INVESTIGATION OF WATER IMPACT OF BLUNT BODIES

by

C. Richard Gerlach

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FINAL REPORT

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13. ABSTRACT

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Three two-dimensional models were constructed having section shapes of a U, UV, and V form, but identical extent of flat bottom. Drop tests were performed on still water and on waves, and impact pressure data was obtained at several locations on the bottom of each model.

For impacts on still water, the peak pressure varies in a complex fashion as a function of basic shape, mass loading, and extent of flat bottom. For impacts on waves, the pressure values are quite random for subsequent drops, and the average value for a large number of samples is greatly reduced from the still water pressure value. It is concluded that the impact mechanism for waves is quite different from the still water impact condition, and the wave data correlates well with model seaworthiness test results.

The effect of bottom elasticity is to generally reduce the peak impact pressure. Work hardening of the elastic bottom ~~can reduce~~ the cushioning effect, causing the peak pressure to increase for subsequent drops.

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TABLE OF CONTENTS

ABSTRACT

This report summarizes results of an experimental study to determine the influence of (a) hull form, (b) water surface state, and (c) elasticity of a model bottom on the peak pressures experienced by a body impacting on a water surface.

For categories (a) and (b), three two-dimensional models were constructed having section shapes of a U, UV and V form, but identical extent of flat bottom. Drop tests were performed on still water and on waves, and impact pressure data was obtained at several locations on the bottom of each model.

It was determined that, for impacts on still water, the peak pressure varies in a complex fashion as a function of basic shape, mass loading, and extent of flat bottom. The V form generally gave lower pressures than the more blunt forms. For impacts on waves, the pressure values are quite random for subsequent drops, and the average value for a large number of samples is greatly reduced from the still water pressure value. It is concluded that the impact mechanism for waves is quite different from the still water impact condition, and the wave data correlates well with model seaworthiness test results.

The effect of bottom elasticity is to generally reduce the peak impact pressure. Work hardening of the elastic bottom can reduce the cushioning effect, causing the peak pressure to increase for subsequent drops.

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

1. Background

Ship bottom damage caused by slamming or water impact is a serious potential problem which must be considered in the design of a new vessel. The great amount of time and money spent each year for the repair of slamming-induced damage is testimony to the magnitude of this problem. Being able to accurately predict slamming induced pressures on the forward bottom of ships is an essential part of good seaworthiness design for new vessels. Unfortunately, at this time we have insufficient knowledge of the very complex interaction between an elastic ship bottom and a typical sea surface, so that the desired predictions cannot be made with any degree of certainty except for particular conditions where experimental data is available.

An accepted experimental practice is to conduct model seaworthiness tests whereby slamming pressure data is collected and then used to predict full-scale impact occurrence and pressures. Slamming predicted in this manner by M. K. Ochi[1] has recently shown excellent agreement with data recorded at sea for the SS WOLVERINE STATE. This agreement between model seaworthiness tests and full-scale slamming validates the use of ship model tests in waves as a design tool. Following this approach, M. K. Ochi[2] has tabulated, from various model seaworthiness tests, impact pressure-velocity relationships for some standard hull section forms.

One problem with model seaworthiness tests is that a great deal of time and expense is involved in performing basic studies of the effect of hull form on impact induced pressures. This is the type of information needed at the early design stage when the overall hull form is being decided. On this basis, the use of the much simpler and less expensive two-dimensional drop tests of the type performed by M. D. Ochi[3] are very attractive.

Prior to the work performed during the study discussed herein and in References 4 and 5 , the relationship between two-dimensional drop tests and model seaworthiness tests was in question. The reason was that these drop tests (performed on still water) generally gave considerably greater peak pressure values than those observed from the model seaworthiness tests. A recent examination of ship model drops on still water compared with model seaworthiness slamming data[6] has also shown significant discrepancy. The question to be answered,then, was: What factors contribute to this discrepancy between drop tests of two-dimensional models (or entire ship models), and model seaworthiness tests?

A large amount of effort has been put forth in recent years (e.g., References 4, 5, 7, 8, 9, 10) to obtain transient pressure data for simple-geometry, blunt bodies impacted on still water, and in some cases[4,5] on a disturbed surface. The objective of several of these studies was to explore various phenomena which might explain the great difference between theoretical impact pressures and pressures observed from the model seaworthiness tests; the predicted peak pressures are generally about two orders of magnitude greater than comparable experimental model results. One possible explanation advanced several years ago was that air trapped under the hull cushioned the impact and several investigators pursued this in some detail.

In the course of earlier work performed by one of the writers[4,5] it was found that, although air trapped under a blunt model impacting on a quiet water surface does result in a significant cushioning effect, the presence of waves on the water surface has an almost overwhelming effect on slamming pressure transients. Consequently, the influence of air trapped when a body impacts on a disturbed surface was concluded to be minor compared with the direct influence of the waves. While the pressure transients obtained from model drop tests on a still water surface are very repeatable from test to test, pressure transients obtained from drop tests on a disturbed surface are random in nature and generally show a mean reduction in peak pressure of about a factor of five, compared with data for an undisturbed surface. The peak impact pressure data shown in References 4 and 5 for simple flat-bottomed models impacted on a disturbed surface compare favorably with seaworthiness impact pressure data reported by M. K. Ochi[2]. This suggested that dropping simple two-dimensional models on a disturbed water surface should indeed give reliable impact pressure data. As noted above, this is a desirable goal since the time and expense involved in exploring the effect of hull shape, bottom elasticity, and other important parameters, would be greatly reduced by using two-dimensional models, rather than performing seaworthiness tests on a series of complete ship models.

The general objective of the work reported herein was to further bridge the gap between simple drop tests for both rigid and elastic models, and the more complicated model seaworthiness tests.

2. Objective and Scope of Entire Study

This study was conducted in four separate phases, and the objective and scope of each phase is indicated below. The results of Phases I and II are reported in References 4 and 5 , respectively. The results of Phases III and IV are given in this report.

Phase I - Water Impact of Blunt Rigid Bodies - Real Fluid Effects[4]

The objective of this phase was to determine, by way of appropriate experimentation, the importance of air density and other real fluid properties on water impact pressures experienced during the low velocity impact of blunt, rigid bodies. To achieve this objective, a number of experiments were carried out using small models impacting normally upon a liquid with a superposed gas. Transient pressures, during impact, were obtained for a number of variations of the real fluid properties, namely; gas density, liquid density, interfacial tension, liquid viscosity, and speed of sound in both fluids. Studies of impact, upon both a quiescent and a disturbed liquid surface, were undertaken. Further, some experiments, designed to yield evidence of the deformation of the liquid surface during impact, were carried out.

Phase II - Water Impact of Blunt Rigid Bodies - Size Scale Effects[5]

The objective of this phase was to determine the effect which model size has on the impact of rigid, flat bodies upon a still water surface; the important dependent variable is the initial peak impact pressure. Another objective of this study was to determine the difference, in terms of peak impact pressure, between two- and three-dimensional air flow from beneath the model prior to impact. Experiments were performed with a number of flat-bottomed, square models ranging in size from 2 inches to 20 inches; impact pressure histories were recorded with each model for a number of drop heights and, where possible, with several model mass loadings. All models were tested under three-dimensional air flow conditions, while only two of the models were tested under two-dimensional air flow conditions. As an added feature, a few experiments were performed by impacting one of the models on a disturbed surface.

Phase III - Water Impact of Blunt Rigid Bodies - Effect of Hull Form

The objectives of this phase were to (a) clarify the effect of hull shape and extent of flat bottom on slamming impact pressures, and (b) to explore the effect of waves for two-dimensional drop tests so that a correlation could be made with model seaworthiness test results. For this purpose, three two-dimensional models were constructed having section shapes identical to the U, UV and V models tested by M. D. Ochi[3]. The models were of different scales, so that the extent of flat bottom was identical for each. Drop tests were performed on still water and on waves, and impact pressure data was obtained at several locations on the bottom of each model.

Phase IV - Water Impact of Blunt Bodies - Effect of Bottom Elasticity

The objective of this phase was to determine the effect which bottom elasticity has on the pressure transients imposed on blunt bodies impacting on a water surface. Drop test models were constructed which had replaceable elastic bottom plates. The models were rectangular in shape and flat-bottomed. Impact pressure was monitored as a function of impact velocity, and bottom plate elastic characteristics. Drop tests were conducted on still water and on waves to establish the effect of surface condition on the water-bottom interaction.

EXPERIMENTAL APPARATUS AND TEST MODELS

1. Drop System and Wave Maker

The drop test facility which was used for the present study is identical to the facility reported in Reference 5 , and is shown in Figure 1. The model is held at the desired drop height by a pneumatically actuated release mechanism, which in turn is supported by a trussed-beam structure. The cylindrical water tank is 5 feet in diameter and 26 inches deep. A horizontal ring baffle, located 6 inches below the top of the tank, and 1/4 inch below the mean water surface, provides wave damping following each test drop. Two vertical baffles, portions of which lie below the water line, can be adjusted to any model width when two-dimensional air flow is required. In the background of this photograph is the wave-generating device, and diametrically opposite the wave maker is a slotted, damping baffle that minimizes reflections of the traveling wave. A side view of the wave generator and baffle is shown schematically in Figure 2. A variable speed hydraulic motor is coupled to the cylindrical wave maker through a gear-linkage mechanism and provides the power for wave generation.

The wave frequency, or alternately the frequency of vertical oscillation of the wave generator, is monitored by an electromagnetic proximity gage that detects the passage of teeth on the drive gear. Theoretically, the wave frequency is limited only by operating constraints of the hydraulic motor and power supply, or the mechanical linkage. In practice, however, satisfactory waves could be generated only at frequencies less than 4 Hz. Above 4 Hz, reflections from the tank wall, induced transverse waves that destroyed the two-dimensional wave pattern. Below 4 Hz the ratio of wave height (double amplitude) to wave length was of the order of 1/12, and this represented approximately the condition of the surface for those drops conducted on waves.

