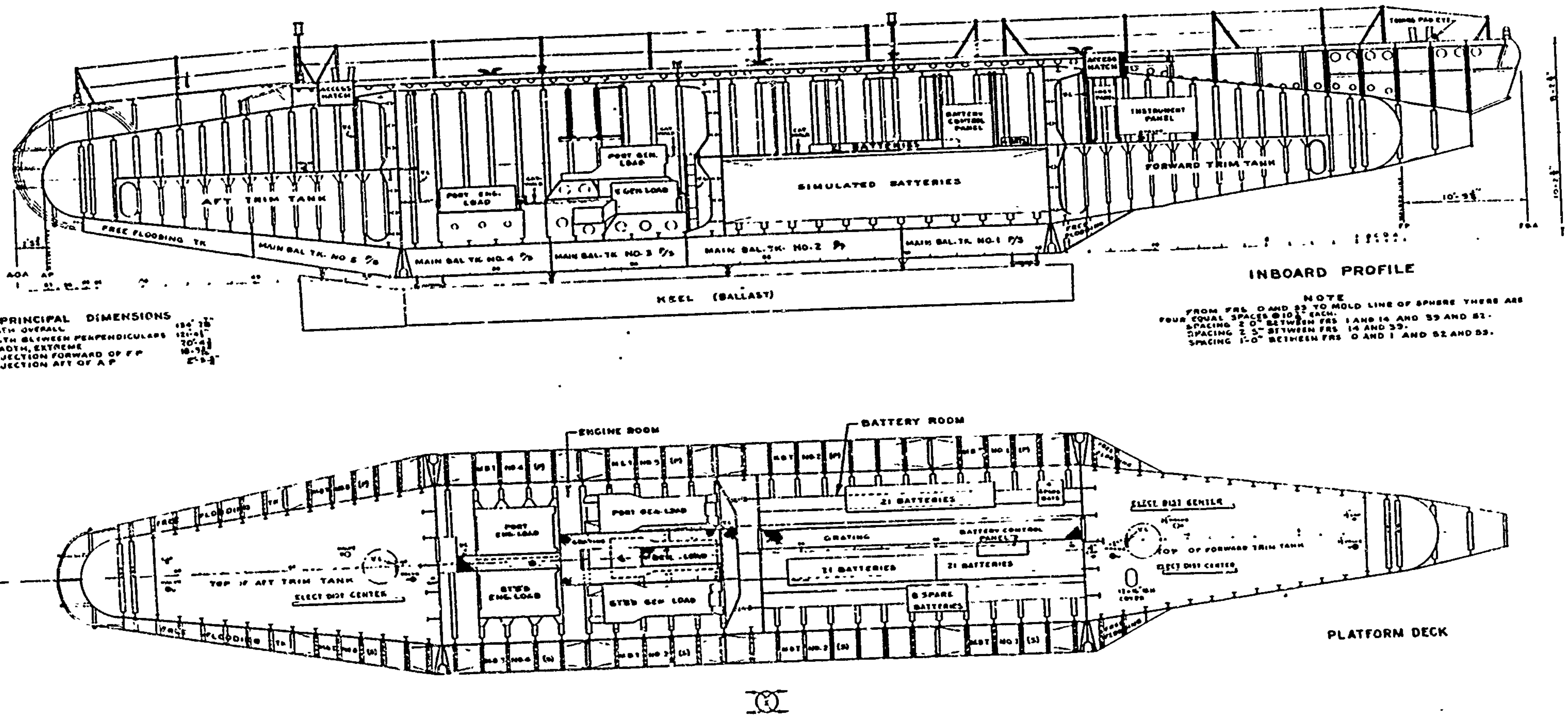


Figure 2.3 Longitudinal profile and plan views of Squaw showing general arrangement.

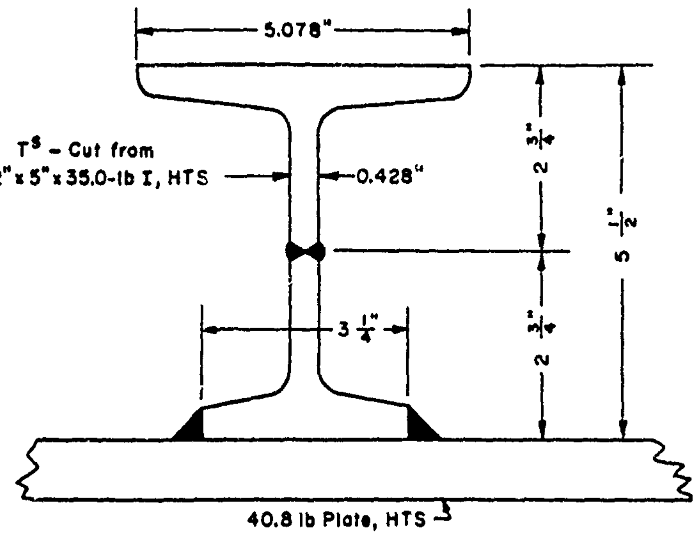


Figure 2.4 Typical frame in cylindrical compartments of Squaw.

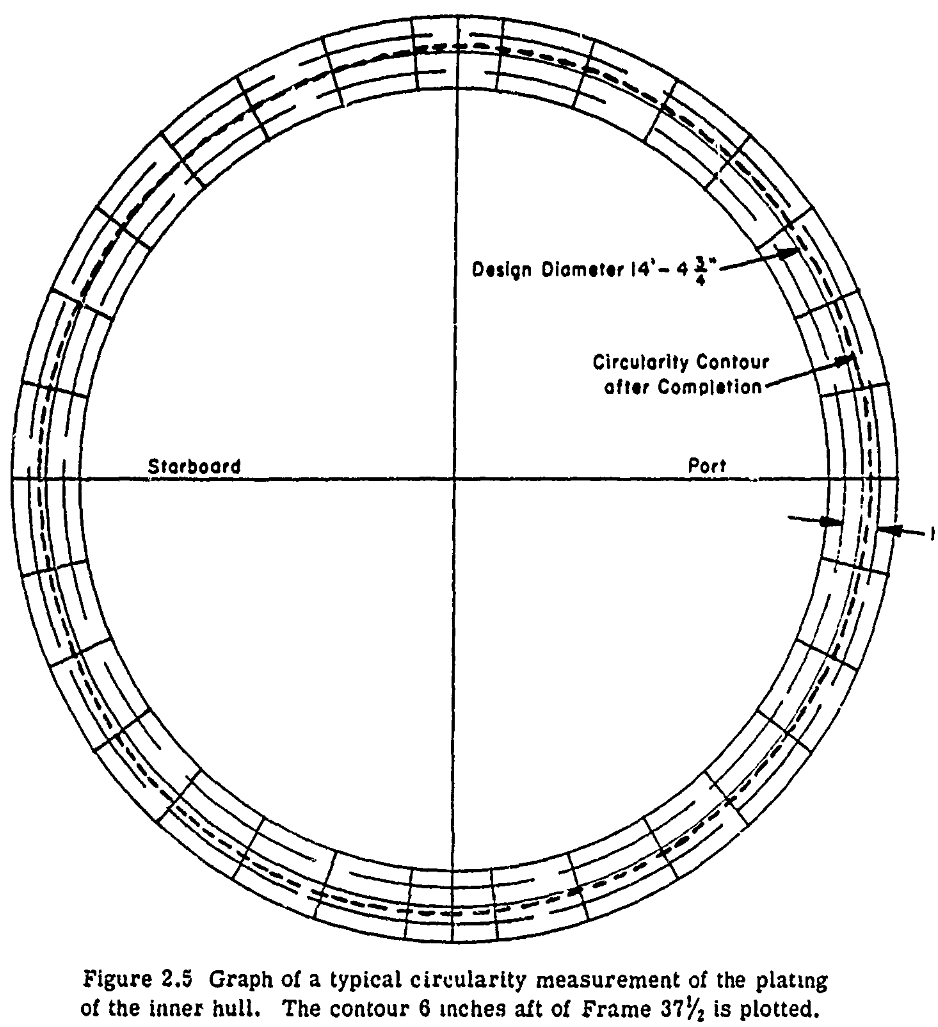


Figure 2.5 Graph of a typical circularity measurement of the plating of the inner hull. The contour 6 inches aft of Frame 37½ is plotted.

the three main engine-generators and the two propulsion motors, all located in the after test section. Each simulated engine-generator weighed 11,900 pounds and each of the simulated motors weighed 25,000 pounds. Each weight was bolted to a foundation scaled from the SS 567. The port engine-generator was isolated from its foundation by means of six EES Type A6L resilient mountings. The other weights were bolted directly to the foundations.

2.2.2 The USS Bonita, SSK 3. The inner pressure hull of the Bonita has a diameter of 15 feet and is fabricated from medium steel (7/8 inch thick) with a yield strength of 34,000 psi. The frames

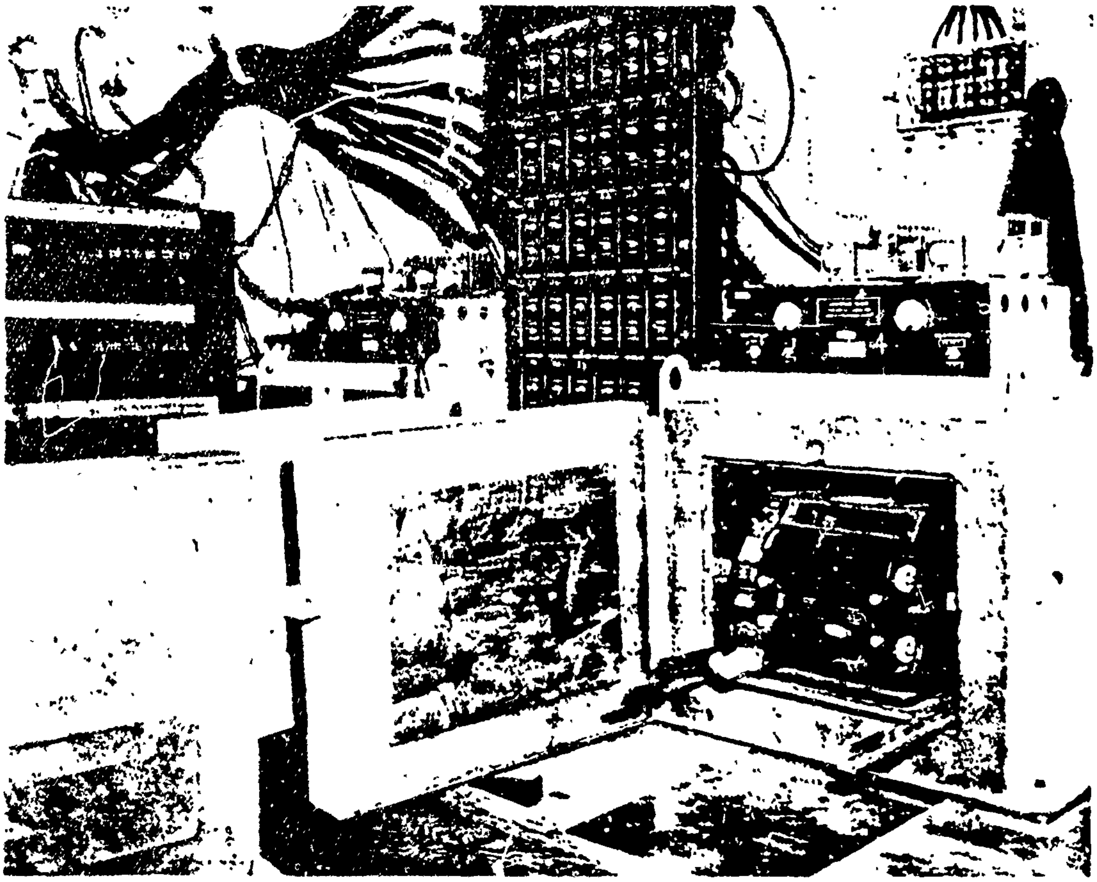


Figure 2.6 View of oscillograph inside lead housing, the walls of which are three inches thick. The unit is located on a shock mounted table.

(6 inches × 6 inches × 22½ pound H sections) are external and spaced 36 inches on centers. At both ends the SSK is single-hulled, circular in section, and internally framed with a frame spacing of 24 inches. The collapse pressure is about 310 psi, Reference 1.

2.3 INSTRUMENTATION

The instrumentation on Squaw 29 for Hardtack was essentially the same as for Wigwam, (References 3, 14, 15, and 16). Deformation of the hull plating and stiffeners was measured with strain gages and variable-reluctance displacement gages. The pressure near the hull was measured with piezoelectric pressure gages. Overall motions of the hull and stiffeners were photographed with high-speed motion-picture cameras. Roll, pitch, depth, and flooding conditions were recorded by means of angle indicators, potentiometer-type pressure gages, and conduction-type flooding gages.

The signals from all pickups on the Squaw were transmitted over three special multiconductor instrument cables to amplifiers and recorders located in a recording center on YFNB 12. Several types of recording systems were used to record the signals. Carrier amplifiers and electromagnetic oscillographs were used with the strain and displacement gages. The signals from roll, pitch, depth, and flooding pickups were recorded directly on oscillographs. Frequency-modulated magnetic-tape recorders were used to record the signals from the pressure gages. The recording film in the oscillographs was protected from radiation by special lead shields, Figure 2.6. All recording instruments were protected from shock motions of the YFNB by being mounted on a special shock-attenuating table (Reference 17).

Strain gages were installed on the USS Bonita to measure the deformation of hull plating and stiffeners. The signals from these gages were amplified and recorded on string oscillographs located in the sonar room in the submarine. Project 3.5 had no other instrumentation on Squaw 29.

Operation of all instruments on both targets during Shot Umbrella was controlled by sequence timers triggered by radio signals supplied by the Edgerton, Germeshausen, and Grier, Inc., (EG&G). Signals were brought into the instrument center on YFNB 12, where they started timers that operated the instruments on Squaw 29. The timing signals for Bonita were received on a YC barge on the surface and carried to sequence timers in the submarine over TTRS-16A cable. For Shot Wahoo, the sequence timers on the Bonita were started manually by a crew member. Power for all instruments on both targets was supplied by storage batteries.

2.3.1 Strain Gages. The active strain gages used were SR-4 Type A-9. This gage has a base length of 6 inches and a resistance of 300 ohms. Type A-2 with a resistance of 300 ohms were used as dummy gages.

All strain gages were wired into four-arm Wheatstone bridges. Most bridges contained one active arm and three dummy gages.

The dummy gages were mounted on 1-by-3-by-3-inch steel blocks placed near the active gages. The complete bridge was wired to a terminal strip attached to the dummy block. Therefore the only long leads were in the power and detector leads, not in the bridge arms.

The bridge circuits were calibrated by shunting a large resistance across one arm. The calibration controls were located in the carrier amplifiers on YFNB 12. Therefore, an allowance was required for the effect of the long leads between the gages and the amplifiers (Reference 3). The signal caused by shunting a resistor across one arm of the bridge is the same as a signal caused by a strain.

$$E_0 = \frac{R}{4R_cF}\left(\frac{R + 2R_l}{R}\right)^2$$

Where: R = the gage resistance

R_c = the calibration resistance

R_l = the resistance of each lead.

For a four-arm bridge with one active arm

$$F = \frac{\text{Gage Factor}}{4} = \frac{2.09}{4} = 0.522$$

The cables used in this test had a resistance of 8 ohms, which reduced the signal by about 10 percent.

About 50 percent of the gages used had been installed for Operation Wigwam. They were found to be still in good condition prior to Hardtack.

All strain gages used on USS Bonita were SR-4 Type A-2. The hookup, circuits and control were the same as on Squaw 29. Since the recording center was located on board the Bonita, cable leads were short and no correction factor was necessary.

2.3.2 Pressure Gages. The pressure gages used to obtain the pressure-time history in the ballast tanks of Squaw 29 were of the piezoelectric type. Each gage consisted of an 8-ply pile of 1¼-inch-diameter tourmaline crystals attached to 100 feet of Simplex coaxial, low-noise cable. The gage sensitivity was approximately 100 $\mu\mu$coulombs/psi.

Waterproofing was accomplished by cold molding a ³⁄₃₂-inch neoprene jacket around each gage.

The manufacturer provided a calibration constant for each gage. After the neoprene coating was applied, each gage was recalibrated at David Taylor Model Basin (DTMB) by the firing of explosive charges underwater at predetermined ranges. The average difference between the DTMB and the manufacturer's calibration was 6 percent. The maximum difference was 9 percent.

Each pressure gage was connected to a magnetic-tape recorder through an auxiliary unit. The unit included a cable-termination network, a step-calibration circuit, and a cathode follower. The frequency response of the cathode follower was flat within 2 percent to about 70 kc.

2.3.3 Displacement Gages. The displacement gages were of the linear-variable differential-transformer type, which produces an electrical signal proportional to the displacement of a movable magnetic core. The coil forms of the units were attached to the port-motor mass, and the movable cores were attached by wooden rods to the hull plating or framing.

Of the four displacement gages installed on Squaw 29, two were recorded on electromagnetic oscillographs and two on tape recorders.

2.3.4 Roll, Pitch, Depth and Flooding Gages. The roll, pitch, depth and flooding gages used are described in detail in Reference 14. A roll, a pitch, and a depth gage were installed in each end compartment. The depth gage was a Bourdon type transducer, the pressure element of the gage being mechanically coupled to a wire-wound potentiometer. Each roll and each pitch gage consisted of a damped pendulum mechanically coupled to a wire-wound potentiometer. The flooding gages consisted of two contacts about an inch apart, supported by a dielectric. Salt water coming in contact with the contacts completed an electrical circuit. Resistors in series and parallel with the contacts served to differentiate between actual flooding and cable disturbances.

2.3.5 High-Speed Motion-Picture Cameras. Nine Fairchild high-speed motion-picture cameras were installed in Squaw 29 to photograph the motion of the hull and simulated equipment. The cameras operated at about 800 frames/sec. The magazine capacity of the cameras was 100 feet; therefore, the recording time was about 5 seconds. Lighting was provided by photoflood lamps resiliently mounted in the test compartments. Power for the lights and camera was provided by two banks of storage batteries.

The cameras were enclosed in resiliently mounted cylindrical lead housings to protect the film from radiation and isolate the cameras from shock motions. The cameras photographed the objects through a port in the bottom of the housing with the aid of a 45-degree mirror outside the housing.

2.3.6 Instrumentation Cables. The signals from the instruments in Squaw 29 were transmitted to the recording center on YFNB 12 through three special multiconductor cables. The cables were manufactured by the Simplex Wire Cable Company, Cambridge, Massachusetts.

Each major cable consisted of 33 four-conductor, shielded, low-noise cables. These were spiraled around a ⅜-inch steel-wire core. The whole assembly was covered with a polyvinyl jacket. The cables were approximately 800 feet long and connected terminal boards in the Squaw and YFNB.

2.3.7 Recording Equipment. The signals from the strain gages and two deflection gages on Squaw 29 were recorded on galvanometer oscillographs through carrier amplifiers. The carrier frequency was 3,000 cps, and the frequency response was uniform within 2 percent from 0 to 500 cps. The galvanometer traces were recorded on 12-inch-wide film, which ran at 60 in/sec. The signals from the piezoelectric pressure gages were recorded on an Ampex Model 814 tape recorder. The signals from the strain gages on USS Bonita were also recorded on galvanometer oscillographs.

2.4 INSTRUMENT LOCATIONS

Thirty-two strain gages, thirteen pressure gages, four displacement gages, two roll gages, two pitch gages, two depth gages, eight flooding gages, and nine high-speed cameras were installed in the Squaw. Only 23 strain recordings were made, the remaining gages being spares. The signals from ten pressure gages were recorded.

TABLE 2.1 LOCATION OF STRAIN GAGES, SQUAW 29

Position Number	Orientation*	Instrument†	Gage Attached To	Location: Frame Number	Location: Degrees Around Hull
S1	C	S‡	Inside hull plating	33½	At crown
S2	C	S‡	Inside hull plating	33½	60 deg stbd from crown
S3	C	S	Inside hull plating	33½	120 deg stbd from crown
S4	C	S‡	Inside hull plating	33½	Bottom of hull
S5	C	S‡	Inside hull plating	33½	60 deg port from crown
S6	C	S	Inside hull plating	33½	120 deg port from crown
S7	C	S‡	Inside hull plating	37½	At crown
S8	C	S	Inside hull plating	37½	16 deg port from crown
S9	C	S	Inside hull plating	37½	32 deg port from crown
S10	C	S‡	Inside hull plating	37½	60 deg port from crown
S11	C	S	Inside hull plating	37½	90 deg port from crown
S12	C	S	Inside hull plating	37½	120 deg port from crown
S13	C	S‡	Inside hull plating	37½	Bottom of hull
S14	C	S‡	Inside hull plating	37½	60 deg stbd from crown
S15	C	S	Inside hull plating	37½	120 deg stbd from crown
S16	C	S	Flange of hull stiffener	34	At crown
S17	C	S‡	Flange of hull stiffener	37	At crown
S18	A	S	Inside hull plating	37½	2 deg port from crown
S19	A	S	Inside hull plating	33½	32 deg stbd from crown
S20	A	S	Inside hull plating	33½	Bottom of hull
S21	A	S	Inside hull plating	38¼	Bottom of hull
S22	C	8S	Inside hull plating	25½	15, 45, 75, and 105 deg port and stbd
S23	X	2S	Inside stern hemisphere	54	Centerline of ship
S24	—	S	Unstrained steel block	—	—

* Sensitive direction of strain gage: C, circumferential; A, axial; X, two gages at right angles.

† S, strain gage, Type A-9; 8S, eight Type A-9 gages connected to give average strain; 2S, two Type A-9 gages connected to give average strain.

‡ Two separate gages installed. Selection of gage for recording was made shortly before final circuit calibration prior to shot.

The locations of the strain gages are listed in Table 2.1 and shown in Figure 2.7. The locations of the pressure gages are listed in Table 2.2 and shown in Figures 2.8 and 2.9. The locations of the displacement gages are listed in Table 2.3. The locations and fields of view of the cameras in Squaw 29 are shown in Figure 2.10.

The gages on Squaw 29 were installed in essentially the same locations as in Operation Wigwam (References 3, 14, and 15).

Nine strain gages at Frame 37½ measured circumferential strain at various positions around the hull. A set of six strain gages also measured circumferential strain at Frame 33½, in the middle of the after test compartment. A set of eight gages installed as a hoop on the plating at Frame 25½ was wired into a single electrical bridge circuit to obtain the average strain over the eight gage locations. Additional gages measured circumferential strain on hull stiffeners. Four strain gages measured the axial strains of the hull plating on the crown, keel, and at the

TABLE 2.2 LOCATION OF PRESSURE GAGES, SQUAW 29

Position Number	Gage Located In	Location		
		Frame Number	Vertical	Transverse
P1	Open water	9	2 ft below bottom of hull	Centerline
P2	Main ballast tank No. 2 stbd	$24\frac{1}{2}$	2 ft below centerline	Near stbd side of hull
P3	Main ballast tank No. 2 stbd	$24\frac{1}{2}$	2 ft above centerline	Near stbd side of hull
P4	Main ballast tank No. 2 port	$24\frac{1}{2}$	2 ft below centerline	Near port side of hull
P5	Main ballast tank No. 2 port	$24\frac{1}{2}$	2 ft above centerline	Near port side of hull
P6	Main ballast tank No. 3 stbd	$30\frac{1}{2}$	3 ft below centerline	Near stbd side of hull
P8	Main ballast tank No. 3 port	$30\frac{1}{2}$	2 ft below centerline	Near port side of hull
P9	Main ballast tank No. 3 port	$30\frac{1}{2}$	2 ft above centerline	Near port side of hull
P12	Main ballast tank No. 2 stbd	$24\frac{1}{2}$	Centerline of hull	Near stbd side of hull
P15	Main ballast tank No. 3 port	$30\frac{1}{2}$	Centerline of hull	Near port side of hull

TABLE 2.3 LOCATION OF DISPLACEMENT GAGES, SQUAW 29

R, Radial (normal to hull).

Position Number	Orientation	Gage Measured Relative Displacement Between Port Simulated Motor And	Location		
			Frame Number	Vertical	Transverse
D1	R	Flange of hull stiffener	35	Centerline of hull	Stbd side of hull
D2	R	Inside of hull plating	$35\frac{1}{2}$	Centerline of hull	Stbd side of hull
D3	R	Inside of hull plating	$35\frac{1}{2}$	Centerline of hull	Port side of hull
D4	R	Inside of hull plating	$35\frac{1}{2}$	At crown of hull	Centerline

TABLE 2.4 LOCATION OF STRAIN GAGES, USS BONITA (SSK 3)

C, Circumferential strain.

Position Number	Orientation	Gage Attached To	Location	
			Frame Number	Position On Hull
S1	C	Flange of hull stiffener	27	At crown
S2	C	Flange of hull stiffener	27	90 deg to port from crown
S3	C	Inside of hull plating	$52\frac{1}{2}$	At crown
S4	C	Inside of hull plating	$52\frac{1}{2}$	26 deg to port from crown
S5	C	Inside of hull plating	$52\frac{1}{2}$	45 deg to port from crown
S6	C	Inside of hull plating	$52\frac{1}{2}$	90 deg to port from crown
S7	C	Inside of hull plating	$52\frac{1}{2}$	90 deg to stbd from crown

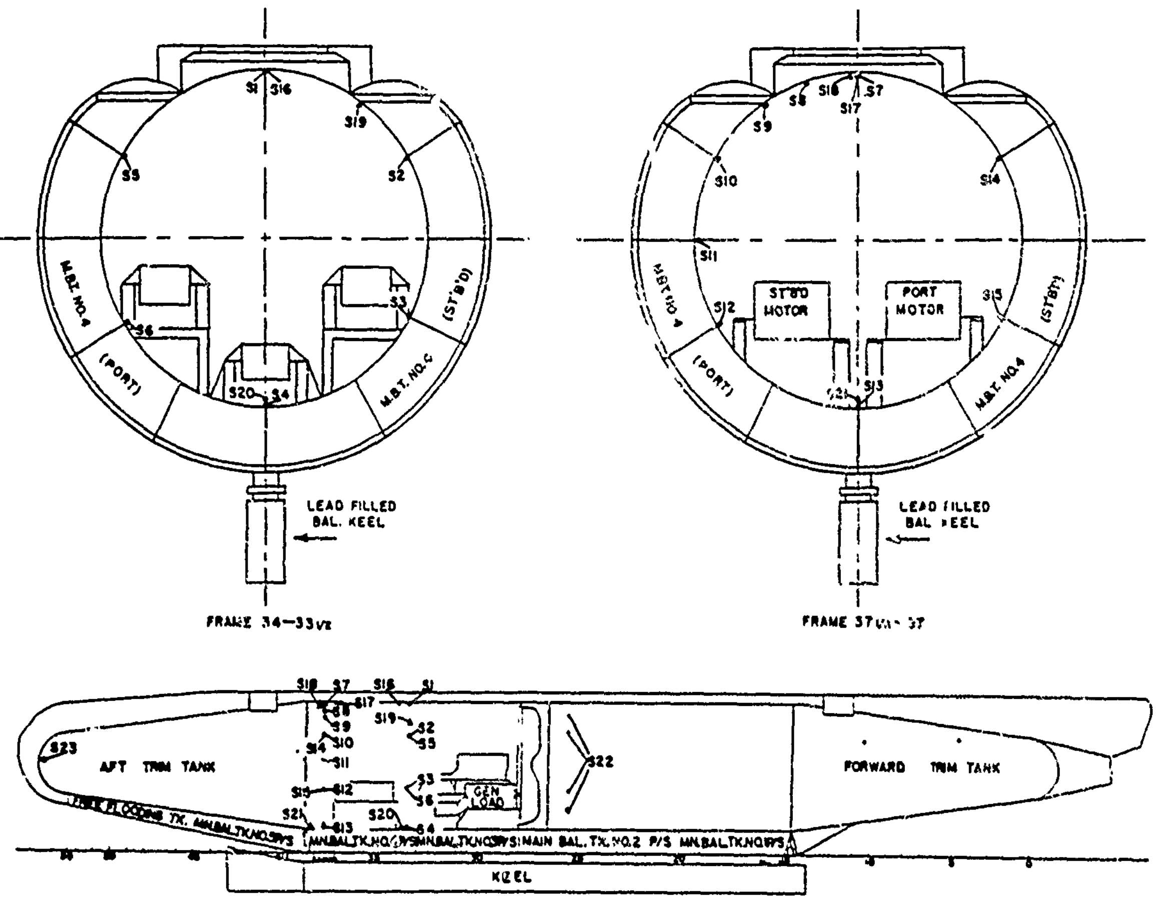


Figure 2.7 Sections of Squaw showing strain gage locations.

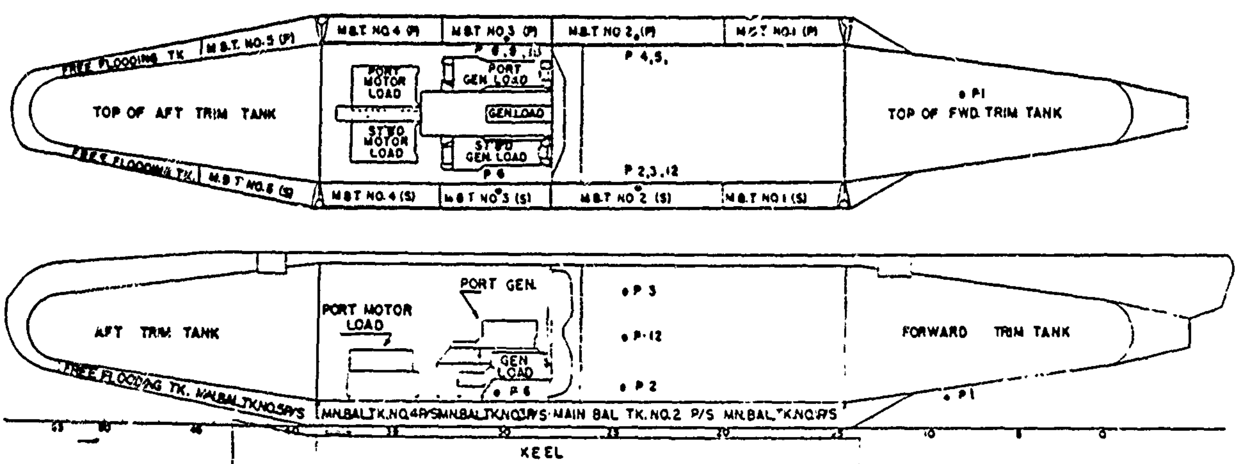


Figure 2.8 Profile and plan view of Squaw 29 showing pressure gage locations.

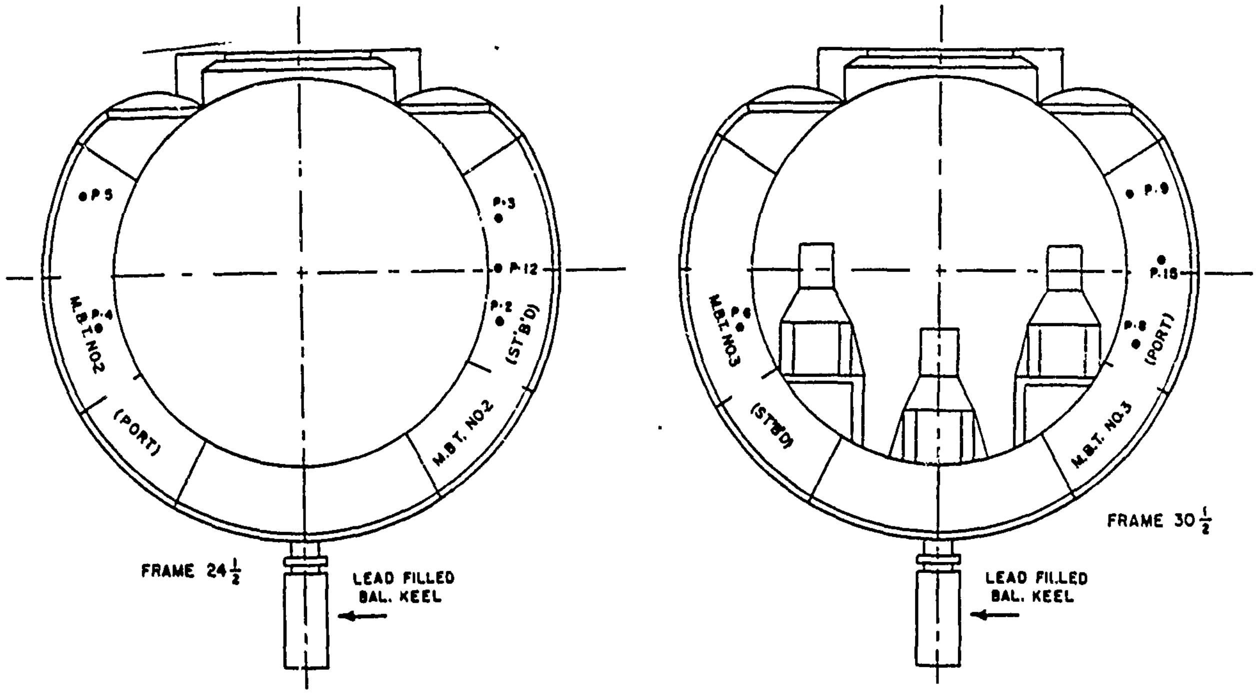


Figure 2.9 Cross sections of Squaw 29 showing pressure gage locations.