2. Rigid, U, UV and V Form Models

Three basic two-dimensional hull form models were constructed having U, UV and V form cross-sectional profiles. The UV form profile, shown in Figure 3, represented a 1/40-scale of Station 3 1/2 on a 520-foot Mariner vessel. These models were identical in form, but not in scale, to those used by M. D. Ochi in an earlier study (Reference 3). All models were constructed of longitudinal wood laminates held together by adhesive and transverse dowels. Wooden surfaces were sealed with lacquer to inhibit moisture absorption and subsequent swelling. The model was mated to the

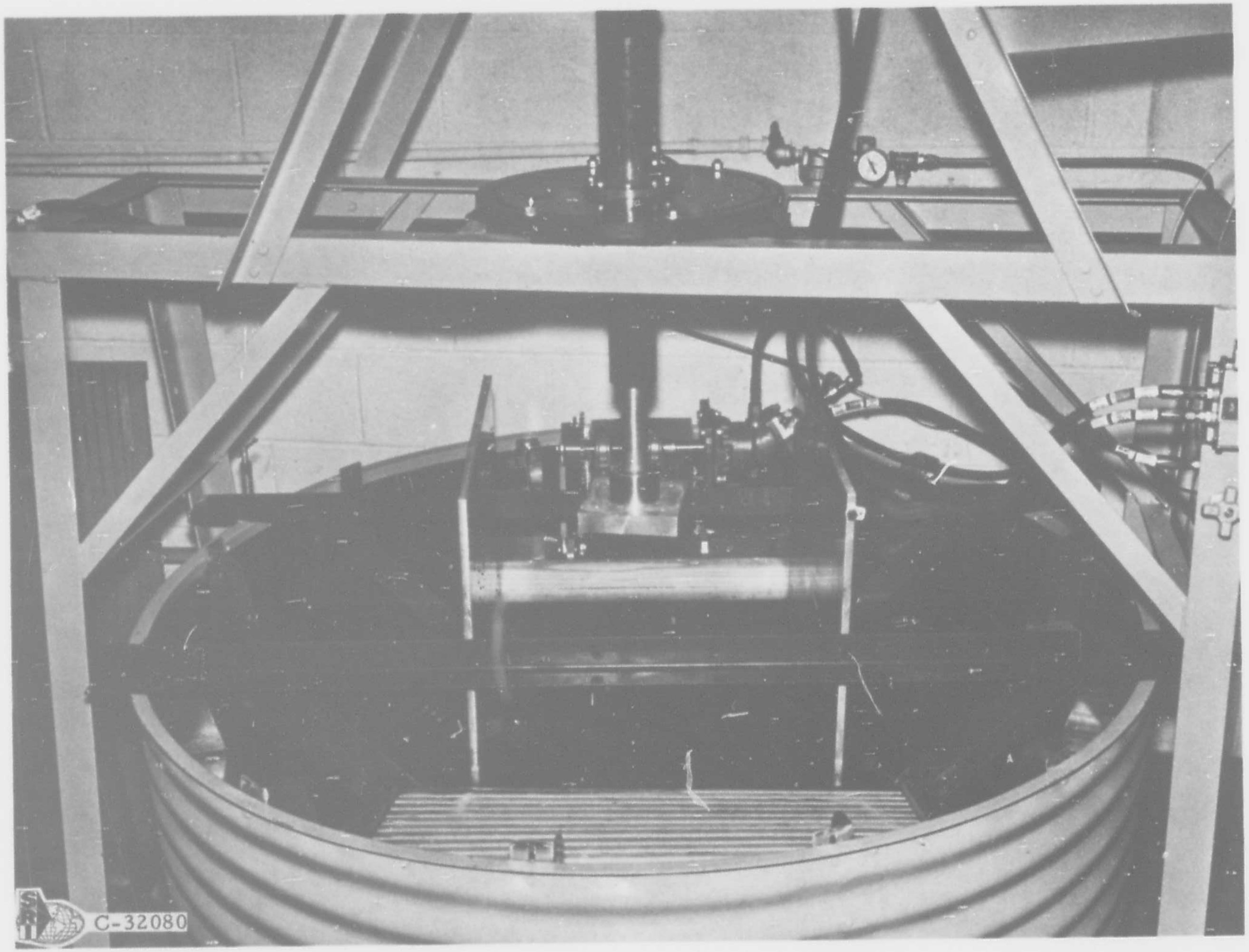


Figure 1. Photograph of Drop Test Facility

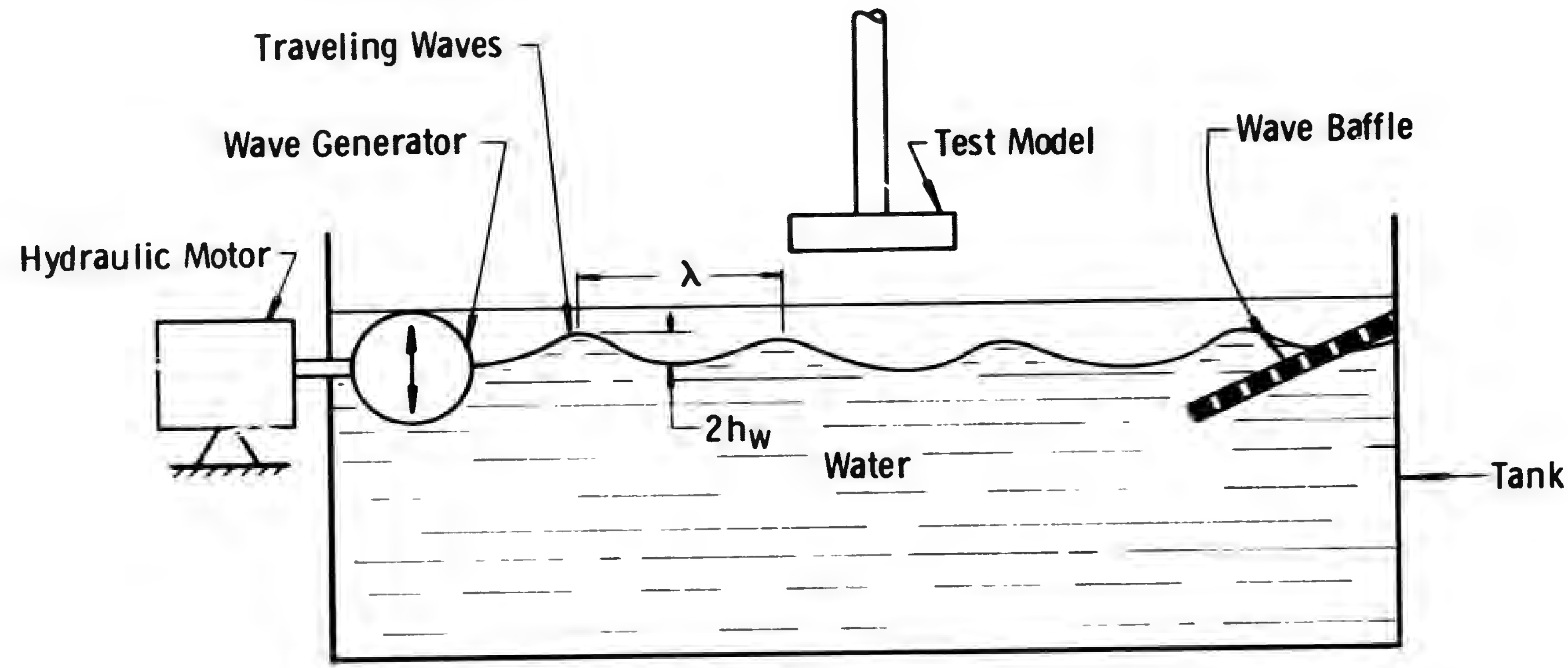


Figure 2. Experimental Setup For Drop Testing On Waves

Figure 3. Photograph of UV Model

drop mechanism through a metal plate securely fastened to the upper surface of the model. Lead weights were bolted uniformly to the upper surface of this plate in order to control the mass of the entire drop system.

In line with the research objective to investigate the effect of extent of flat bottom on impact pressure, the basic UV form was twice modified, each time adding more flat bottom. These three versions, in order of increasing flat bottom width, were designated -0, -1, and -2. Figure 4 presents half-body profiles for the basic models as well as the UV modifications.

All hull form models were 12 inches long with the exception of the V-1 model (basic model was designated V-0) whose length was decreased to 4 inches in an attempt to increase the mass loading during impact as well as to determine the effect of two- versus three-dimensional air flow on the impact pressure. The U and UV series were 4 inches deep at the keel, whereas the V series employed a keel depth of 4.5 inches. Table I contains a compilation of the various model parameters.

Table I
Hull Model Parameters

Model	Planform Area, ft^2	Drop Weight, lb
U	0.31	20
UV-0	0.80	23,50
UV-1	0.89	25,50
UV-2	1.0	46
V-0	1.67	36,104
V-1	0.56	51

The mounting locations for the pressure transducers used on the wooden U, UV and V models are defined in Table II. These locations duplicated those used by M. D. Ochi[3].