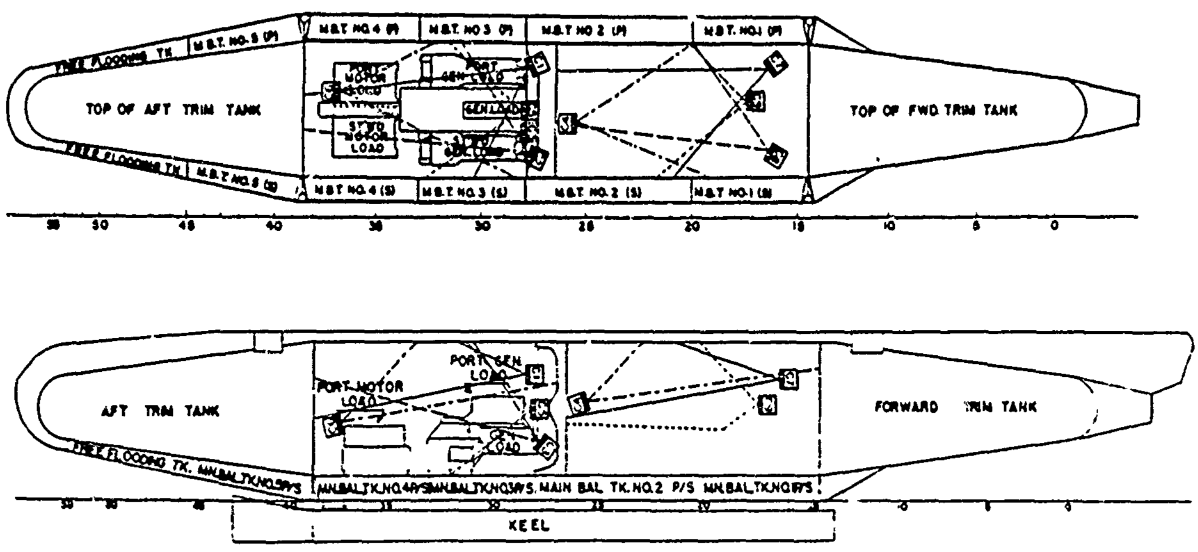


Figure 2.10 Sections of Squaw showing field of view of cameras; plan view shown at top, inboard profile at bottom.

intersection of the outer hull with the pressure hull. One channel measured the strain in the hemispherical nose at the stern. One channel monitored an unstrained gage bridge to check on spurious signals and cable noise.

The pressure gages were installed in the tanks outside the test sections and below the hull at the forward and after ends of the Squaw. The displacement gages measured the horizontal dis-

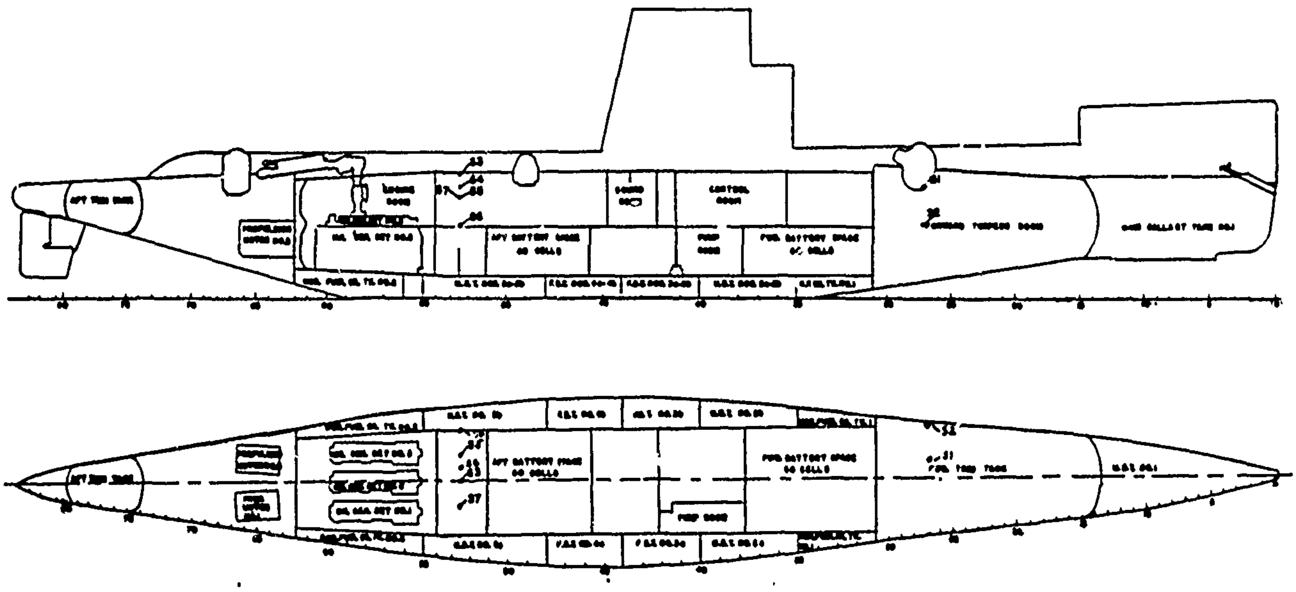


Figure 2.11 Inboard profile and plan views of SSK 3 showing location of strain gages.

placement of the stiffener at Frame 35, starboard; the horizontal displacement of the hull plating at Frame 35½, port and starboard; and the vertical displacement of the crown at Frame 35½.

Roll, pitch, and depth gages were located in each of the conical end sections of Squaw 29. Two flooding gages in each of the four compartments were installed to indicate the condition of flooding in each compartment, one gage being placed near the keel and one at deck level.

Instruments on the Squaw were connected to a terminal board in the forward compartment. The three special multiconductor instrument cables led from this board through watertight glands to the recording center on YFNB 12.

The locations of the seven strain gages on USS Bonita are listed in Table 2.4 and shown in Figure 2.11. The gages were placed at a typical bay of the inner pressure-hull plating and at locations where previous deep-dive tests on SSK 1 had shown that high strains could be expected (Reference 1).

Two strain gages at Frame 27 measured the circumferential strain at the crown and at the intersection with the deck. Five strain gages at Frame 52½ measured circumferential strain at various locations around the hull.

The strain gages installed on SSK 3 for this test were calibrated as a function of static pressure by a test submergence to 400 feet.

Chapter 3

INSTRUMENTATION RESULTS

Most of the instrumentation functioned satisfactorily. The informative portions of the oscillograms obtained are reproduced in Figures 3.1 through 3.9. Since the Bonita was present for both Operation Hardtack shots, the data for it are presented first. The more-extensive data for the Squaw follows.

Figures 3.1, 3.2, and 3.3 reproduce the significant portions of the records for USS Bonita during Shot Wahoo. The velocity-time records for Project 3.3 are also contained in these figures. Figure 3.1 represents the response to the direct shock wave;[1] Figure 3.2 shows the response to the shock wave reflected from the ocean bottom; this pulse arrived after the direct wave. Figure 3.3 shows the response to a third pulse, the origin of which has not been determined. The third shock arrived after the direct wave.

Figure 3.4 gives the response of USS Bonita to the shock wave of Shot Umbrella.

Strain and displacement records for the Squaw in Umbrella are of principal interest. The action portions of the traces are presented in Figures 3.5 and 3.6. Figure 3.5 shows the response to the direct shock wave which arrived after the zero fiducial and Figure 3.6 shows the response to a second pulse, believed to be caused by the closure of cavitation. This arrived at the Squaw after the zero fiducial. The associated pressure records, reproduced from the tape recorders, are sketched in Figures 3.7, 3.8, and 3.9.

The differences in starting times on the different channels are due to the different arrival times of the pressure wave at the gages. All times are measured from the radio-transmitted fiducial or zero signal.

The high-speed cameras installed in Squaw 29 were intended in part to record the growth of damage to the hull during Shot Umbrella. The motion pictures obtained graphically illustrate the shock motions of the hull's equipment. The motions, however, were too small to permit accurate measurements of the deflections of the hull and stiffeners. The pictures agree qualitatively with the oscillograms as to the loading events. However, no numerical data from the motion pictures is presented in this report.

Key values of the parameters read from the oscillograms are presented in Tables 3.1 through 3.5.

The peak strains, all compressive, observed in the Bonita during Shots Wahoo and Umbrella are listed in Table 3.1.

The initial peak strains and permanent sets in Squaw 29 in Umbrella are listed in Table 3.2. The rise time to peak strain was at each hull location. These strains and sets were caused by the action of the initial shock wave. The second pulse, believed to originate with the closure of cavitation, caused noticeable strains and a slight increase in the permanent set. The strains and sets caused by this wave are also tabulated.

The pressures measured in the ballast tanks of Squaw 29 are listed in Table 3.3. In general, the duration of the direct-wave pressure pulse was about The highest pressure recorded, was measured by the gage located 2 feet below the bow.

The pressures considered to be caused by the closure of cavitation were characterized generally by a gradual increase in pressure. The durations were about The pressures in this pulse, fairing through the spikes, are listed in Table 3.3. The highest pressure, was measured by the gage in tank Number 3, port, a few feet below the centerline.

[1] The zero fiducial time signal was not received.

Page 29 deleted.

TABLE 3.5 ROLL, PITCH, DEPTH, AND FLOODING OF SQUAW 29 BEFORE SHOT UMBRELLA

Gage And Location	Reading 3 Hours Before Shot*
Roll gage in forward cone	0 deg roll, no variation
Pitch gage in forward cone	3 deg bow down, no variation
Depth gage in forward cone	52 feet deep to the centerline, no variation
All eight flooding gages (two in each compartment)	No flooding

* No records obtained at shot time.

Pages 31-34 deleted.

Figure 3.9 Pressure-time records obtained in tanks of Squaw for closure of cavitation. The calibration constant gives the pressure per unit deflection for each channel.

Displacements at Frame 35 starboard between the frame and the simulated motor and between the hull plating at Frame $35\frac{1}{2}$ port and the motor are given in Table 3.4.

An observation of the depth, angle of roll, angle of pitch and condition of flooding of Squaw 29 was made 3 hours before Shot Umbrella. The results are shown in Table 3.5. It is believed that these values indicate the condition of Squaw 29 at zero time. Oscillograms were not obtained, because the oscillograph did not run.

Chapter 4
DAMAGE TO SQUAW 29 DURING SHOT UMBRELLA

4.1 LOSS OF BUOYANCY DURING TEST

After Shot Umbrella, difficulty was encountered in surfacing Squaw 29.

Air pumped into tank Number 3 starboard escaped through tank Number 2 starboard. The Squaw could be held almost awash at the surface by continuously blowing tanks.

In order to recover buoyancy lost by rupture of the tanks, the external ballast keel was removed by detonating charges on contact with the keel support. The Squaw was then towed to the Pearl Harbor Naval Shipyard. After drydocking, a thorough inspection of the inner and outer hull was made.

4.2 BALLAST TANKS

4.3 REMOVAL OF BALLAST KEEL

Large holes were made in the outer hull plating when the external ballast keel, Figure 2.3, was removed after Shot Umbrella. The keel, removed to regain buoyancy lost by rupture of the ballast tanks, was broken loose by detonating explosive charges in contact with the keel support brackets. The resulting damage was generally localized at the outer hull. In some cases it caused the failure of bolts securing simulated machinery inside the Squaw. These bolts had been deformed during Shot Umbrella. Damage to the outer hull is shown in Figures 4.11 and 4.12.

4.4 CYLINDRICAL PRESSURE HULL

Dishing of the pressure-hull plating was observed after Shot Umbrella. Deformation of the plating was determined by measuring the indentation between frames, as shown in Figure 4.13.

Pages 37-38 deleted.

Figure 4.5 Closeup ___ shown in Figure 4.4. Arcs drawn on photo show depressed area of pressure hull. Dashed line shows location of Frame 43 inside hull.

Figure 4.6 Exterior of Squaw, after conical section, starboard side, after Shot Umbrella. Note the extensive deformation of the outer hull plating.

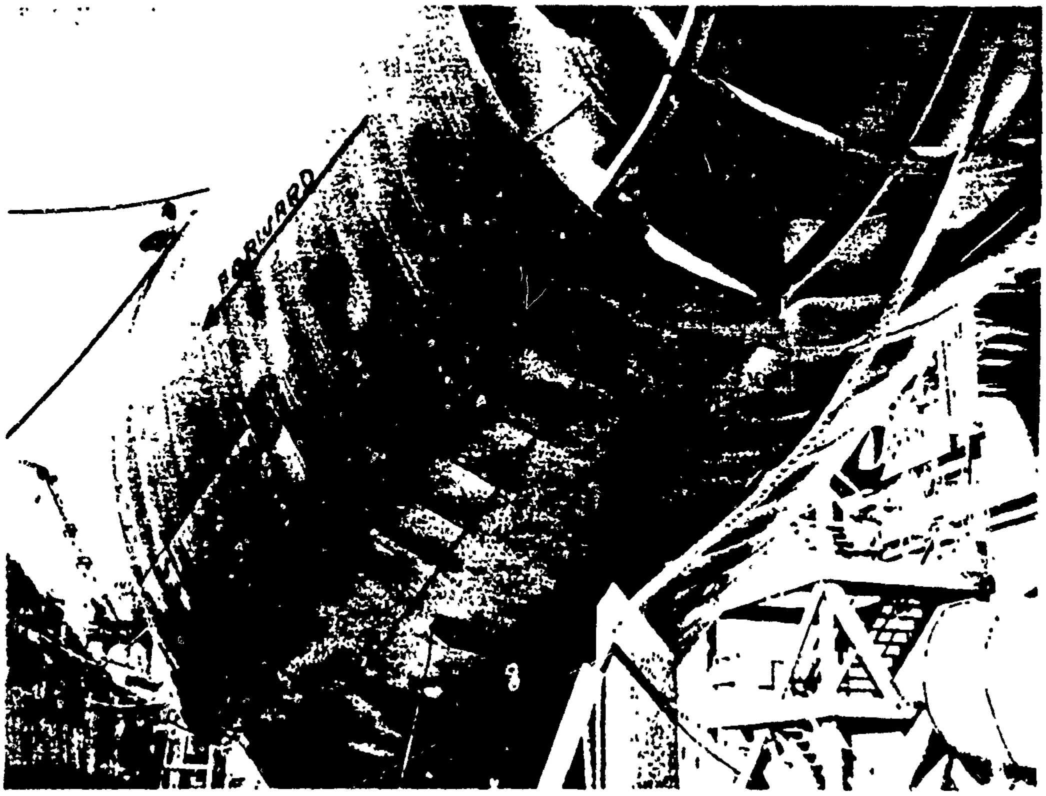


Figure 4.7 After conical section of Squaw, port side, after Shot Umbrella.

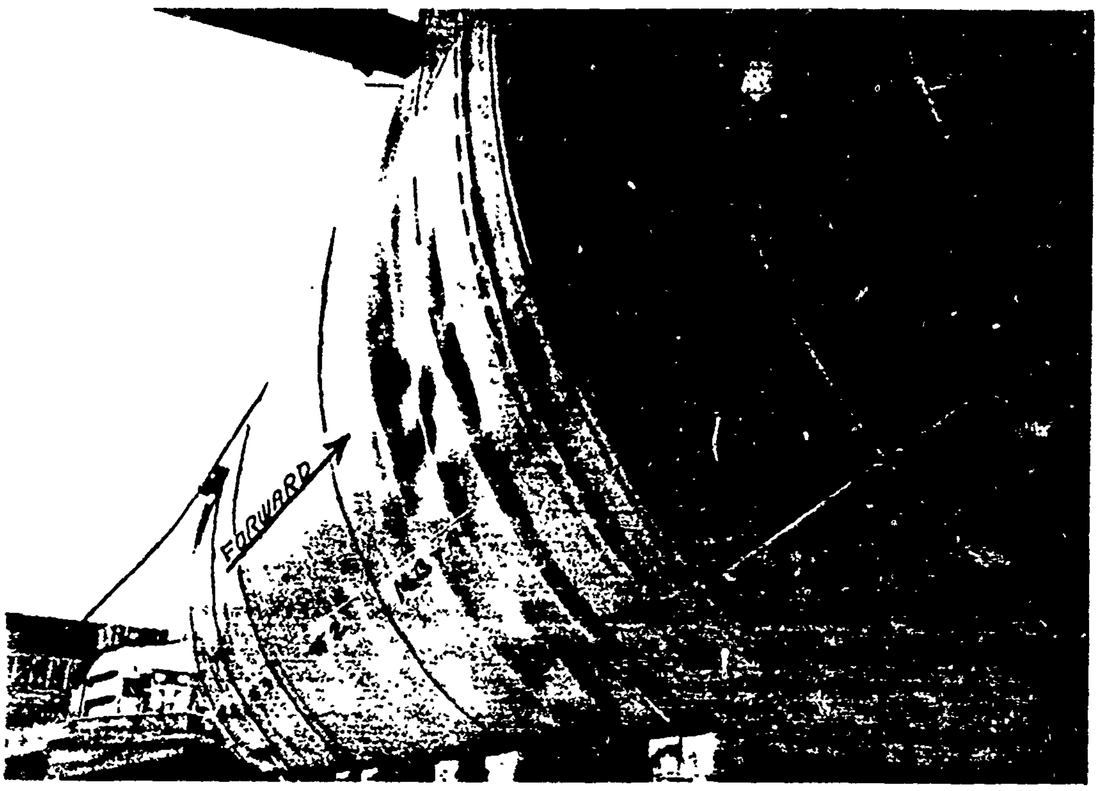


Figure 4.8 Squaw starboard side looking aft, after Shot Umbrella.

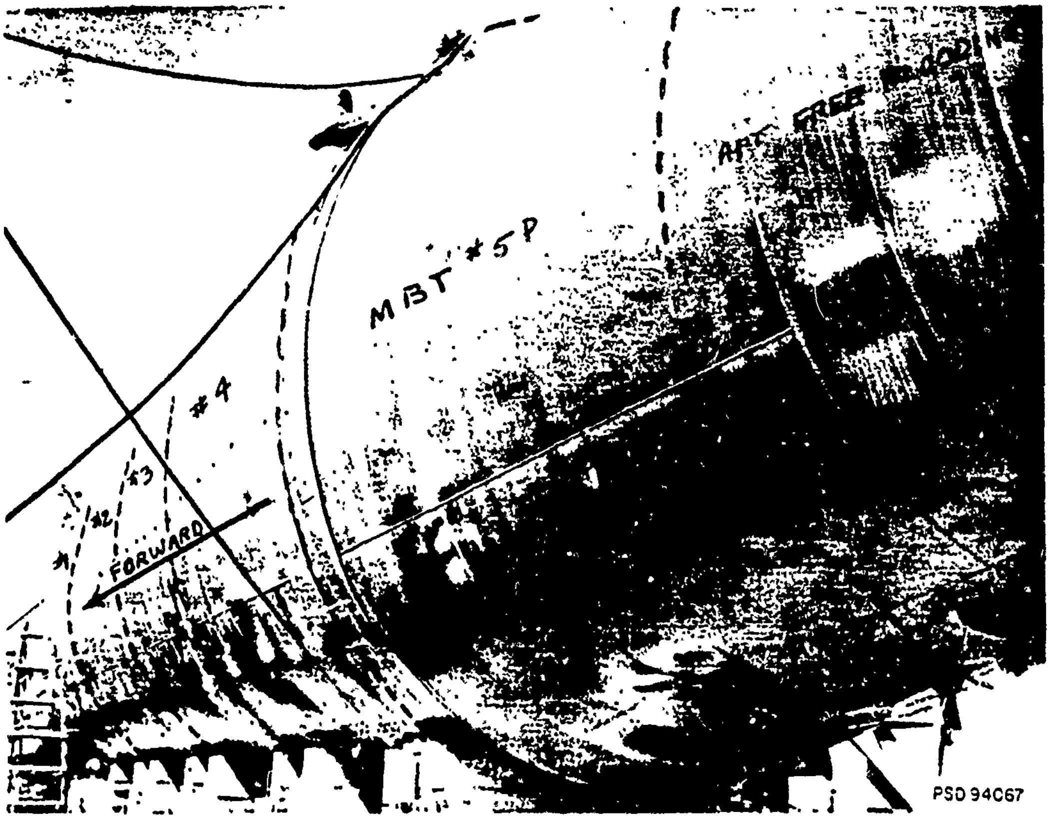


Figure 4.9 Squaw port side looking forward after Shot Umbrella. Dashed lines show boundaries of tanks.

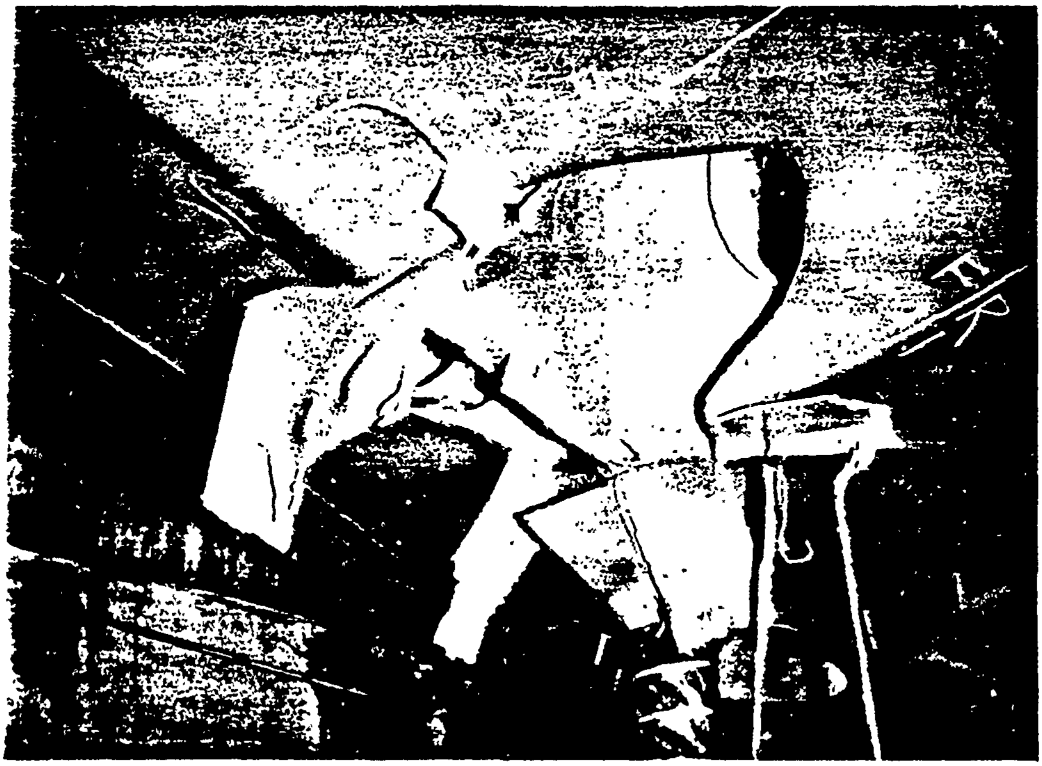


Figure 4.11 View looking up at keel at Frames 41 and 42 showing damage to bottom of Squaw which resulted from removal of ballast keel. Plating was torn by explosion of chemical charges in contact with keel support brackets.

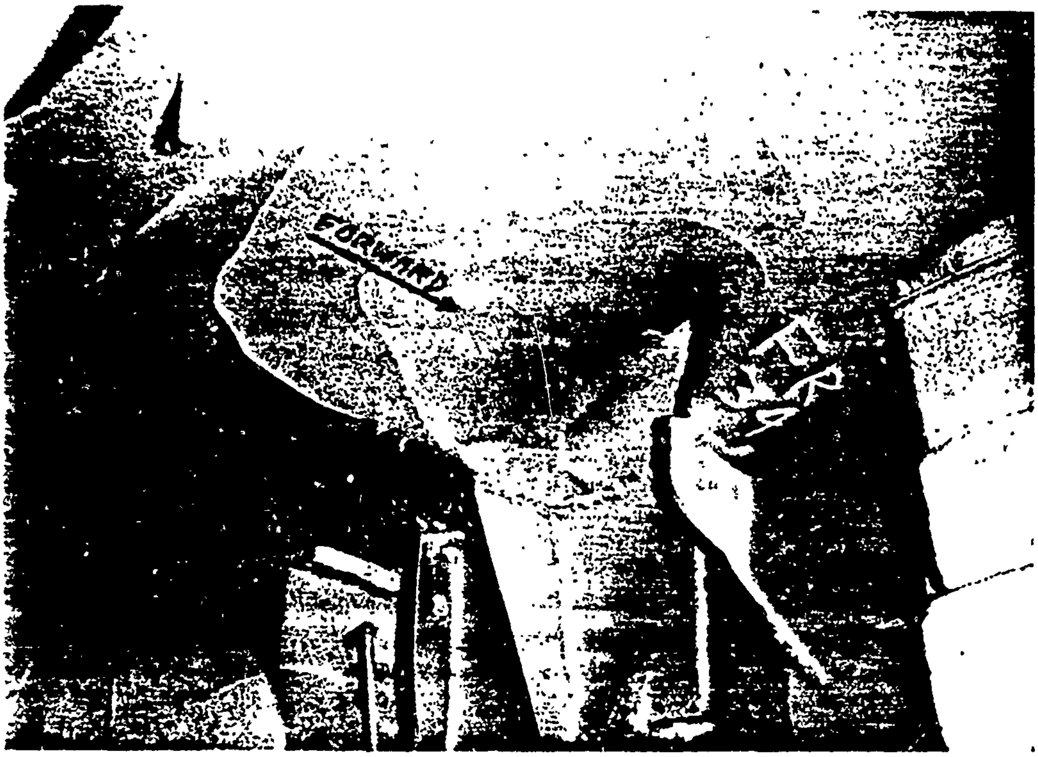


Figure 4.12 View looking up at keel at Frames 34 and 35 showing damage to bottom of Squaw which resulted from removal of ballast keel.

In addition, a special recorder was used to scribe profiles of the inner hull plating and framing on a template. The device was similar to one used during construction of the Squaw. A typical circularity profile, made during construction, is shown in Figure 2.5.

The maximum deformation of the hull plating relative to the frames, in the cylindrical test section of the Squaw, $^7/_8$ inch, was measured 15 inches aft of Frame 34. Circumferential and longitudinal contours of this dish are shown in Figure 4.14. The maximum occurred at the crown 23 degrees to port of the vertical centerline, in the portion of the hull that is not enclosed by ballast tanks.

The deflections at three distances between Frames 37 and 38 are plotted in Figure 4.15. The graph shows a deflection of $^3/_4$ inch at a position 45 degrees to starboard from the keel and a deflection of $^5/_8$ inch at 45 degrees to port of the keel. The average deflection was $^1/_2$ inch inward for the lower half of the hull except at the keel, which was not deflected.

It is noteworthy that the largest deflection at the crown, $^5/_8$ inch, occurred at the longitudinal welded seam, 15 degrees to starboard of the crown. A lobe was also centered about the longitudinal seam 15 degrees to port of the keel. The average deformation over the unenclosed crown was $^3/_8$ inch. A somewhat smaller average, $^1/_4$ inch, was observed for the portion of the upper hull enclosed by the ballast tanks.

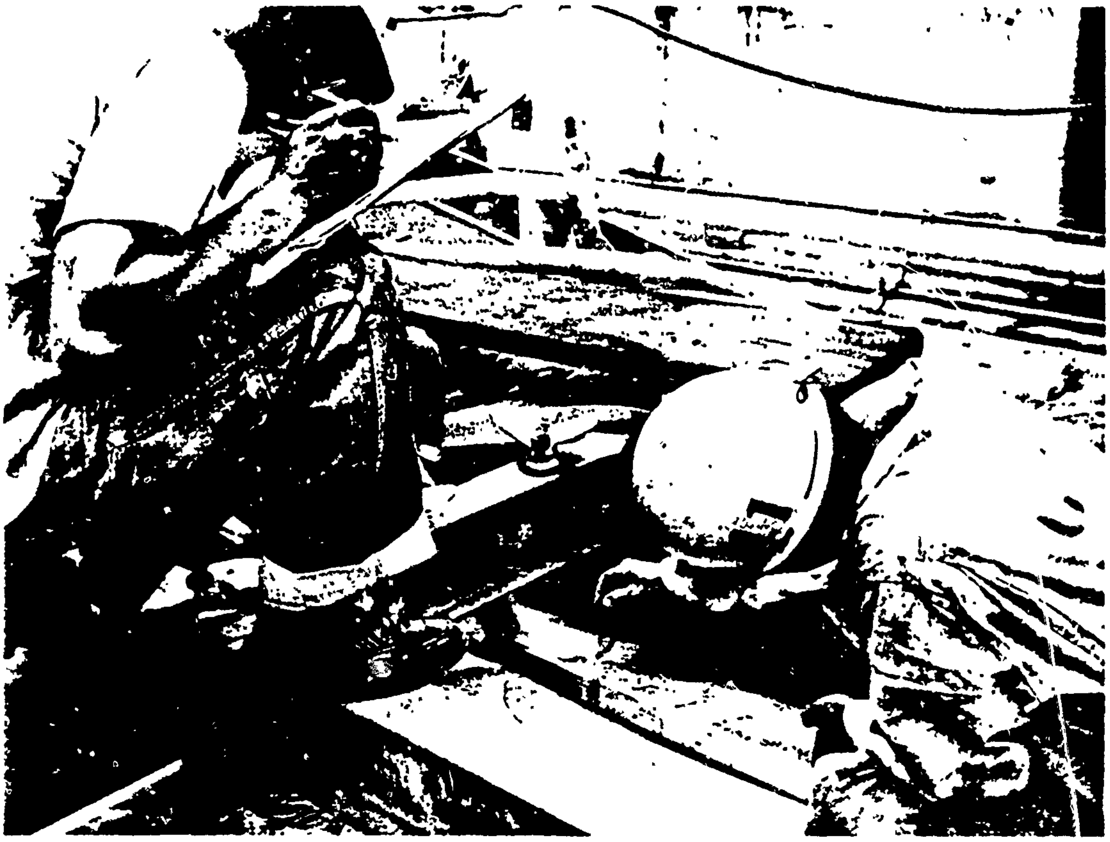


Figure 4.13 Measurement of deformation of pressure hull between frames.

A $^3/_4$-inch deflection of the inner hull plating occurred at Frame $16^1/_2$, $22^1/_2$ degrees port from the crown, Figure 4.16. Noticeable dishing also occurred at Frames $15^1/_2$ and $17^1/_2$ along the welded seam 15 degrees starboard of the overhead. These dishes are shown in Figure 4.17.

4.5 CONICAL ENDS

The largest plating deflection of the pressure hull, $1^9/_{16}$ inches, was measured in the after cone, the end of the target closest to the charge. The deformation occurred at the intersection of the pressure hull, ballast tank, and superstructure between Frames 42 and 43. It is shown in Figures 4.4 and 4.5 and plotted in Figure 4.18. It should be noted that in the conical section the frame spacing was only 24 inches. The largest deflection in the cylindrical test section, in which the frame spacing was 29 inches, was $\frac{7}{8}$ inch.

More dishing was centered along the longitudinal welding seam at midbay. Figure 4.19 is a section of the aft cone at an angle of 15 degrees to the horizontal, i.e., in the plane of the seams.