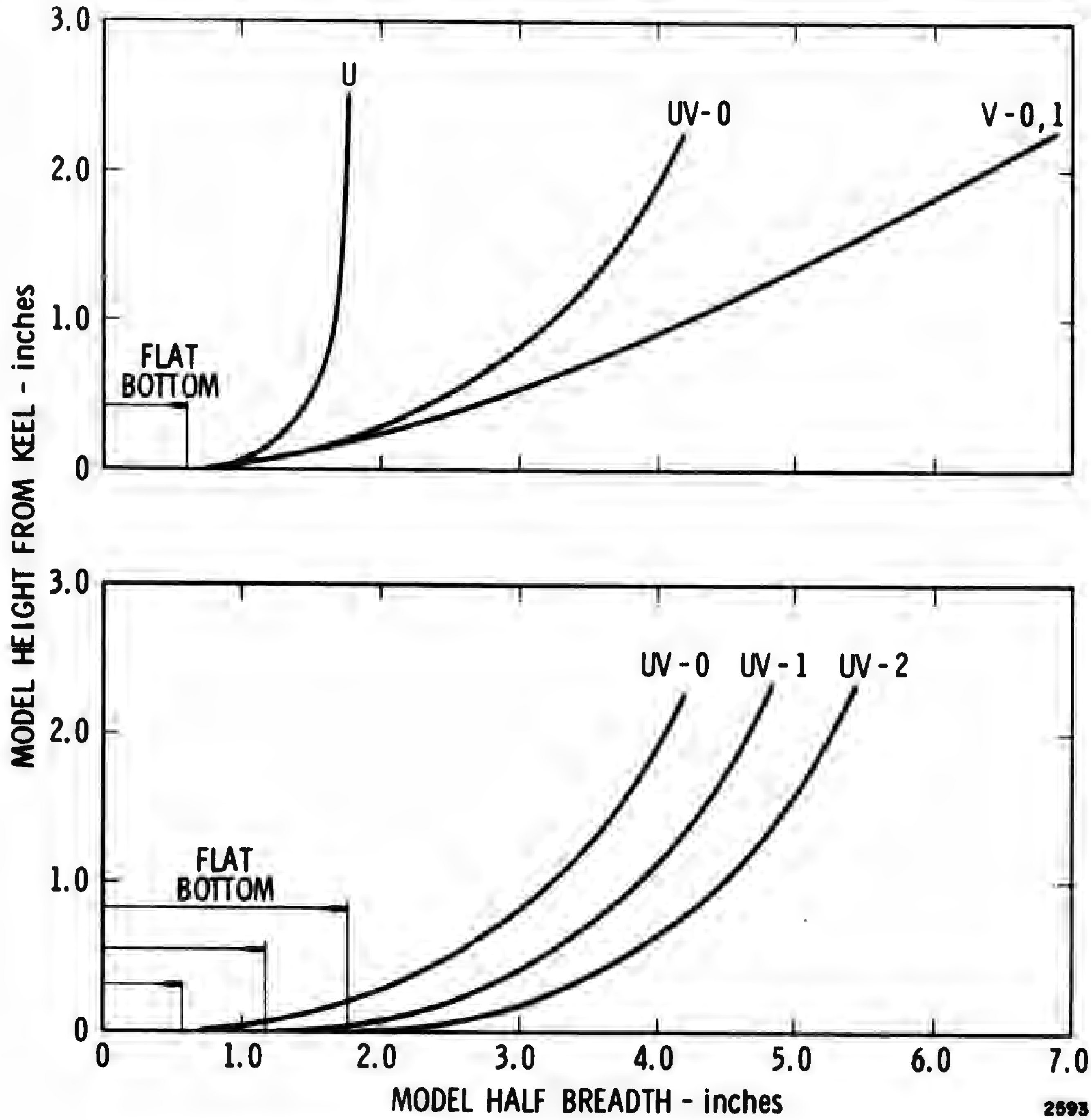
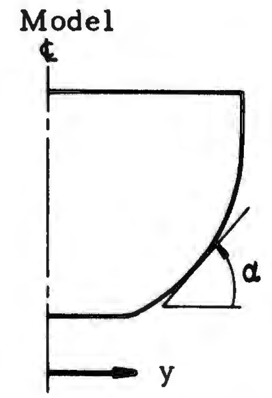


Figure 4. Hull Model Section Forms

Table II
Transducer Locations on Model Hull Forms



Model	Transducer Location Relative to Keel, y (in.)	Local Slope, α (^{o})
UV-0	0	0
	1.1	10
	2	21.5
	3	37
UV-1	0	0
	.6	0
	1.7	10
	2.6	21.5
UV-2	0	0
	.6	0
	1.2	0
	1.7	0
	2.3	10
	3.2	21.5
	4.2	37
V-0, 1	0	0
	2.5	15.7
	4.8	23.5
	8.6	36
U	0	0
	.4	0
	.7	6
	1.1	22.5

3. Flexible Bottom Model

The flexible bottom models consisted of flat plates of varying thicknesses, and a mounting form. This mounting form was prepared from the nominal 12 x 12 inch, 80-pound, mass saturated structure reported in Reference 4 by recessing the flat surface 1/2-inch to within 1.0 inch of the boundary. The flexible plates, with the same planform as the original model, were securely attached to the mounting body by numerous screws located 1/2 inch from the edges. The recessed cavity was vented to the atmosphere to permit the air behind the plate to escape during impact, thus eliminating a potential data error caused by the resistive cushioning of this gas.

The installed plate simulates a structure with a modified clamped boundary condition, and grossly approximates a ship hull panel mounted between consecutive bulkheads and longitudinals. A single flush-mounted pressure transducer was installed at the geometric center of the plate. This transducer was mounted on a small aluminum fixture which was bolted and epoxied to the test plate. The model body, plate and transducer mount are presented in Figures 5 and 6. Variations in bending rigidity were obtained by altering the plate thickness while keeping the material properties constant (6061-T6 aluminum). Thicknesses of 0.25, 0.125, 0.09, and 0.05 were tested. The plates were drop tested from heights ranging from 2 to 12 inches onto a quiescent water surface, and onto waves.

4. Instrumentation

The basic instrumentation utilized for all tests consisted of one or more pressure transducers (Kistler Model 603A), an inhouse designed output amplifier system, and an oscilloscope with an attached Polaroid camera for obtaining impact pressure histories. In earlier work, the 603A Kistler transducers had been verified to have adequate frequency response for our purposes. The Kistler charge amplifier, however, was somewhat frequency limited, so the SwRI amplifier was utilized. This unit, which is a wideband, low noise and high input impedance design, has the following characteristics:

(1) Input impedance — 200-MΩ, shunted by variable input capacitor

(2) Output impedance — 45-Ω

(3) Input noise — 16-μV, RMS

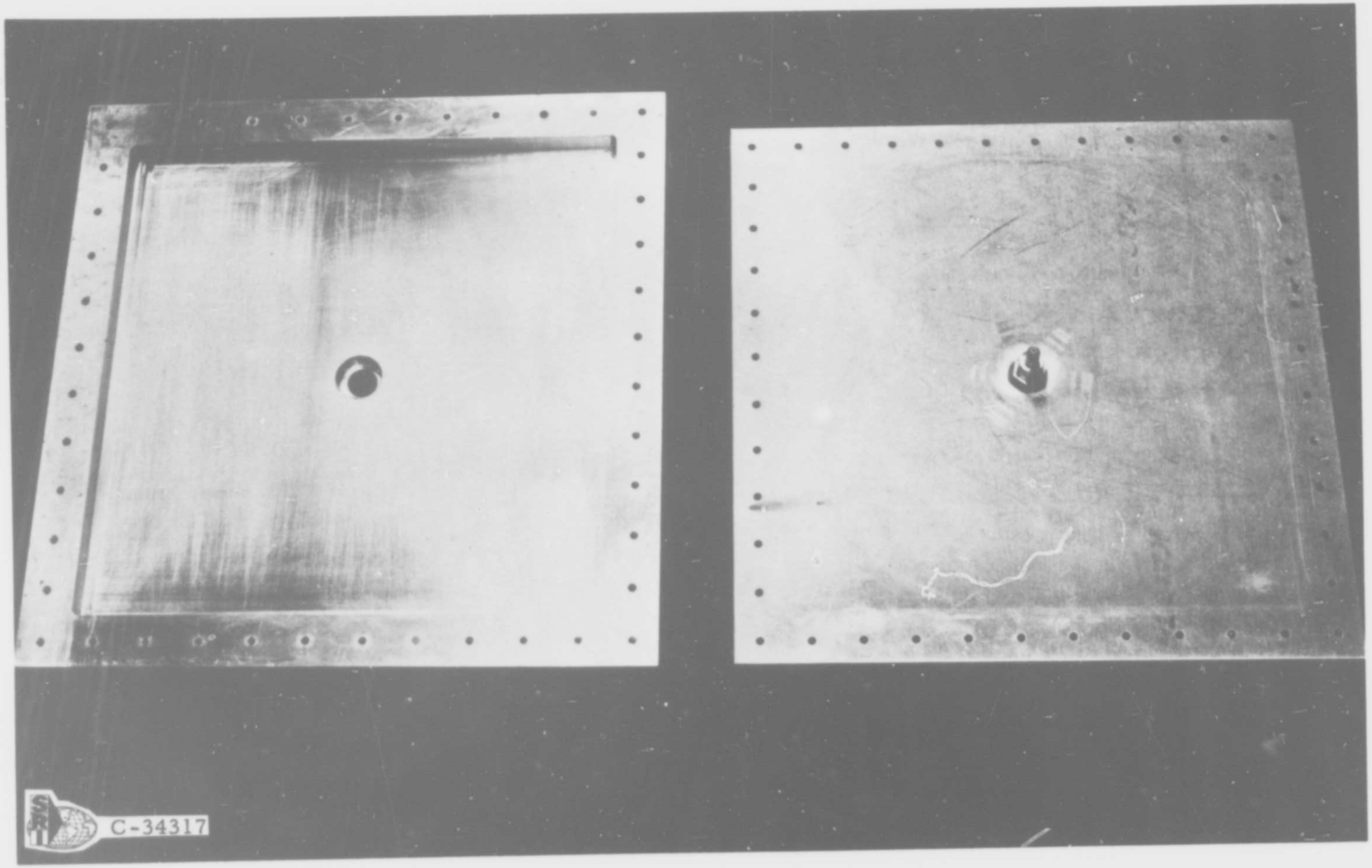


Figure 5. Flexible Plate Model - Interior Surface

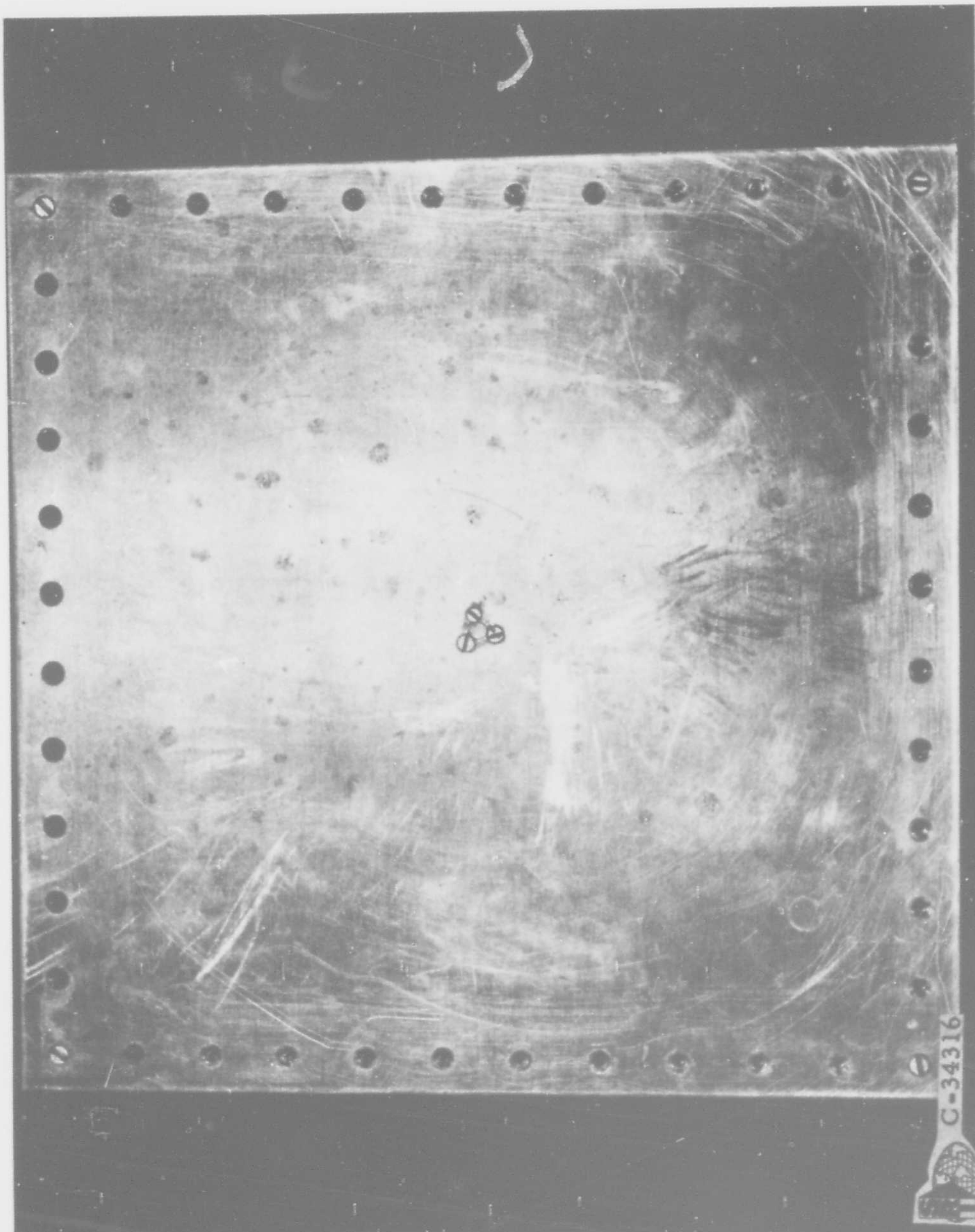


Figure 6. Flexible Plate Model - Impact Surface

(4) Bandwidth (with cable and transducer)— 2.5 Hz to 3 MHz, with critical damping at the corner frequencies.

(5) Maximum output voltage — 8 ,Vpp

(6) Voltage gain — 20.0-dB.

The pressure instrumentation system described above operated satisfactorily without any sign of pressure-induced ringing, even with rise times of the order of a few microseconds. When used with the flexible bottom model, however, some minor acceleration induced errors were observed because of the plate vibration. The transducers were supposedly acceleration compensated, but because this was not a perfect compensation, some errors occurred. An attempt was made to cancel out this error,but it proved to be more trouble than it was worth. The error cancellation was achieved by "adding out" an acceleration signal obtained from an accelerometer mounted immediately next to the pressure transducer on the same mounting fixture (see Figure 5).

This cancellation scheme was "calibrated" by mounting the accelerometer-transducer-fixture system on an electrodynamic shaker. At a given frequency and excitation level, the accelerometer channel gain was tuned to null out the resultant "sum" signal. Unfortunately, the gain required varied as a function of frequency. Ideally, then, perfect compensation could be achieved at only one frequency. Comparison of pressure histories with and without the use of this compensation showed primarily a change in the fine detail of the trace, but no significant change in the peak pressure amplitude. All data presented herein was obtained without compensation for acceleration-induced errors.

EXPERIMENTAL RESULTS--EFFECT OF HULL FORM

1. Experimental Plan

Drop test experiments were conducted on a quiescent and a disturbed water surface. For each surface condition, model geometry was systematically varied to investigate:

a. The effect of basic hull form on peak impact pressure distribution, and

b. The effect of extent of flat bottom on the peak pressure distribution.

In the course of the above experiments, information was also obtained on the sensitivity of impact pressure to the degrees of freedom available to the escape air under the model. Finally, the two-dimensional impact data was compared with model seaworthiness test results.

All data was obtained in the form of oscilloscope records showing the impact pressure history for the four transducer channels. For drops on still water, each data point presented represents an average of at least three drops. As in prior work[4,5], the pressure data repeated well on still water if care was exercised to insure (a) that no water droplets were present on the model bottom, (b) that the water surface was indeed still, and (c) that the model bottom was parallel to the water surface.

Pressure data for drops on waves was also obtained in the form of oscilloscope records. However, in this case, many more drops were performed in view of the random nature of the pressure histories. Typically from 20 to 100 drops were made on waves.

2. Impact on a Quiescent Water Surface

a. Effect of Hull Form

The U, UV and V form series of models, including the dimensional modifications, were drop tested on a quiescent water surface from heights ranging from 2 to 12 inches. Each model, with the exception of the U form, was tested using at least two model weights. The basic forms as well as their modifications, drop weights and planform areas were summarized earlier. The primary reason for increasing drop weight or decreasing model length (V series) was to increase the mass loading toward saturation. For each of these model conditions the experimental results were displayed in the following form: Peak impact pressure as a function of impact velocity with local body slope (beam-wise transducer location) as a parameter and are presented in Figures 7 through 15. As anticipated, the pressure-velocity relationship is generally log-linear. The anticipated overall effect of increasing the mass loading on the models was to increase the impact pressure for a given drop height. However, inspection of the UV and V series will reveal that the gains are minimal, indicating that even though a more nearly mass saturated condition was achieved by increasing model weight, a nearly saturated condition existed initially.

The V-1 model, with its abbreviated length, was dropped between the vertical baffles to insure a two-dimensional air flow beneath the model during impact. It can be assumed that the two-dimensional flow was achieved with the longer model lengths.

The UV-0 (50 lb) and V-1 (51 lb) represent the most nearly mass-saturated conditions for these two models. If the impact pressures for these models and the U form model at a drop height of 6 inches are normalized with respect to the square of the impact velocity (5.68 ft/sec), then a direct comparison can be made with the results obtained by M.D. Ochi[3]. This comparison is shown in Figure 16. For body slopes greater than 10 degrees, the logarithm of the normalized impact pressures of this study decay linearly with body slope as did those of Ochi. It appears that the V-1 model (higher mass loading with vertical baffles) was not truly mass saturated. For body slopes less than 10 degrees it appears that there is a considerable discrepancy between the two sets of data. However, private communication with M. D. Ochi revealed that the current data points are probably more valid because of the use of higher fidelity transducers, and more rigid models. The overall trends of the two sets of data do tend to support each other.

b. Effect of Extent of Flat Bottom

The effect which flat bottom width has on the peak impact pressure profile can be illustrated by combining Figures 8, 10 and 11 for the UV-0, 1 and 2 models, and presenting the results for a fixed drop height. Such a combination is presented in Figure 17 for a 6-inch drop height. Note that the abscissa is composed of two segments which together account for the varying flat bottom width and the local body slope outboard of the flat bottom.

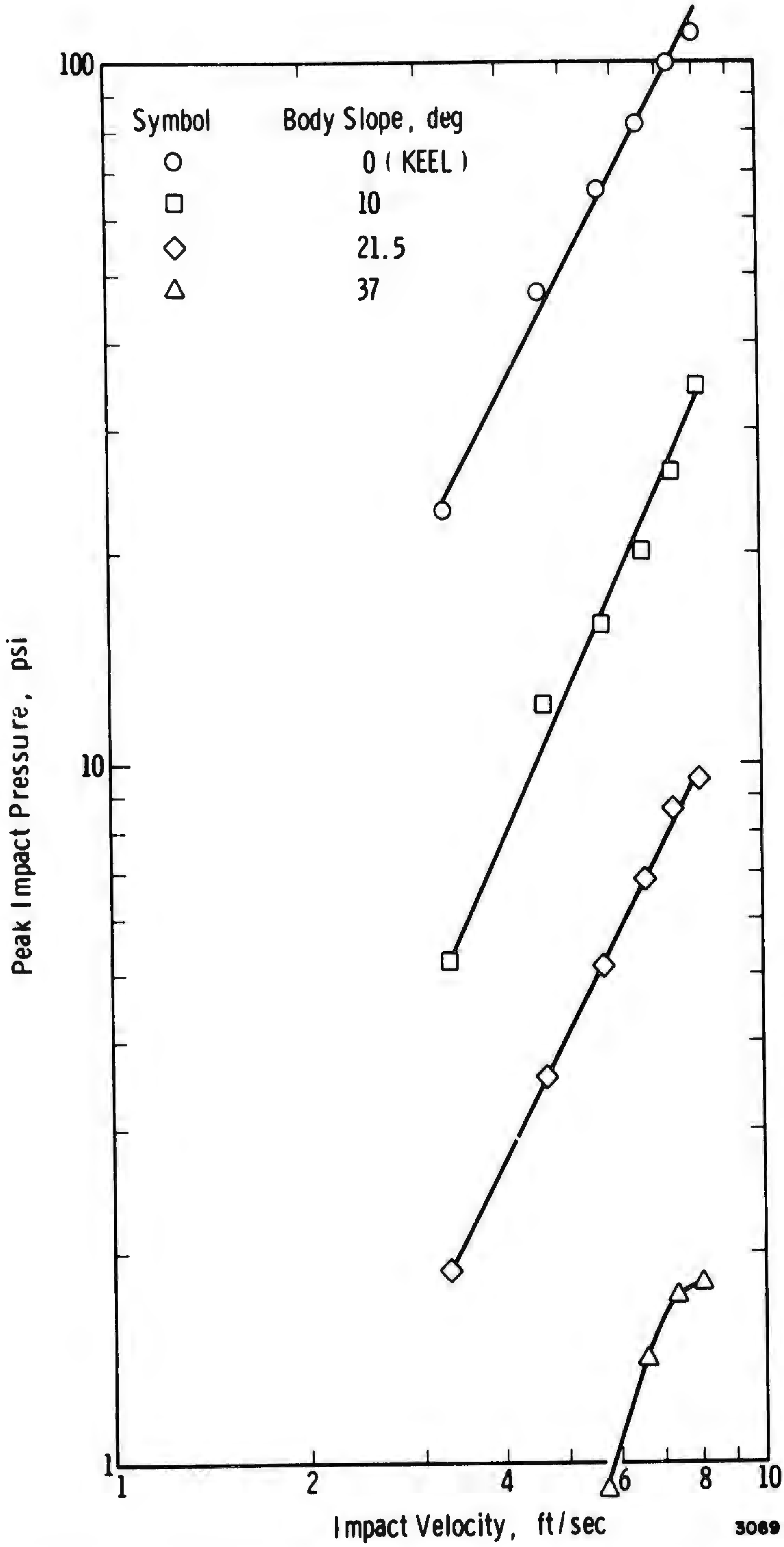


Figure 7. Variation Of Peak Impact Pressure With Impact Velocity For The UV-0 Model (23 lb) On Still Water