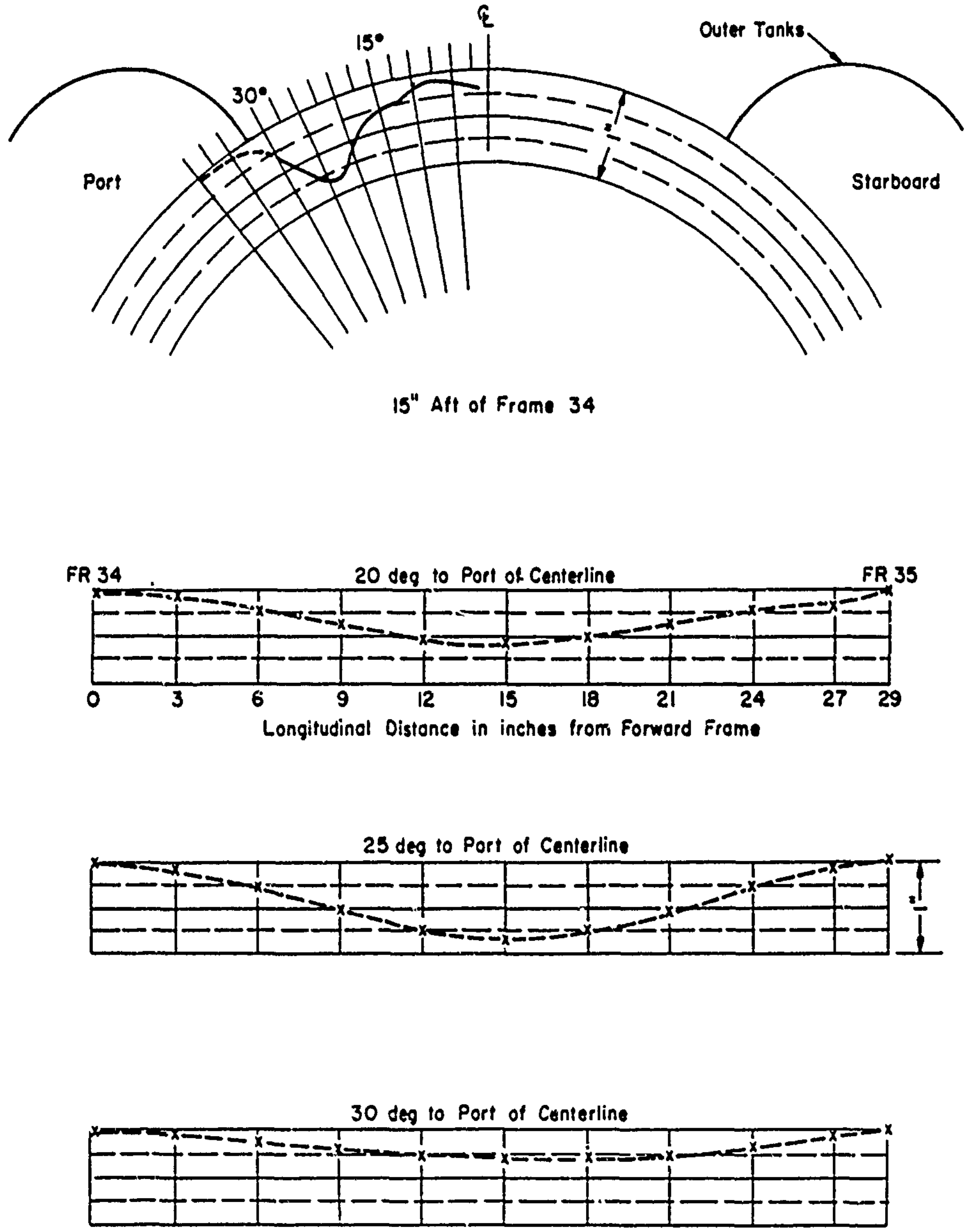


Figure 4.14 Dishing contours for the maximum deformation of the pressure hull in the cylindrical section.

The distortion of the hull plating between frames is shown in this figure and in a photograph, Figure 4.20. The deformations on the port and starboard sides were roughly the same, the maximum deformations on each side, $\frac{13}{16}$ inch, occurring between Frames 42 and 43. On both sides of the compartment, the average deformation was smaller at the narrow end.

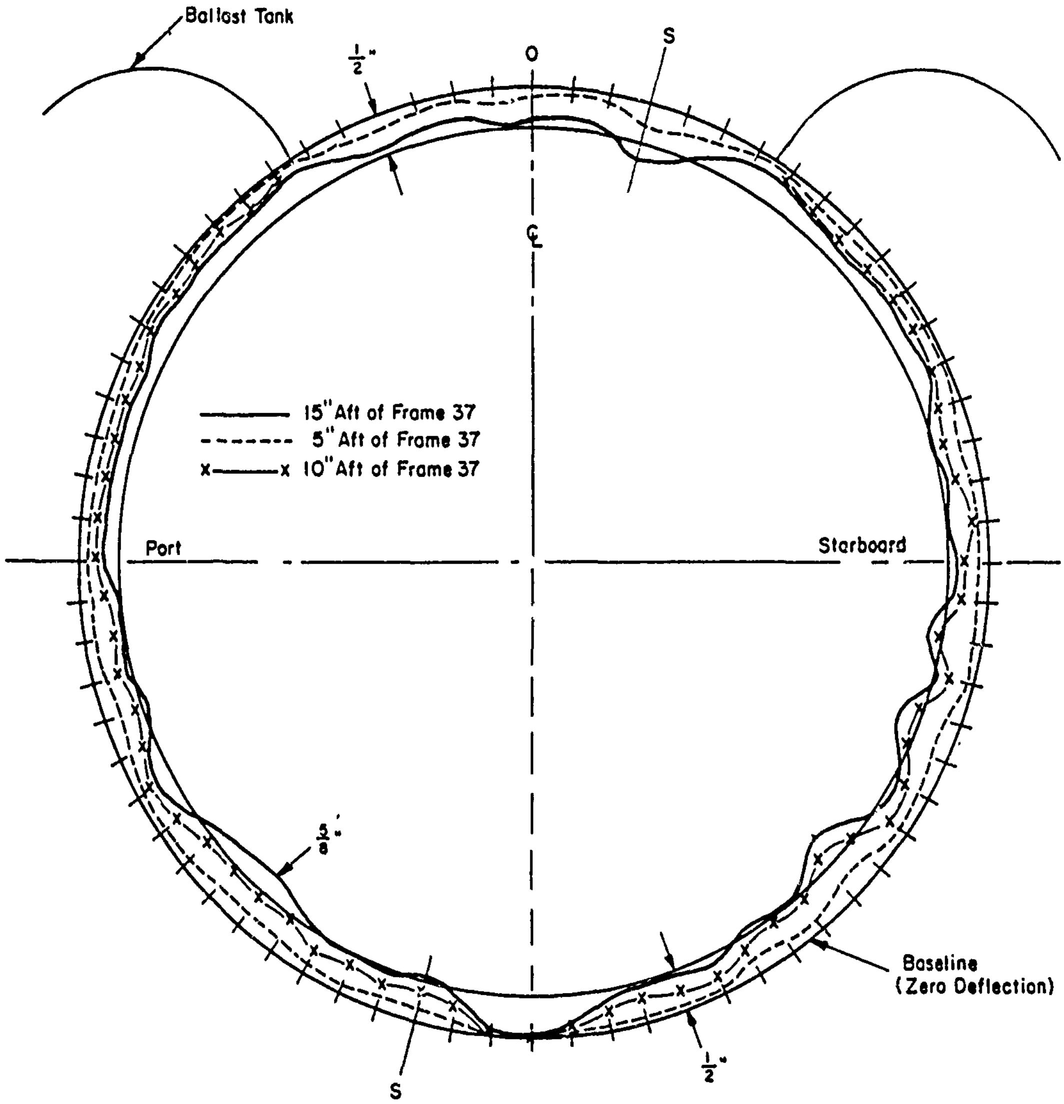


Figure 4.15 Plating deflections at positions between Frames 37 and 38. The deflections are measured with respect to stiffeners.

In the forward cone, the end farthest from the charge, there was not only dishing between frames, but in addition, Frame 9 was pushed in about an inch, Figures 4.21 and 4.22. This damage was centered 15 degrees starboard from the keel.

The large deformation at the intersection of pressure hull, tank, and superstructure in the after cone and the deformations along the seams in both the conical and cylindrical sections may have resulted from welding effects.

4.6 BULKHEAD

The Squaw has bulkheads at Frames 14½, 26½, and 38½. The ¼-inch plating of all three bulkheads buckled between stiffeners. Although yielding was general, the areas of maximum deflection were near the periphery of the bulkheads about 45 degrees port and starboard from the overhead.

A maximum plating deflection of about an inch was measured in the forward and aft bulkheads and ¾ inch in the midships bulkheads. The buckling in the forward and aft bulkheads was

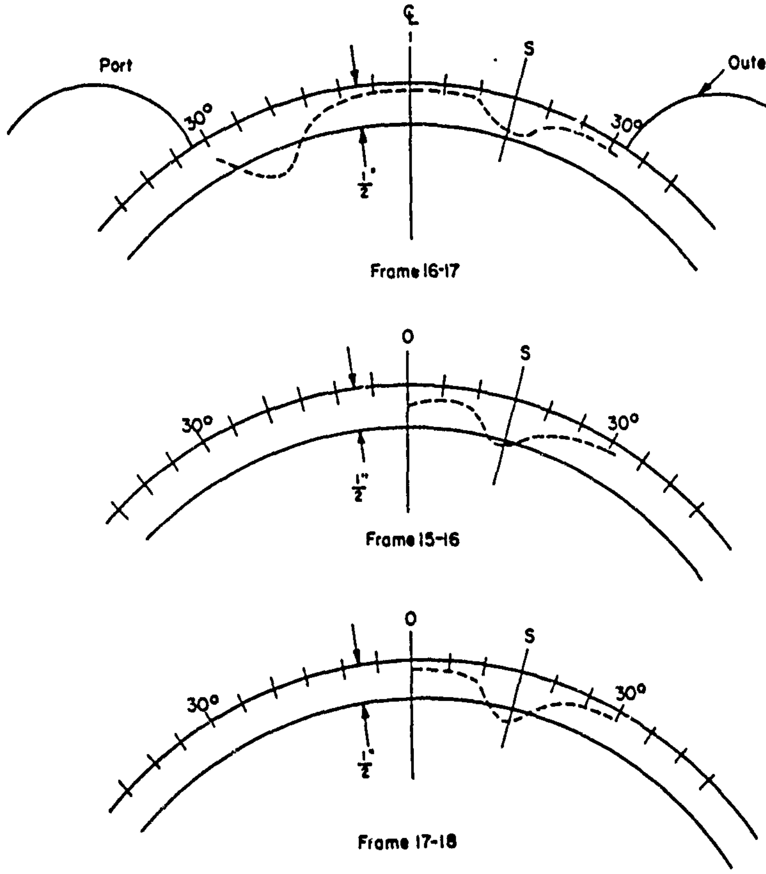


Figure 4.16 Dishing contours at centers of selected bays in the cylindrical section between Frames 15 and 18.

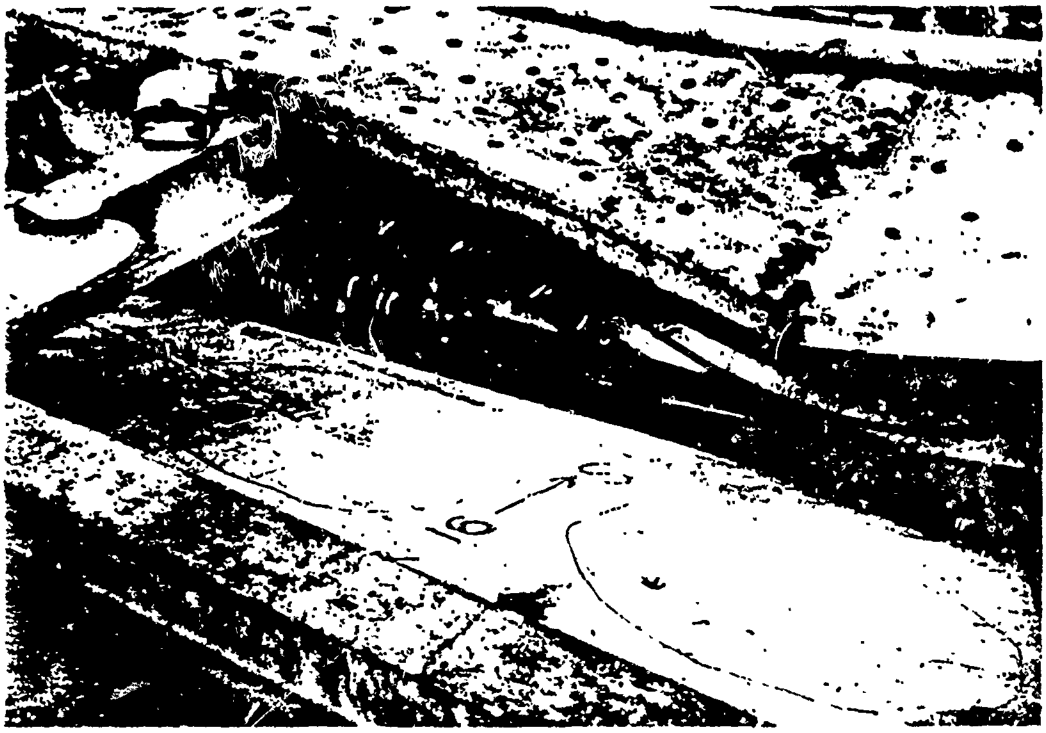


Figure 4.17 Dishing of crown in cylindrical section between Frames 15 and 17.

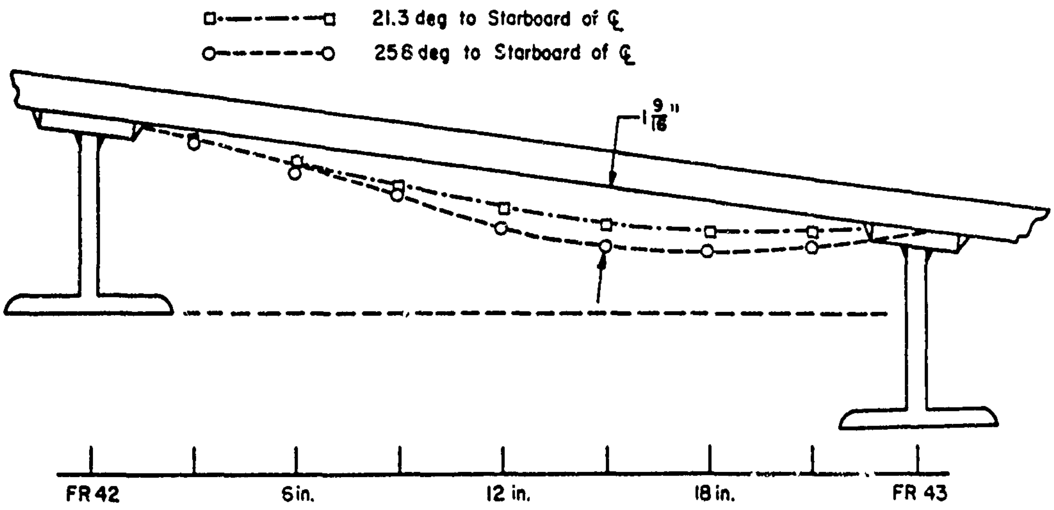


Figure 4.18 Deflection of hull plating in after cone.

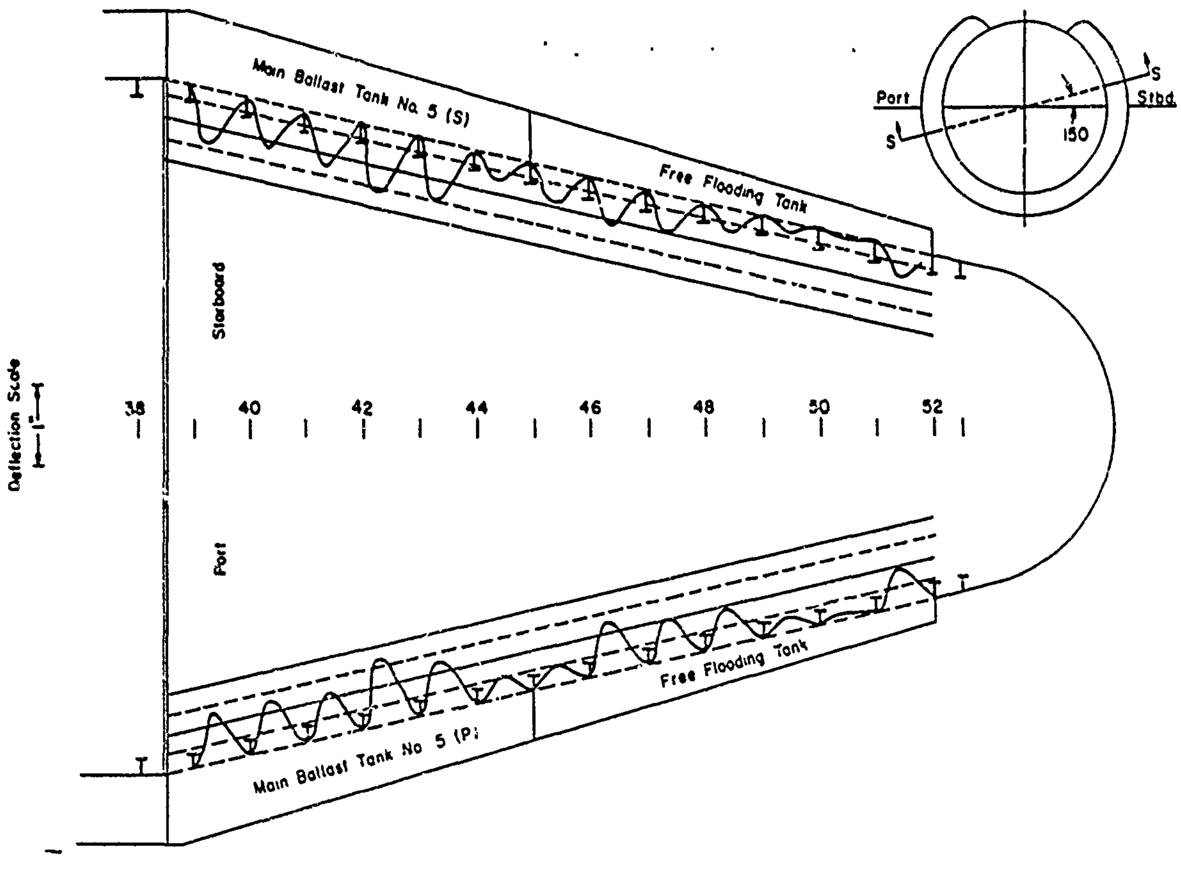


Figure 4.19 Dishing between frames along longitudinal seams in aft cone. Location of seam is shown in upper right.

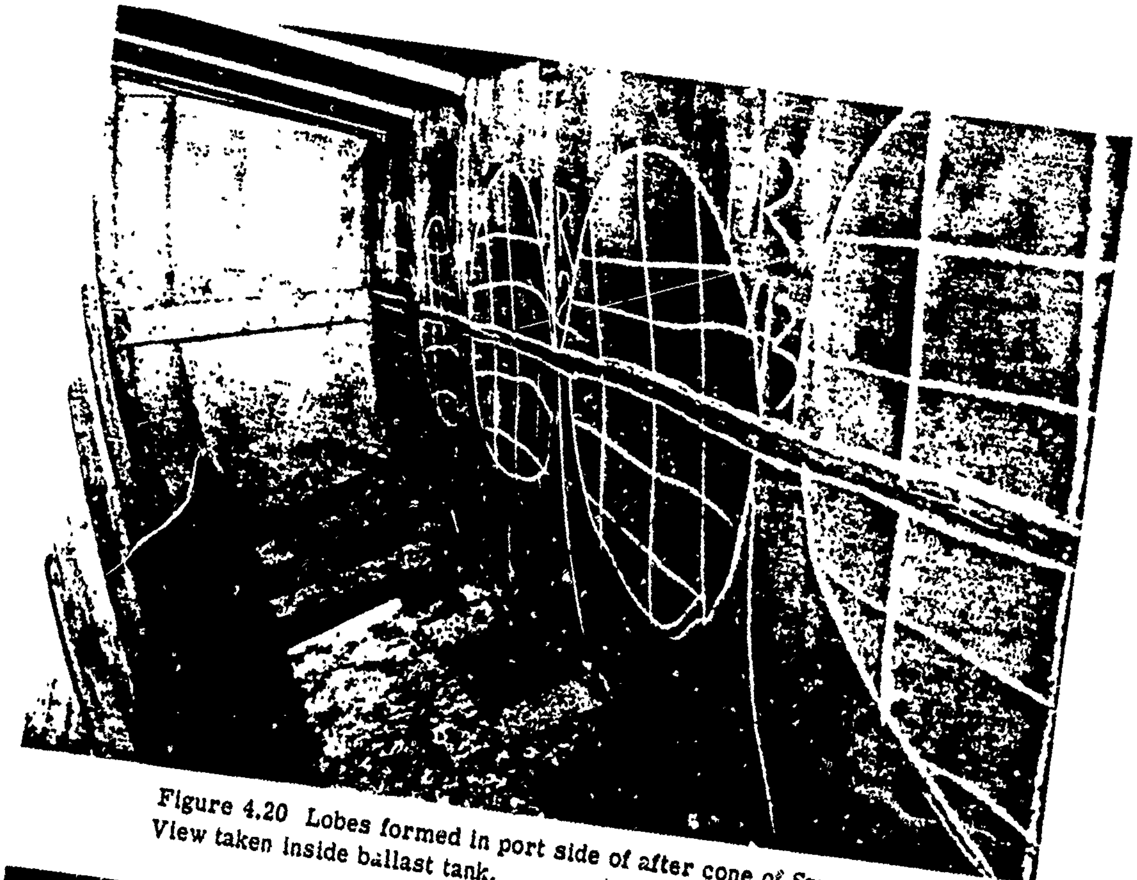


Figure 4.20 Lobes formed in port side of after cone of Squaw. View taken inside ballast tank.

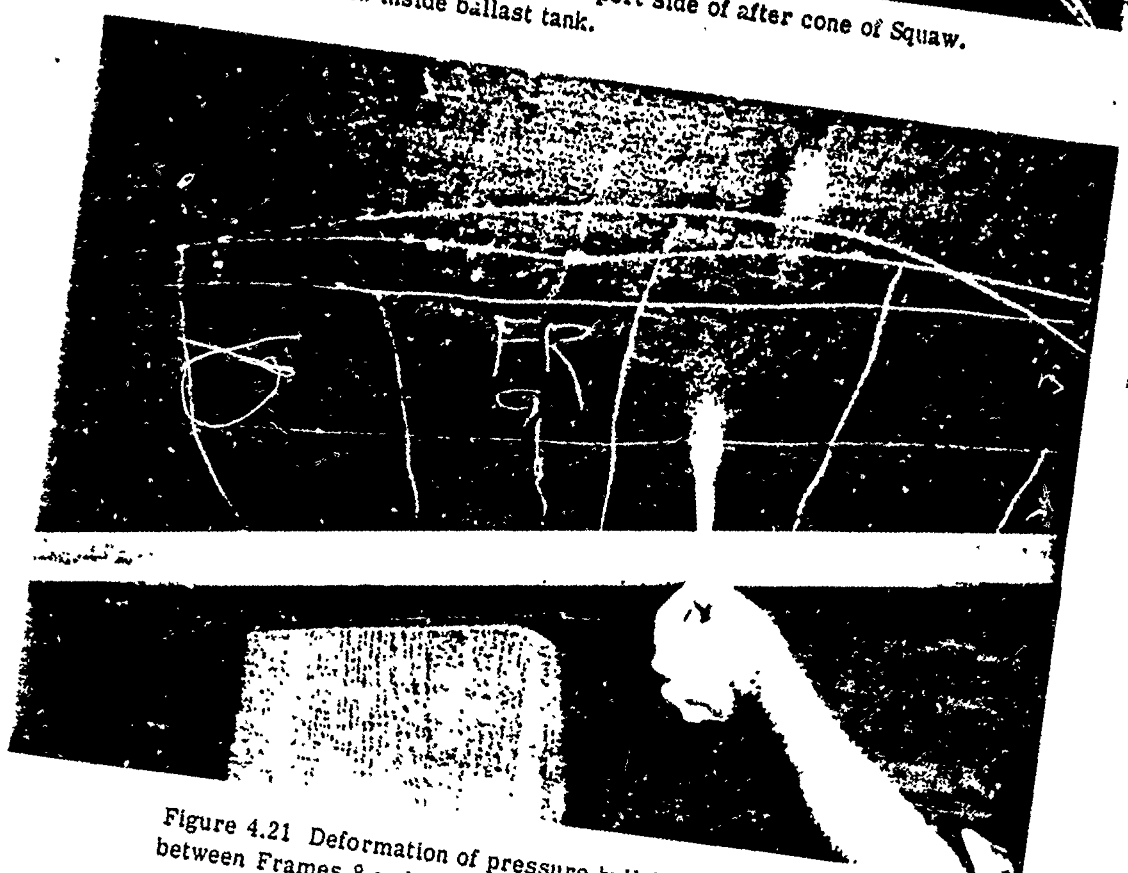


Figure 4.21 Deformation of pressure hull frame and plating between Frames 8 and 10 in the forward cone.

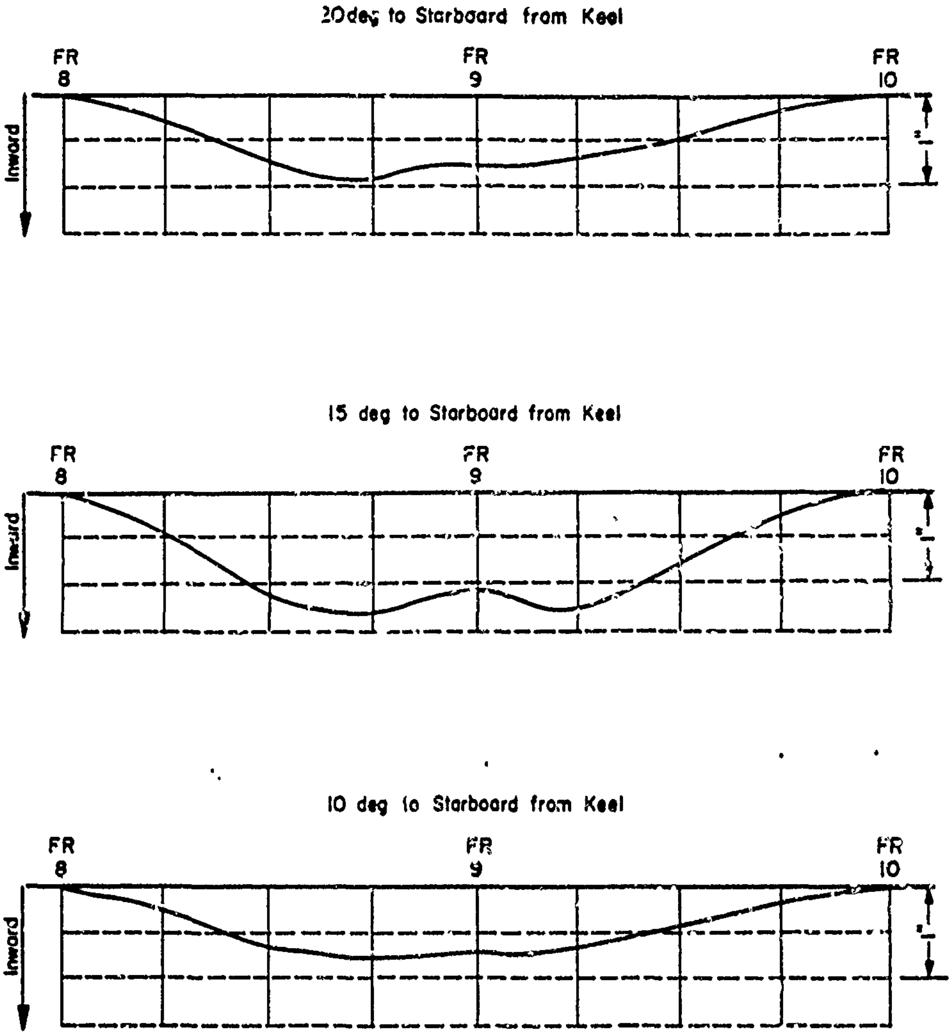


Figure 4.22 Dishing contours resulting from deformation of pressure hull frame and plating between Frames 8 and 10 in the forward cone.

mainly into the test compartments; i.e., away from the bulkhead stiffeners. The bulkhead in the midbulkhead was toward the aft, in this case, toward the stiffeners. Figure 4.23 shows the deformation contours for one area of the aft bulkhead and the areas of major lobing for all the bulkheads.

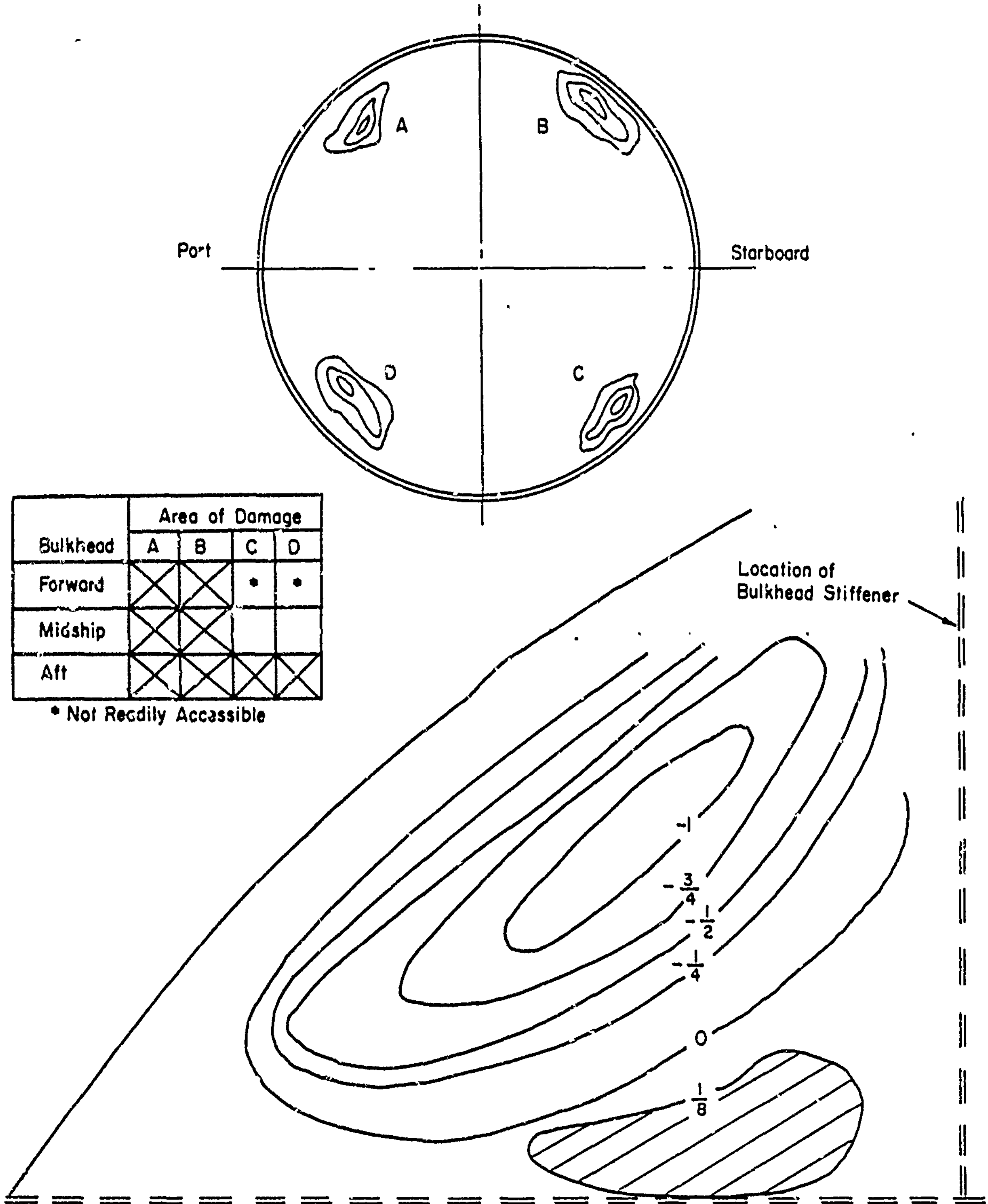
There was no measurable buckling of the bulkhead stiffeners.

4.7 DIAMETER MEASUREMENTS

Diameter measurements of both the plating and stiffeners were made as part of the damage survey. Deviations of the measured values from the nominal inner diameters of the cylindrical portion are shown in Table 4.1.

Examination of eleven measurements on eight frames discloses an average shrinkage of $^{7}/_{32}$ inch. This is not a large amount. Because of the precision with which the Squaws were constructed, the change observed may represent a real reduction rather than an experimental error. The buckling of the plating in the bulkheads supports this conclusion, since it indicates a reduction in Squaw cross section.