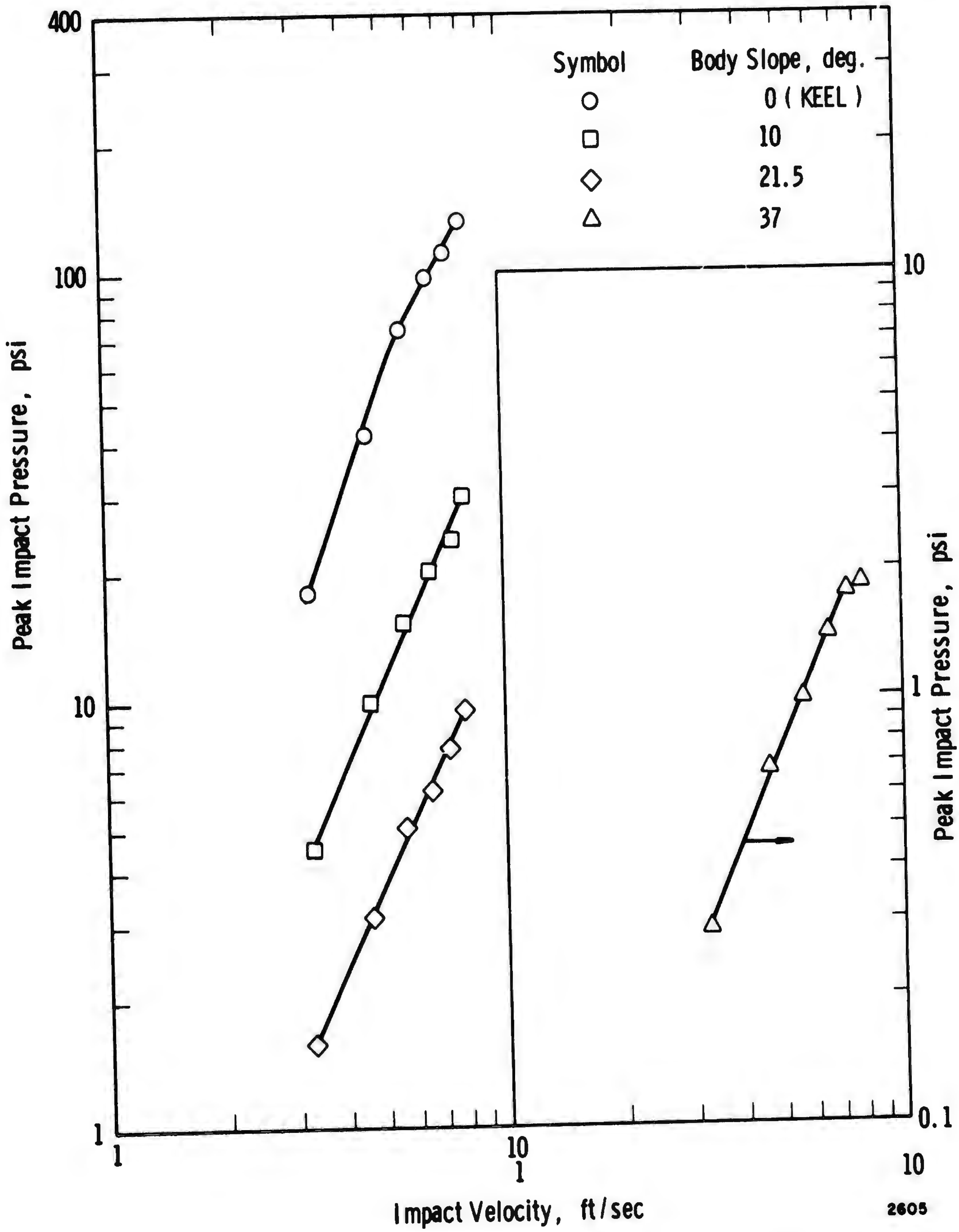


Figure 8. Variation Of Peak Impact Pressure With Impact Velocity For The UV-0 Model (50 lb) On Still Water

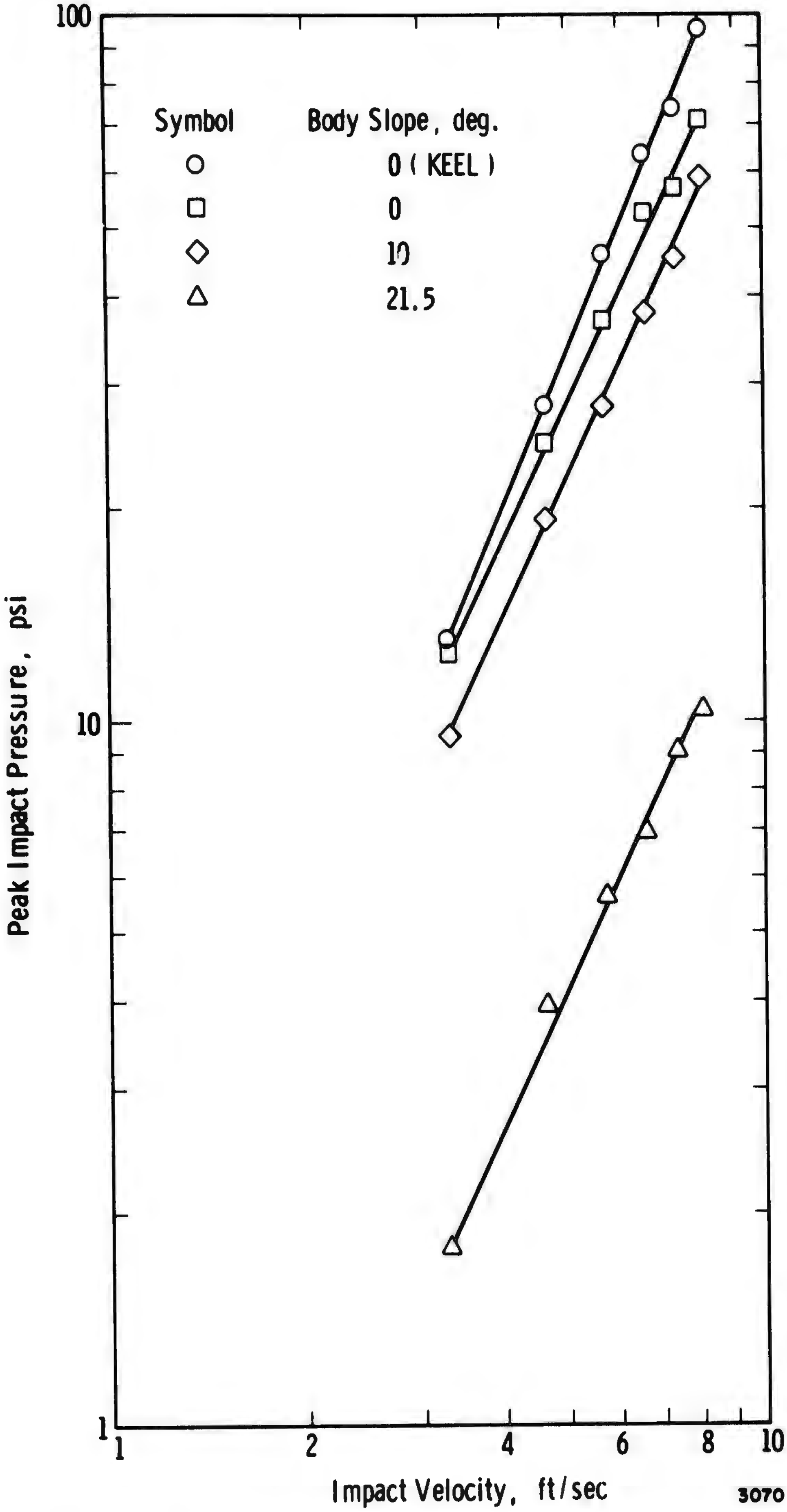


Figure 9. Variation Of Peak Impact Pressure With Impact Velocity For The UV-1 Model (25 lb) On Still Water

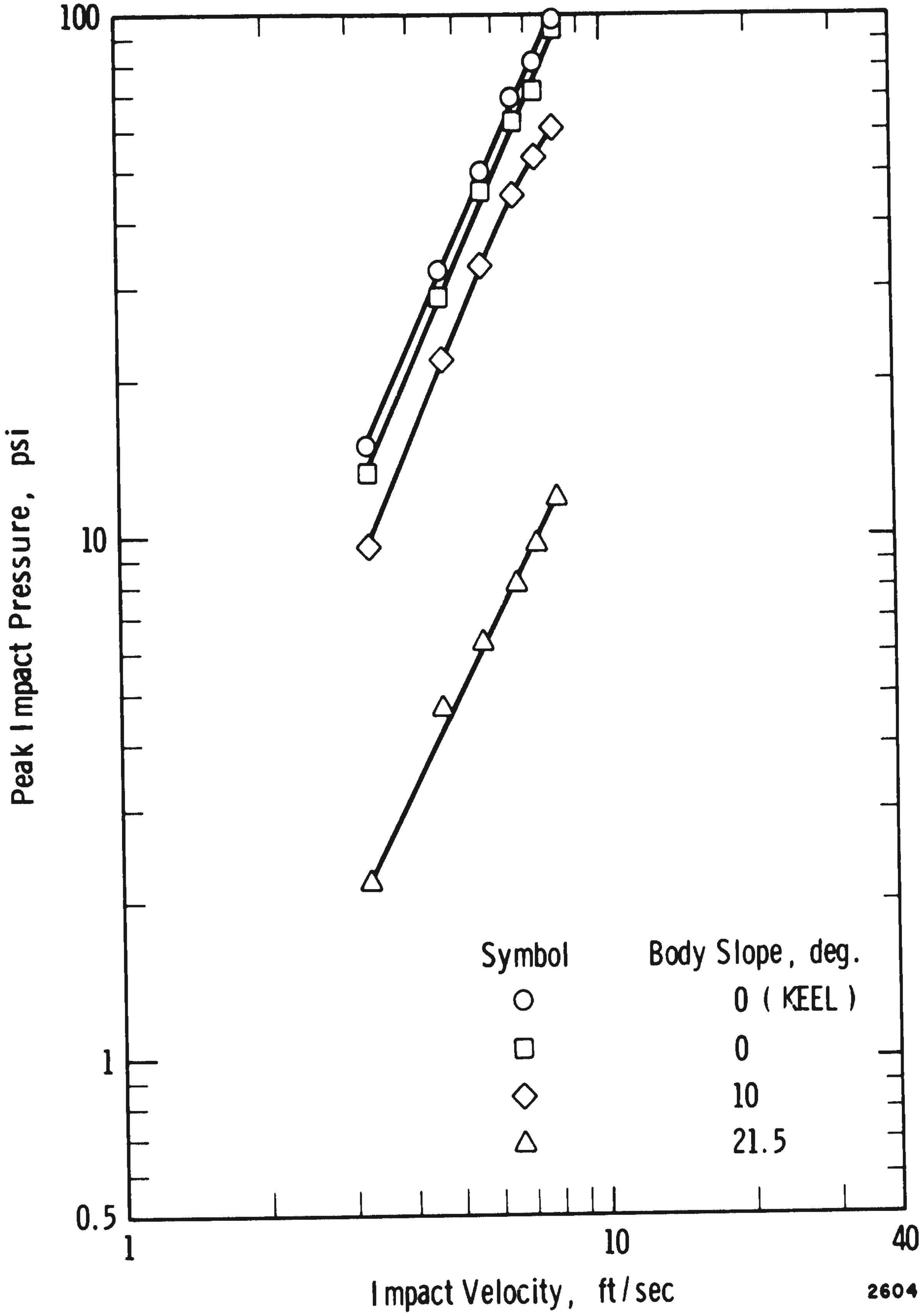


Figure 10. Variation Of Peak Impact Pressure With Impact Velocity For The UV-1 Model (50 lb) On Still Water

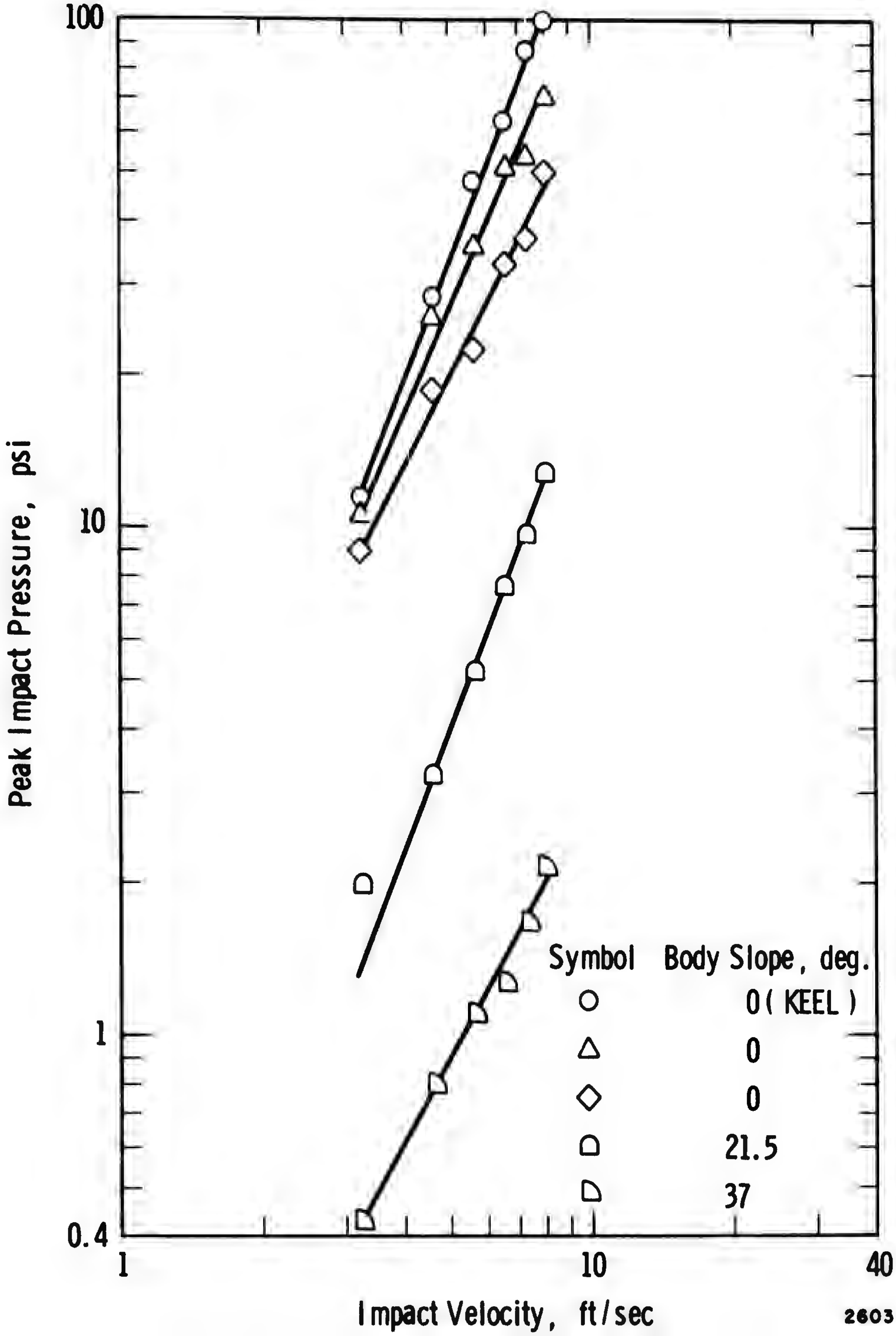


Figure 11. Variation Of Peak Impact Pressure With Impact Velocity For The UV-2 Model (46 lb) On Still Water

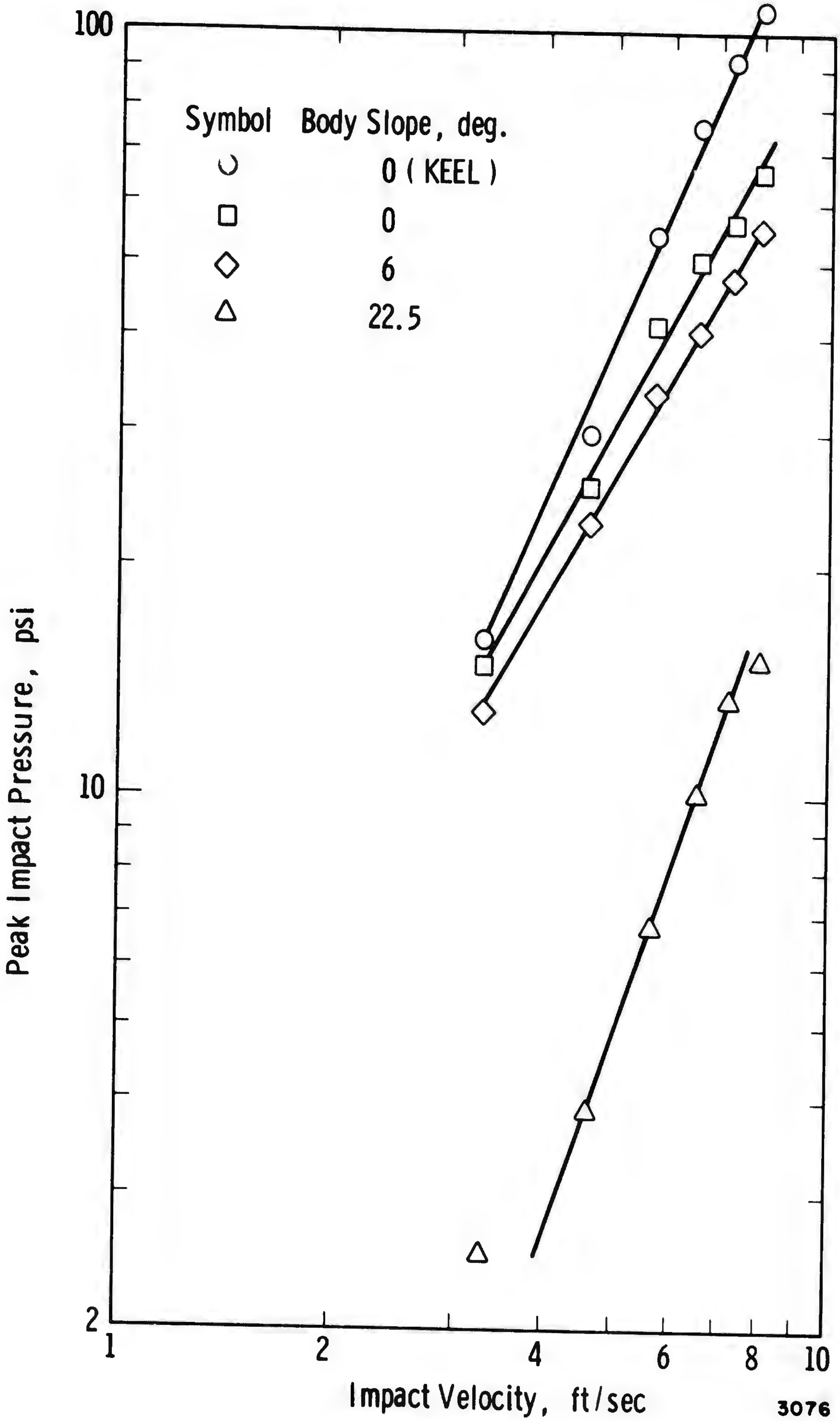


Figure 12. Variation Of Peak Impact Pressure With Impact Velocity For The U Model (20 lb) On Still Water