Six measurements were of horizontal diameters. The average reduction was only $^{1}/_{16}$ inch. On the other hand, five vertical diameters showed a reduction of $^{13}/_{32}$ inch. The difference in be-



Bulkhead	Area of Damage A	B	C	D
Forward	X	X	*	*
Midship	X	X		
Aft	X	X	X	X

* Not Readily Accessible

Figure 4.23 Damage to bulkheads. Upper portion shows schematically the areas of major bulkhead damage. The lower portion shows actual contours of damage to the aft bulkhead in area "A". Insert table shows areas of damage at each bulkhead.

TABLE 4.1 CHANGES IN DIAMETER IN CYLINDRICAL COMPARTMENTS AFTER SHOT UMBRELLA

Location	Orientation	Deviation From Design Diameter†	Location	Orientation	Deviation From Design Diameter†
	deg	in		deg	in
$14\frac{1}{2}$ inches aft of Frame 30	0	$-\frac{9}{16}$	Frame 34	90	$-\frac{1}{8}$
23 inches aft of Frame 30	0	$-\frac{9}{16}$	$14\frac{1}{2}$ inches aft of Frame 34	90	$-\frac{5}{16}$
$14\frac{1}{2}$ inches aft of Frame 32	0	-1	$14\frac{1}{2}$ inches aft of Frame 35	90	$-\frac{5}{16}$
6 inches aft of Frame 33	0	$-\frac{3}{4}$	$14\frac{1}{2}$ inches aft of Frame 36	90	$-\frac{1}{4}$
$14\frac{1}{2}$ inches aft of Frame 33	0	$-\frac{7}{8}$	20 inches aft of Frame 36	90	$-\frac{7}{32}$
Frame 34	0	$-\frac{5}{8}$	Frame 37	90	$-\frac{5}{16}$
$14\frac{1}{2}$ inches aft of Frame 34	0	$-\frac{5}{8}$	$14\frac{1}{2}$ inches aft of Frame 37	90	$-\frac{9}{16}$
Frame 35	0	$-\frac{11}{32}$	Frame 38	90	$-\frac{1}{16}$
6 inches aft of Frame 35	0	$-\frac{15}{32}$	6 inches aft of Frame 38	90	0
15 inches aft of Frame 35	0	$-\frac{9}{16}$	$14\frac{1}{2}$ inches aft of Frame 33	15	$-1\frac{1}{8}$
Frame 36	0	$-\frac{1}{4}$	$14\frac{1}{2}$ inches aft of Frame 33	30	$-\frac{13}{16}$
$14\frac{1}{2}$ inches aft of Frame 36	0	$-\frac{7}{16}$	$14\frac{1}{2}$ inches aft of Frame 33	60	$-\frac{3}{8}$
Frame 37	0	$-\frac{3}{8}$	6 inches aft of Frame 33	15	$-1\frac{15}{32}$
6 inches aft of Frame 37	0	$-\frac{1}{2}$	6 inches aft of Frame 37	15	$-1\frac{5}{16}$
$11\frac{1}{2}$ inches aft of Frame 37	0	$-\frac{5}{8}$	$14\frac{1}{2}$ inches aft of Frame 37	15	$-1\frac{3}{4}$
Frame 38	0	$-\frac{1}{2}$	6 inches aft of Frame 37	60	$-\frac{11}{32}$
6 inches aft of Frame 38	0	$-\frac{17}{32}$	$14\frac{1}{2}$ inches aft of Frame 37	60	$-\frac{3}{4}$
14 inches aft of Frame 38	0	$-\frac{1}{2}$	$14\frac{1}{2}$ inches aft of Frame 37	105	$-1\frac{1}{16}$
Frame 28	90	$\frac{1}{16}$	$14\frac{1}{2}$ inches aft of Frame 37	115	$-1\frac{1}{4}$
6 inches aft of Frame 28	90	$-\frac{1}{8}$	6 inches fwd of Frame 15	90	$-\frac{1}{8}$
$14\frac{1}{2}$ inches aft of Frame 28	90	$-\frac{1}{16}$	$14\frac{1}{2}$ inches aft of Frame 16	90	$-\frac{1}{2}$
Frame 31	90	$-\frac{3}{16}$	$14\frac{1}{2}$ inches aft of Frame 17	90	$\frac{3}{16}$
$14\frac{1}{2}$ inches aft of Frame 31	90	$-\frac{3}{16}$	$14\frac{1}{2}$ inches aft of Frame 18	90	$\frac{3}{16}$
17 inches aft of Frame 31	90	$-\frac{3}{16}$	$14\frac{1}{2}$ inches aft of Frame 19	90	$\frac{1}{16}$
23 inches aft of Frame 31	90	0	$14\frac{1}{2}$ inches aft of Frame 20	90	$-\frac{1}{8}$
Frame 32	90	$-\frac{1}{8}$	$14\frac{1}{2}$ inches aft of Frame 21	90	0
$11\frac{1}{2}$ inches aft of Frame 32	90	$-\frac{1}{4}$	$14\frac{1}{2}$ inches aft of Frame 22	90	$-\frac{5}{16}$
17 inches aft of Frame 32	90	$-\frac{3}{16}$	$14\frac{1}{2}$ inches aft of Frame 23	90	$-\frac{5}{16}$
6 inches aft of Frame 33	90	$-\frac{1}{8}$	$14\frac{1}{2}$ inches aft of Frame 24	90	$-\frac{5}{16}$
$14\frac{1}{2}$ inches aft of Frame 33	90	$-\frac{5}{16}$	$14\frac{1}{2}$ inches aft of Frame 25	90	$-\frac{7}{16}$
			$14\frac{1}{2}$ inches aft of Frame 26	90	0

* Degrees to starboard of centerline at overhead.

† The design inner diameter of the cylindrical shell was 14 feet $4\frac{3}{4}$ inches; the design inner diameter of the (internal) stiffeners was 13 feet $5\frac{3}{4}$ inches.

havior between the vertical and horizontal diameters may be the result of the pressure field peculiar to the Umbrella geometry. It may also be that detonation of the charges to sever the ballast keel produced the difference.

The reduction in diameter of the plating is much more marked. The average of six measurements at Frame $37\frac{1}{2}$ gives a reduction of 1 inch. At Frame $33\frac{1}{2}$ five measurements give an average shrinkage of $\frac{7}{8}$ inch.

Chapter 5
DISCUSSION

5.1 RANGE AND ATTITUDE OF TARGETS

The range of USS Bonita from Shot Wahoo was determined by fixes that the crew obtained just prior to the detonation and from sonar tracking of Bonita by USS Orleck (DD 886). The SSK 3 was submerged at a depth of 50 feet to the keel, with her port side facing the charge, at a range of 18,000 feet.

The range and attitude of Bonita and Squaw 29 during Shot Umbrella were obtained by measurement of the arrival times of the pressure wave at various gage locations. The times were measured with respect to a telemetered fiducial signal generated at the time of the detonation. The time scale was provided by a 1,000-cps tuning fork, which was recorded on all oscillographs and on the tape recorder. The angle between the longitudinal axis of the targets and the direction of propagation of the pressure pulse was obtained from the difference in arrival times of the shock wave at gages located at various positions along the hull. From the distance between gages and the velocity of the shock wave in water, the time to travel the portion of the targets between gage locations was determined. By comparing this time with the time it should have taken to cover this distance if the longitudinal axis were parallel to the direction of propagation, the angle between the longitudinal axis and the direction of propagation was determined. The velocity of propagation was computed by standard methods using the measured pressure in the water.

It was determined that for Shot Umbrella, Squaw 29, which was submerged at a depth of 52 feet to the centerline, and stern toward the charge, was at a range of 1,680 feet to the center. The intended range was 1,600 feet to the center. The SSK 3, which was submerged to a depth of 54 feet to the keel with bow toward the charge, was at a range of 2,880 feet to the center of the submarine.

5.2 HULL RESPONSE OF BONITA (SSK 3)

5.2.1 Shot Wahoo. The peak strains measured in Bonita during Shot Wahoo are listed in Table 3.1.

Three distinct pulses were noted. The first pulse was the direct shock wave, the second, which arrived later, was the bottom-reflected wave. The origin of the third pulse, which arrived after the direct, cannot be determined precisely.

Free-field pressures were not obtained at this range. However, from the pressure measurements made at 9,190 feet (Reference 7) it appears that the peak pressure, direct or reflected, at the range of Bonita was probably less than 100 psi, with a duration of less than for the direct wave. The estimated pressure for the direct wave excluding refraction and anomalous propagation was with a nominal cutoff Bonita was in the anomalous region. This and refraction effects reduced the pressure in the direct wave to something less than that in the reflected wave. The bottom-reflected pressure, based on isovelocity water and a reflection coefficient of 0.5 (Reference 7), is estimated to have been Refraction appears to have had a smaller effect on the reflected wave than on the direct wave.

The maximum strains recorded were less than half the yield strain and were caused by the shock wave reflected from the ocean bottom. This pulse lasted longer than the direct, and the hull responded more fully as a result.

The oscillograph records (Figures 3.1 and 3.2) show that the initial pulse caused low amplitude oscillations, whereas the reflected wave caused a strain-time pulse that lasted for From the hydrostatic calibration of the strain gages, the pressure in the reflected wave is calculated to have been which would suggest that the hull reached equilibrium with the pressure wave. The nominal cutoff time was about If cavitation began at this time, the release of the total external pressure on the hull might explain the negative swings of the strain records.

5.2.2 Shot Umbrella. The maximum strains measured on Bonita during Shot Umbrella are shown in Table 3.2. These strains were caused by the directly transmitted pressure pulse. A later pulse was recorded, but the strains were small. All initial strains are compressive and rose to a peak value No permanent set was observed. The highest strain recorded was on the flange of Frame 27, 90 degrees to port from the crown, near the intersection of the frame with the deck. High strains were expected at this position in accordance with measurements made during the deep submergence tests. The gages on the hull plating at Frame $52\frac{1}{2}$ gave an average strain Static strains of this magnitude were recorded at a depth of 270 feet during the deep dive tests, i.e..

The peak field pressure at Bonita during Shot Umbrella was with a duration of about (Figure 5.1). Except for the 90-degree gage at Frame 27, this caused strains that were only about the static yield strain (yield is $1{,}100 \times 10^{-6}$) of the hull plating material. Presumably the short duration did not allow the response to build up.

5.3 PRESSURES ON SQUAW

5.3.1 Characteristics of Pressures in Tanks. All gages in any one tank indicated simultaneous arrival times of the direct shock wave after the fiducial.) The pressure-time histories from the gages lowest in the tanks showd initially a sharp rise to peak pressure. It will be remembered the tank bottoms are open. At progressively higher positions, the magnitude of the initial peak decreased. At the top, the rise was not sharp, probably because the wave traveled through the tank bulkheads. The peak pressure also decreased for the higher gages.

At the gages located closest to the tank openings, the initial sharp rise in pressure caused the hull to move in rapidly, reducing the pressure.

At all positions after the pressure increased for and then decayed slowly. The duration of the pressure pulse in the tanks was 6 msec. There was no significant pressure variation between the port and starboard gages.

The maximum pressure measured in the tanks was The record, Figure 5.2, shows that the pressure was reduced to less than half, presumably by the relief pressure from the hull motion. The pressure then increased before decaying to zero.

A second pressure pulse was recorded at about after the zero fiducial, presumably caused by the closure of cavitation. This pressure pulse was characterized by a gradual increase in pressure, Figure 3.9. The duration of this pulse was There were several higher peaks of short duration (less than 1 msec) superimposed on the main wave, but those were faired through in reading the record.

The maximum pressure in the cavitation pulse was recorded by the gage closest to the tank opening in MBT 3 port. The other two gages in this tank recorded pressures of at the centerline and 3 feet above the centerline. This variation in pressure with height in the tank is similar to that observed in the direct wave pressure records. The pressures in MBT 2 were generally lower than in MBT 3 (Table 3.3).

5.3.2 Comparison with Field Pressures. The pressures measured near the Squaw differed substantially in magnitude and duration from Project 1.1 values plotted in Figure 5.1 (Reference 18). Comparison of the data in Table 3.3 with the values for 1,680 feet in Figure 5.1 shows that the peak pressure was smaller in the tanks. On the other hand, comparison of the pressure-time histories plotted in Figure 5.2 shows greater duration for the pressures in the tanks. The areas under the curves seem to be equal, i.e., impulse seems to be conserved.

The differences in form of the incident and tank pressures are at least partially due to the effects of the hull and tank. The pressures are modified by transmission through the outer skin, reflection from the hull, diffraction around the hull, and radiation from local hull motions. The latter effects are discussed in Section 5.4.2.

No comparison of the cavitation-closure pressures is made, because the field-pressure measurements were made at a different orientation with respect to the weapon. The closure of cavitation did not seem to be uniformly orientated with respect to the center of detonation.

5.4 DYNAMIC RESPONSE OF SQUAW HULL

5.4.1 Characteristics. The strain measurements showed the strains to rise to peak values, generally well into the plastic range, in several msec. Gages on the hull reached peak values in whereas gages on frames showed peak strains in more nearly This response time is large, compared with the duration of the field pressure and also with theoretical estimates for end-on response to elastic attack (Reference 9). The occurrence of permanent set voids the possibility of evaluating the theory for end-on response. It may be observed that the response time is greater, as would be expected from a reduction of Young's modulus in the plastic region.

Following the peak, the strains fell away to a stationary value corresponding to permanent set. Table 3.2 indicates elastic recoveries markedly in excess of the static value of about 0.002. This suggests that the dynamic elastic range considerably exceeds the static.

The axial gages show an initial compressive strain. This was a precursor stress wave in the inner shell resulting from the thrust of the pressure applied to the stern. The compression lasted until the shock wave in the water reached the gage locations. At this time, due to the radial pressure load, the axial strain became tensile, and the circumferential strain became compressive.

5.4.2 Comparison with Applied Pressure. In Figure 5.3 the pressure near the bottom of ballast tank Number 3 starboard, the field pressure from Project 1.1, and the strain recorded by the circumferential gage nearest this location (Frame 33½ at 120 degrees starboard from the crown) are plotted on a common time scale.

Perhaps the most striking feature of the plot is that the peak strain was reached after the incident pressure fell to zero. Apparently the shell acquired a large kinetic energy and continued its inward motion as the incident pressure vanished. However, the maximum velocity of the shell, i.e., maximum slope of the strain-time curve, occurred before the field pressure fell to zero.

Several features of the curves suggest that a large fraction of the kinetic energy was not converted into plastic work. One indication is the large elastic recovery. A related indication is that the outward velocity, after the peak strain was reached, was not small compared to the inward velocity. There was, therefore, considerable outward kinetic energy. The outward velocity should have made the shell radiate acoustic energy. That the shell did so is evident from the tank pressure, which persisted several milliseconds after the field pressure disappeared. A similar phenomenon occurs in the scattering of sound by submarine shells.

The energy radiated outward was lost to the damage process. One clue to the energy loss follows from elastic recovery. In Figure 5.3, the elastic and plastic strain components are about equal. Thus, if the stress-strain curve is idealized by an elastic (sloping) portion and a horizontal portion of equal strain, the elastic energy is half that absorbed plastically, or a third of the total. The calculation is obviously approximate only. The ratio of the elastic portion to the total would decrease for larger damage.

The interchange of energy back and forth between the Squaw and the water started when the pressure wave first struck the hull. As the hull moved inward, it absorbed energy from the water and dropped the pressure well below the incident value. The motion relieved the pressure. However, this relief action was not so great as to cause the pressure to drop to zero and produce cavitation. Subsequently, the hull fed back energy, i.e., pressure, as it decelerated and reversed velocity.

The strains caused by the pressures associated with the widespread cavitation in the lagoon showed a more-gradual rise in agreement with the characteristic of the pressure-time history. Only one pressure higher than the static collapse pressure was recorded. Nevertheless, additional permanent set was produced. A similar phenomenon occurs in hydrostatic tests of welded submarine models. It is common practice at DTMB in performing hydrostatic tests on models to load and unload the models several times in approaching the collapse pressure. Permanent set is frequently observed for loads beyond half of the collapse pressure. Another factor is that the pressures during Shot Umbrella were applied dynamically and, if sustained sufficiently, could do somewhat more damage than equal static pressure, because of inertial effects.