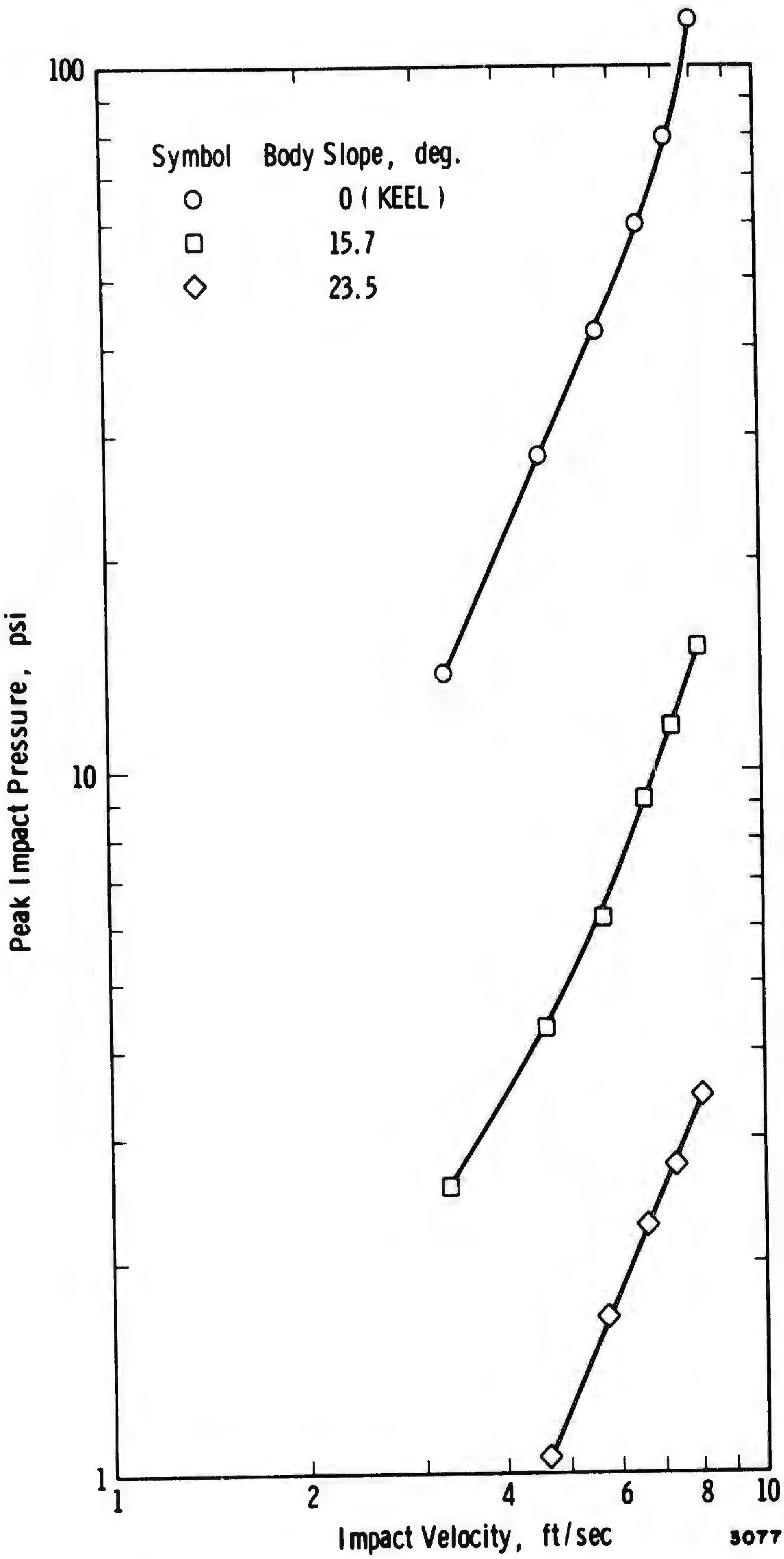


Figure 13. Variation Of Peak Impact Pressure With Impact Velocity For The V-0 Model (36 lb) On Still Water

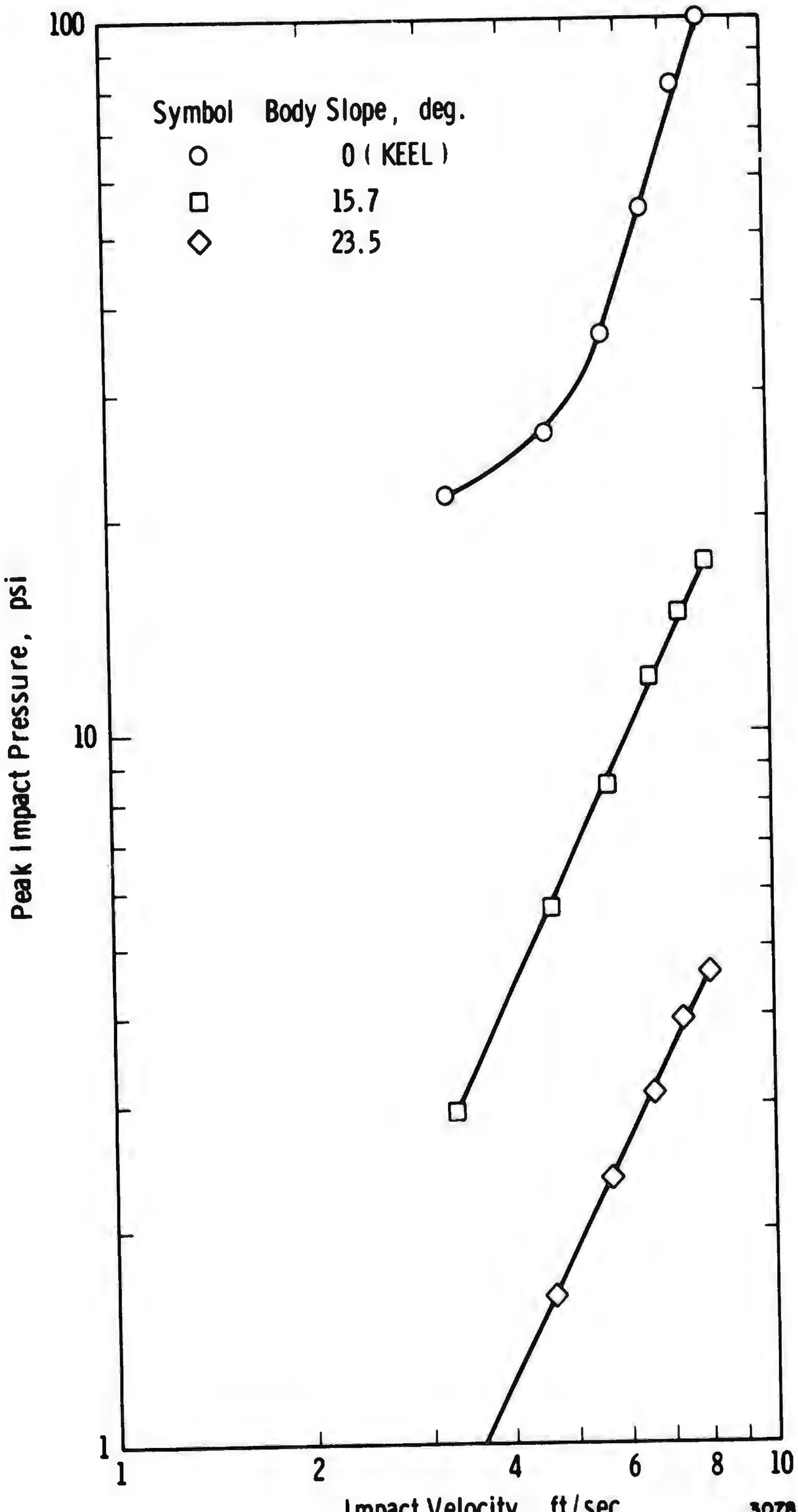


Figure 14. Variation Of Peak Impact Pressure With Impact Velocity For The V-0 Model (104 lb) On Still Water

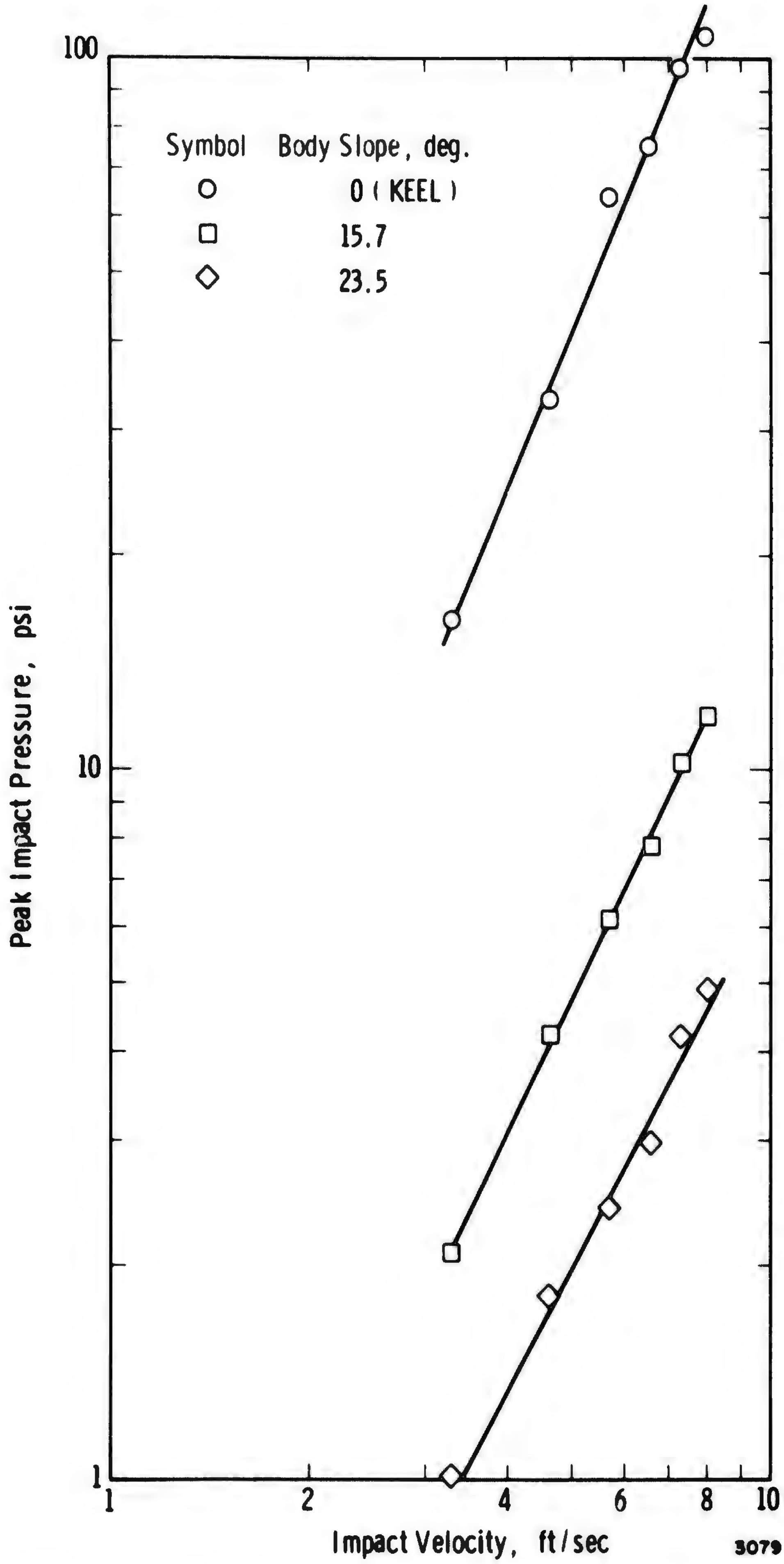


Figure 15. Variation Of Peak Impact Pressure With Impact Velocity For The V-1 Model (51 lb) On Still Water