For example, Reference 6 reports pressure and greater associated with closure of cavitation as recorded by mechanical pressure gages at 1,200 feet from surface zero. Knowledge of the entire pressure history is necessary in order to determine which phases are important and to include them in lethal radius estimates.

5.5 DAMAGE AND EXPLOSION RESISTANCE OF SQUAW 29

5.5.1 Comparison of Permanent Strains and Diameter Changes. Measurements of dynamic strains on the pressure-hull plating and frames showed that as a result of Shot Umbrella, the hull was plastically deformed in compression at all hoop strain gage locations. In addition, measurements of diameters made after the test indicated that the pressure hull was smaller than the design diameter at almost every position. Assuming that the strains measured resulted from a uniform compression, the changes in radius corresponding to the permanent strains were computed and are given in Table 5.1. For comparison with the diameter measurements, the change in radius determined from diametrically opposite gage positions is added.

TABLE 5.1 DECREASE IN HULL DIAMETERS

Frame Number	Angle From Crown Degrees To Starboard	Computed From Strain Measurements: Permanent Set	Computed From Strain Measurements: Decrease In Radius	Computed From Strain Measurements: Decrease In Diameter*	Decrease In Diameter Computed From Diameter Measurements
			in	in	in
33½	0	0.0016	0.14	0.54	0.88
	180	0.0046	0.40		
	60	0.0018	0.16	0.38	0.34
	240	0.0026	0.22		
37½	0	0.0040	0.35	0.56	0.63
	180	0.0024	0.21		
	90	0.0074	0.64	1.28†	0.56
	60	0.0031	0.27	1.05	0.75
	240	0.0090	0.78		
	120	0.0090	0.78	1.25	1.25
	300	0.0054	0.47		
34	0	0.0041	0.35	0.70†	0.63
37	0	0.0075	0.65	1.30†	0.38
Average	—	—	—	0.88	0.68

* Sum of changes in radius at diametrically opposite positions.
† Twice the change in radius, no measurement at opposite position was made.

There is rough agreement between the two sets of measurements, particularly at those positions at which strains were measured at diametrically opposite locations. The average decrease in diameter was 0.48 percent from strain measurements and 0.37 percent from diameter measurements.

5.5.2 Weakness at Welds. The greatest deformation, and consequently the greatest weakness of the Squaw, appeared to be associated with welding. Dishing between frames occurred generally along the welded seams. The largest deformation, occurred in a small area in which tanks, superstructure, and a frame were welded to the same region of the pressure hull. The tendency toward deformation in the welded areas suggests some loss in the strength of material as a result of welding. However, ordinarily HTS does not exhibit such a reduction of strength.

5.5.3 Weakness of Hull near Bulkhead. In general, maximum deformations of the hull occurred at various locations in the plating between Frames 37 and 38, the first full bay beyond a bulkhead. (The only larger deformation occurred at a seam between Frames 33 and 34.) In tests with small models of the SS 563 class of submarine, maximum deformation also occurred in the first full bay beyond a bulkhead. These tests include hydrostatic tests and tests with large underwater explosions simulating Operation Wigwam (Reference 9). Reinforcing of such bays should be considered. In this respect it appears that if the submarine is designed for uniform strength along the length, it would also perform well under loading by nuclear weapons.

5.5.4 Mode of Deformation of Hull. The Squaw was deformed in uniform compression, as evidenced by the compressive sets in strain, the decreased hull diameter, and the deformation around the periphery of the bulkheads.

The deflections of the stiffeners were too small for any tendency toward instability to develop.

5.5.5 Lethal Damage. Damage to the Squaw appears to have been far short of lethal. The major dishing of the cylindrical portion of the hull was slightly less than one plate thickness. On the other hand, failure might require deformations of five to ten plate thicknesses. However, tears in the plating may occur at smaller deflections. Information on which to base a correlation of deformation and tearing under nuclear attack is needed.

5.5.6 Damage to Ballast Tanks. In the worst cases the damage was probably due to air pockets in the tanks. Effective ways to completely vent tanks should be found.

5.6 COMPARISON WITH WIGWAM

Selected data on the hull response of Squaws to Wigwam and Umbrella are presented in Table 5.2. During the Wigwam shot, Squaws 12 and 13 were submerged at a depth of about 250 feet in deep water and subjected to attack by a nuclear device 2,000 feet deep. Squaw 12 was at a horizontal range of 5,150 feet, Squaw 13 at 7,200 feet. Squaw 12 was Squaw 13 was not. However, based on hull response measurements, Squaw 13 was Neither target was recovered.

From Table 5.2 it may be observed that at identical gage locations, strains and deflections on the Squaw 12 were greater than on the Squaw 13. Comparing Squaw 12 with Squaw 29, it is seen that unambiguous data are available only on peak deflections at Frames 35 and $35\frac{1}{2}$. Here, the deflections on Squaw 12 were enormous, compared to those on Squaw 29 during Shot Umbrella. Comparing strains in the engine compartment of Squaw 29 with those of Squaw 13, it is seen that both peak and set strains were larger on the Squaw 29.

Although larger strains were recorded in the battery compartment than in the engine compartment of Squaw 13, a comparison with Squaw 29 cannot be made directly, since no strains were measured in the battery compartment of Squaw 29. However, Frames $25\frac{1}{2}$ and $37\frac{1}{2}$ were both near a bulkhead. If the strains at Frame $25\frac{1}{2}$ on Squaw 13 are compared with those at Frame $37\frac{1}{2}$ on Squaw 29, it will again be observed that Squaw 29 sustained larger strains. Similarly, comparing strains at Frame 22 on Squaw 13 with those at Frame 34 on Squaw 29 (both near the center of a compartment) and those at Frame 25, Squaw 13, with those at Frame 37, Squaw 29, an identical observation may be made.

It appears, therefore, that Squaw 29 was damaged at least as much as Squaw 13. If this conclusion is correct, then Squaw 13 was not heavily damaged.

Page 60 deleted.

Damage trends in model scale tests do so suggest (Reference 9). There is also increased possibility of plating fracture, if deformation were increased by a considerable amount.

During Shot Umbrella, there was impulsive loading of the structure by a pulse of very short duration. Thus, damage to Squaw 29 resulted from kinetic energy acquired in a few milliseconds and absorbed or reradiated in a few more milliseconds. (This is in contrast with the behavior observed in the engine room of Squaw 13 in the Wigwam test. There, the motion of the hull seemed to be in approximate equilibrium with the applied pressure with inertial effects small.) How much initial shock wave or structural kinetic energy is required under such circumstances to result in lethal damage is not evident, but enough would be necessary to do the plastic work on the structure associated with deformation and provide for incidental radiation losses. Presumably, lethal damage would also be the result of instability and tearing. The time required for the motion and damage to be completed would be large compared to the short duration of the incident pressure wave.

Chapter 6
ESTIMATES of SAFE and LETHAL RANGES

One of the ultimate goals of underwater explosion research is to be able to predict the lethal range for a submarine for all possible charges, sizes, and environmental conditions. Such information should be of great value to weapon and submarine designers and to tactical planners. Even for nuclear weapons, the range of charge sizes is large. The shock waves produced may be long or short, may undergo reflection from the ocean bottom, and may be cut off by reflection from the surface. They are subject to refraction and to nonlinear effects for shallow geometries. Cavitation may occur, and its closure could produce pressures capable of increasing damage. The charge burst may be deep or shallow, as may be the target. Submarine hulls have varying degrees of strength against hydrostatic pressure. They may be constructed of several varieties of steel, or even of aluminum, which have different dynamic strength and failure characteristics.

Under the circumstances, well-substantiated theoretical formulas for estimating safe and lethal ranges could eliminate the need for test data under a great variety of circumstances. Unfortunately, there are no precise theoretical formulas to cover all cases. Specifically, there are none for the Hardtack conditions. As stated in Chapter 1, there are empirical approaches that can be used to make estimates for the Hardtack situation. It is of interest to examine what light Operation Hardtack sheds on these empirical formulas. It is also of interest to determine what additional range predictions may be extracted from the performance of USS Bonita and Squaw 29 by more or less direct extrapolations. Finally, in this chapter are more general remarks concerning safe and lethal radii in shallow water.

6.1 OPERATION HARDTACK RESULTS AND EMPIRICAL FORMULAS

<u>6.1.1 Excess Impulse.</u> In Table 6.1 are listed the excess impulses acting on USS Bonita and Squaw 29 during Shots Wahoo and Umbrella. The results of the tests are in accordance with expectations of Reference 19 that both targets would be certainly safe.

The only entry in Table 6.1 of much interest is that of Squaw 29. Hull-wise, it was certainly safe, although there was hull damage. Whether or not the same value of excess impulse, would have been certainly safe for Wigwam loading is conjectural.

On the basis of Reference 19, the certainly lethal value of excess impulse for a Squaw would be about For Shot Umbrella, this should have occurred at This range should be increased to allow for pressures associated with the closure of cavitation. Adequate data for doing this is not available, unfortunately.

<u>6.1.2 Shock Factor.</u> Table 6.2 lists the shock factors for USS Bonita and Squaw 29. Also listed are values of shock factors considered to be lethal on the basis of tests with chemical explosives. Lethal damage is assumed to occur when the hull is deformed about five hull thicknesses.

Here again the results are in accordance with predictions. The attack was below lethal.

Shock factor is not a reliable indicator of damage for pulses of long duration. On the basis of of the energy incident on Squaw 12 during Operation Wigwam, the shock factor was about 1.0, i.e., less than lethal. However, its use for pulses of short duration seems justified.

Assuming a lethal shock factor of 1.2, the lethal range for Squaw 29 should have been about under Shot Umbrella conditions. This distance should be increased to allow for pressures associated with the closure of cavitation. Unfortunately, adequate data are not available.

6.2 ESTIMATES OF LETHAL RANGE FOR SQUAW 29 DURING SHOT UMBRELLA AND SIMILAR ATTACKS

The estimates of hull lethal radius for Squaw 29 during Shot Umbrella made in Sections 1.4, 6.1, and 6.2 are summarized below.

Basis	Range to Near End, in feet
Comparison with Skipjack	
Excess impulse	
Shock factor	

The estimates are reasonably consistent. No basis is known for selecting among them. A range of 1,325 feet is probably not too far off.

On the basis of the criteria used above, extrapolations to not too different circumstances should be possible with fair accuracy. In passing, it may be noticed that Project 1.1 data does

not show a consistent increase of the energy flux with depth beyond periscope depth for Shot Umbrella. For this reason, no increase of damage should have occurred had Squaw 29 been deeper.

6.3 SAFE RANGES FOR USS BONITA DURING SHOTS WAHOO AND UMBRELLA

From the Operation Hardtack data for Bonita and Squaw 29, it is possible to derive estimates of safe ranges in a comparatively straightforward manner.

First consider USS Bonita during Shot Umbrella. The peak pressure acting on the vessel was Hull yielding did not occur.

In isovelocity water, the Wahoo-type of nuclear device would have produced a pressure of The duration at 50 feet would have been assuming acoustic cutoff. Since the pressure, energy, and excess impulse in the wave were less than acted on Bonita during Umbrella, the Bonita would not have sustained hull damage. Refraction during Wahoo would further have reduced the severity of attack. Calculations taking refraction into account indicate that the excess impulse and shock factor applied to Bonita during Umbrella occurred at 5,800 feet during Wahoo. The pressure in the wave reflected from the bottom was less than the collapse pressure.

6.4 PERFORMANCE OF NUCLEAR WEAPONS IN SHALLOW WATER

Hardtack Umbrella, like Crossroads Baker, involved detonation of nuclear devices in shallow water. Both demonstrated that, in comparison with deep burst and deeply submerged targets, bursts in shallow water are considerably less effective. A natural question under the circumstances concerns the possible improvement in lethal range that might be effected by increasing the size of the charge. A rough estimate is possible and may be of interest.

In shallow geometries the propagation of the shock wave is nonlinear. However, the impulse may be conserved. Consider a weapon on the bottom in water of depth D. Let the submarine be at depth d and range R from the weapon which is equivalent to W pounds of TNT. All distances are in feet. The impulse to cutoff is given approximately by

$$I = 21{,}600\left(\frac{W^{1/3}}{R}\right)^{1.13} \times 0.4\,\frac{d}{R}\,D$$

$$= 8{,}640\,\frac{W^{0.38}}{R^{2.13}}\,Dd$$

If reflection from the bottom is independent of charge weight, the effect may be included by varying the constant term. The precursor wave and early cavitation apparently affect the impulse at distant ranges. However, the analysis is intended only a rough guide, which may stimulate further study. Finally, it is assumed that the total impulse is an index of damaging power of the shock wave. Similar analyses, using either shock factor or excess impulse, are possible, but are more involved. (Because of the erosion of the peak pressure in the shock wave due to nonlinear effects at the free surface, energy and excess impulse both would yield a more rapid decay of damaging power than would total impulse.)

In the equation above, the relation of interest is that between R and W, for fixed depths and impulse, viz:

$$R \ \alpha\ W^{0.18}$$

Thus, if the lethal radius is

This estimate is surprisingly small. For a 1-kt device, the range would be in Eniwetok lagoon.

Further study of such questions appears desirable. Obviously, more-reliable estimates can be made when pressure-time data are available.

Chapter 7
CONCLUSIONS

The operations of Project 3.5 were successful in that instrumental records of strains and pressure were obtained on both Squaw 29 and Bonita. These combined with observations on damage allow some refinement of estimates for safe delivery and damaging ranges.

One of the main objectives of Project 3.5 in Operation Hardtack was not realized: Squaw 29 was not severely damaged during Shot Umbrella. As a result, the instrumental data allow correlation of load and response for conditions of small damage, rather than for the more useful case of large damage.

Under Umbrella conditions, a target such as Squaw 29 would survive with slight to moderate hull damage

For Umbrella conditions, the hull-lethal range to the nearest portion of the hull of a Squaw-like target is estimated ·

Pressures associated with the closure of cavitation caused permanent strains in Squaw 29, which were superimposed on the damage done by the shock wave.

A submarine such as USS Bonita, SSK 3, may deliver without hull damage in the Umbrella geometry from the center of the submarine.

The hull damaging radii for nuclear weapons attacking submarines in shallow water are small relative to radii for deep burst and submergence in deep water. The lethal radius in shallow water changes slowly with yield, possibly as the yield to the 0.18 power.

The USS Bonita sustained no hull damage during Shot Wahoo at a range of 18,000 feet. It is considered that it would not have sustained hull damage in isovelocity water and as close during Wahoo.

The wave reflected from the bottom during Wahoo was not strong enough to contribute to hull damage to Bonita, even at 5,800 feet.

The small degree of damage to Squaw 29 in Umbrella is in agreement with predictions based on Crossroads Baker results and Snay's pressure estimates. It also agrees with estimates based on the observed pressure field and the concepts of excess impulse and shock factor. The data does not permit conclusions regarding severe loads and damage.

The most vulnerable structural components on Squaw 29 were the main ballast tanks. However, it is not believed that they would have been damaged if all air had been bled from the tanks.

The welded areas in the Squaw pressure hull sustained more damage than did similar areas not near welds.

As is frequently the case in static collapse of submarine models, relatively large deformation occurred in the first full bay from a bulkhead.

Chapter 8
RECOMMENDATIONS

1. Since Shot Umbrella yielded information on plastic deformation of submarine hulls for only one specific hull and one specific condition of attack and since theories of hull damage are presently in too rudimentary form to allow estimates of damage for the general case to be made with confidence, model-scale tests are recommended. Data from the model tests would allow the extension of empirical formulas into areas not covered by full-scale results, including effect of orientation of the target. The results obtained from Shot Umbrella could serve as a check point for more general formulas developed from the model tests.

2. Time histories should be calculated of the pressure waves produced by nuclear weapons in shallow water with selected depths and bottom types. Pressures associated with the closure of cavitation should be included. Knowledge of the loads coupled with a method of correlating them with damage would permit reliable estimates of lethal radii in shallow water. In particular, the effects of varying charge weight and water depth should be clarified. Crossroads Baker data on submarine damage would become more useful.

3. If the first recommendation above is not adopted and if another test operation is conducted, Squaw 29 could very well be included in a shallow underwater shot with the intention of severely damaging it. Doing so might give information on the deformation of the shell possible without tearing. Structural weaknesses requiring correction might be disclosed.

4. Efforts to determine the cause of weakness of welded areas of Squaw 29 should be continued. If necessary, portions of the hull should be cut out for study and replaced by other material.

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