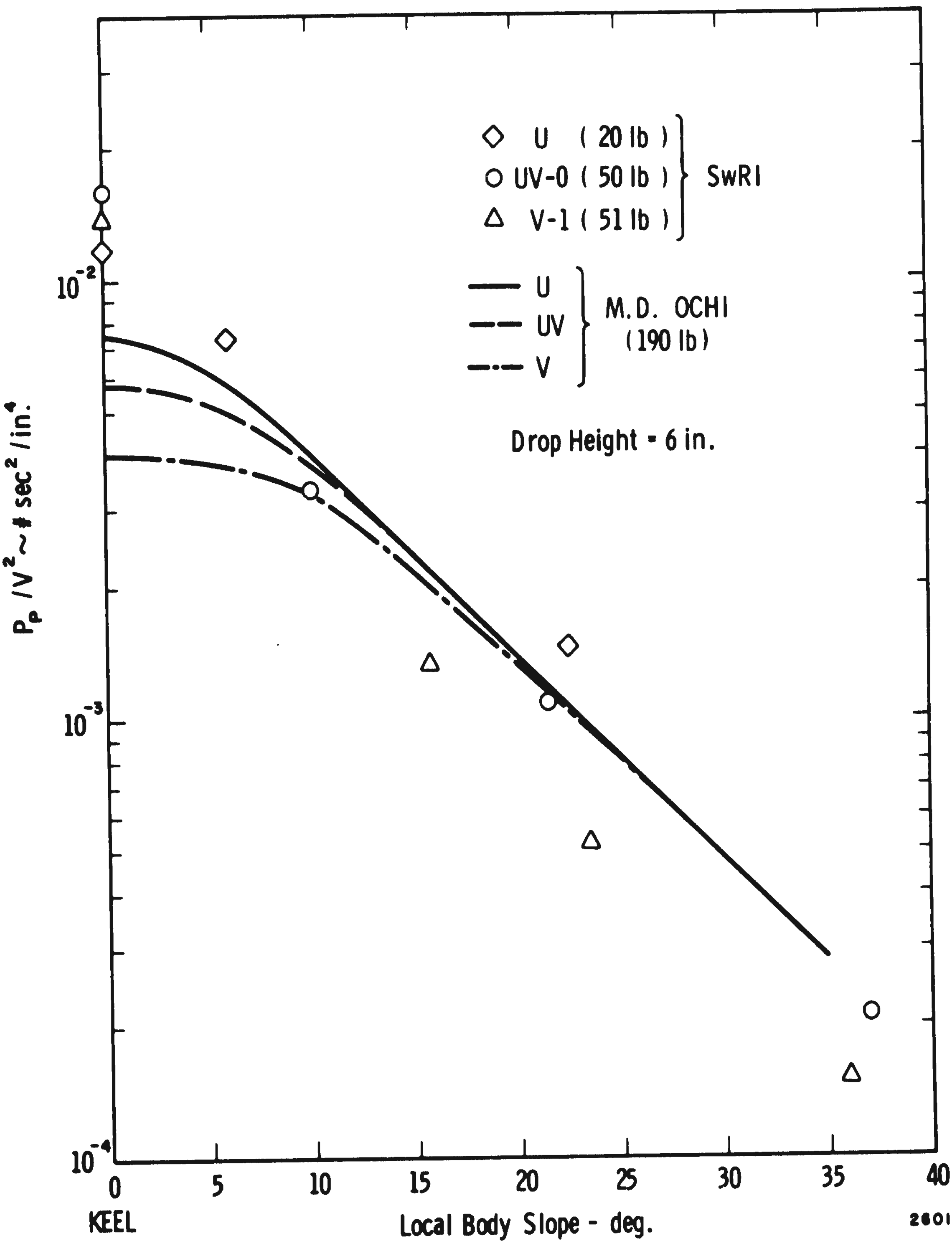


Figure 16. Dimensionless Peak Impact Pressure As Function Of Local Body Slope For Three Model Sections On Still Water

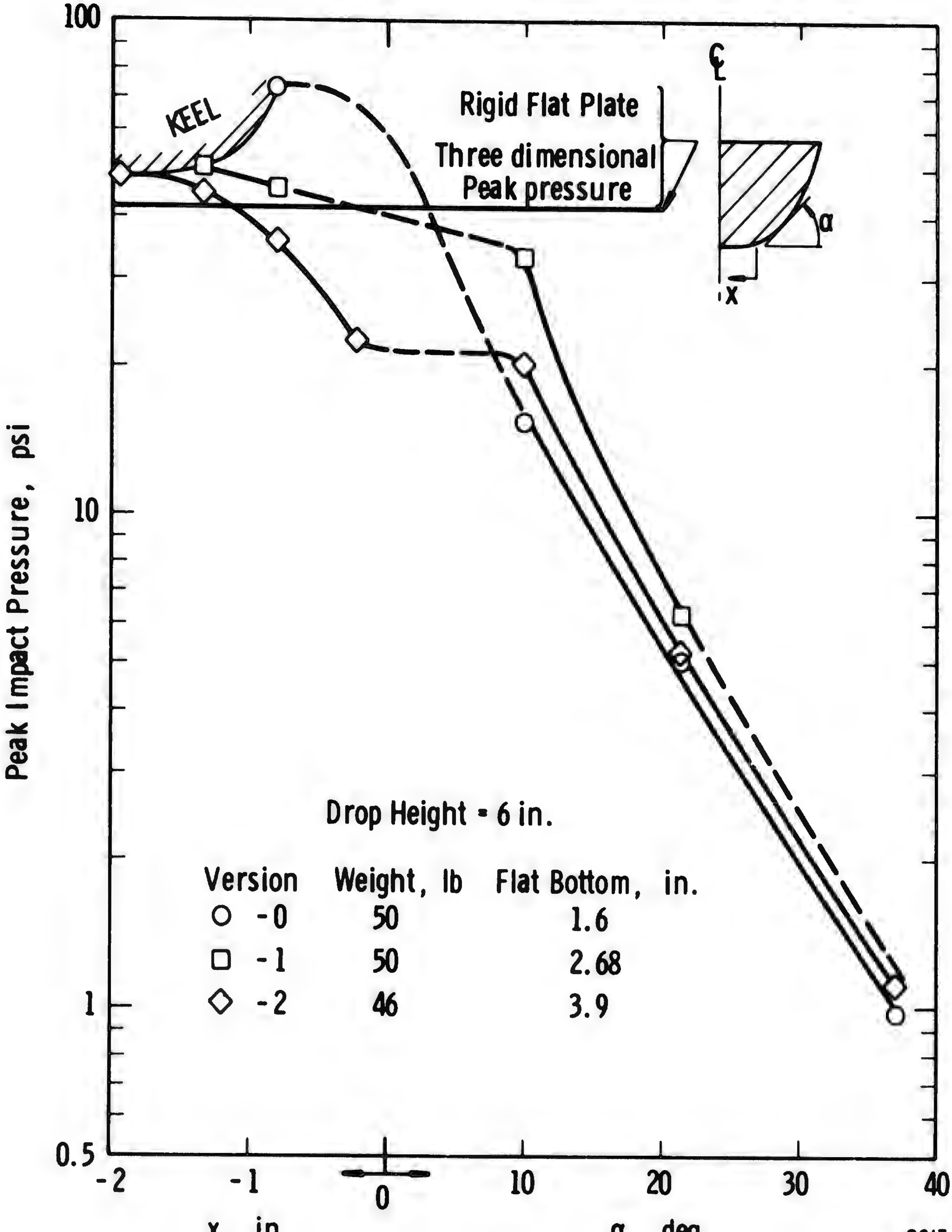


Figure 17. The Effect Of Flat Bottom Width On The Peak Impact Pressure Distribution For The UV Model In Still Water

For body slopes greater than 10 degrees, impact pressure is a function only of local slope but not flat bottom width. This result indicates, as before, that the pressure distribution is not a function of model breadth for body slopes greater than 10 degrees. Inboard of the 10 degree station impact pressure is strongly dependent on extent of flat bottom. The manner in which keep pressure varies with flat bottom extent is quite predictable in view of the recent results of Chuang[8].

Since the UV model was nearly mass saturated, intuition suggests that as the extent of flat bottom increases, the keel peak impact pressure should approach the impact pressure of a mass saturated flat plate having the same planform area as the UV model. A three-dimensional,mass saturated, flat plate impact pressure (nominal 80 psf mass locaing and 1 sq. ft. planform area) obtained from Reference 5 , has been superimposed on Figure 17 to indicate that this is indeed the case. For large flat bottom widths, the lateral surface outboard of the flat bottom has negligible effect on keep pressure. On the other hand, as the flat bottom width diminishes toward zero, the ability of the flat bottom to trap air for cushioning also diminishes, thus resulting in an increased impact pressure at the keel. It has been shown by Chuang[8] that for the wedge entry problem that keel impact pressure increases with dead rise angle up to 3 degrees. Further increases in dead rise angle result in reduced keel pressures. One interpretation might be that as flat bottom width decreases on the UV model the effective dead rise angle increases. Another interpretation of the effect of flat bottom follows from the results reported in Reference 5, dealing with size scale effect for impact of blunt bodies. It was shown that there is a definite trend toward higher peak impact pressures as the model size is reduced, assuming the mass loading is held constant.

c. Two- Versus Three-Dimensional Air Flow Effects

The data presented thus far for the V form model reflects a reduced model length and a two-dimensional air flow condition. For the sake of completeness, this model was also dropped without end plates (baffles) to insure a three-dimensional air flow. The two conditions are presented in Figure 18. The first observation is that the impact pressure for this model is affected little by imposed air flow restrictions, but the two-dimensional pressure is marginally greater than the three-dimensional pressure. This result can be interpreted to mean that, at the effective dead rise angle of the V model, a negligible amount of air is trapped in either configuration, hence a minimal difference in the effect of cushioning on impact pressure.

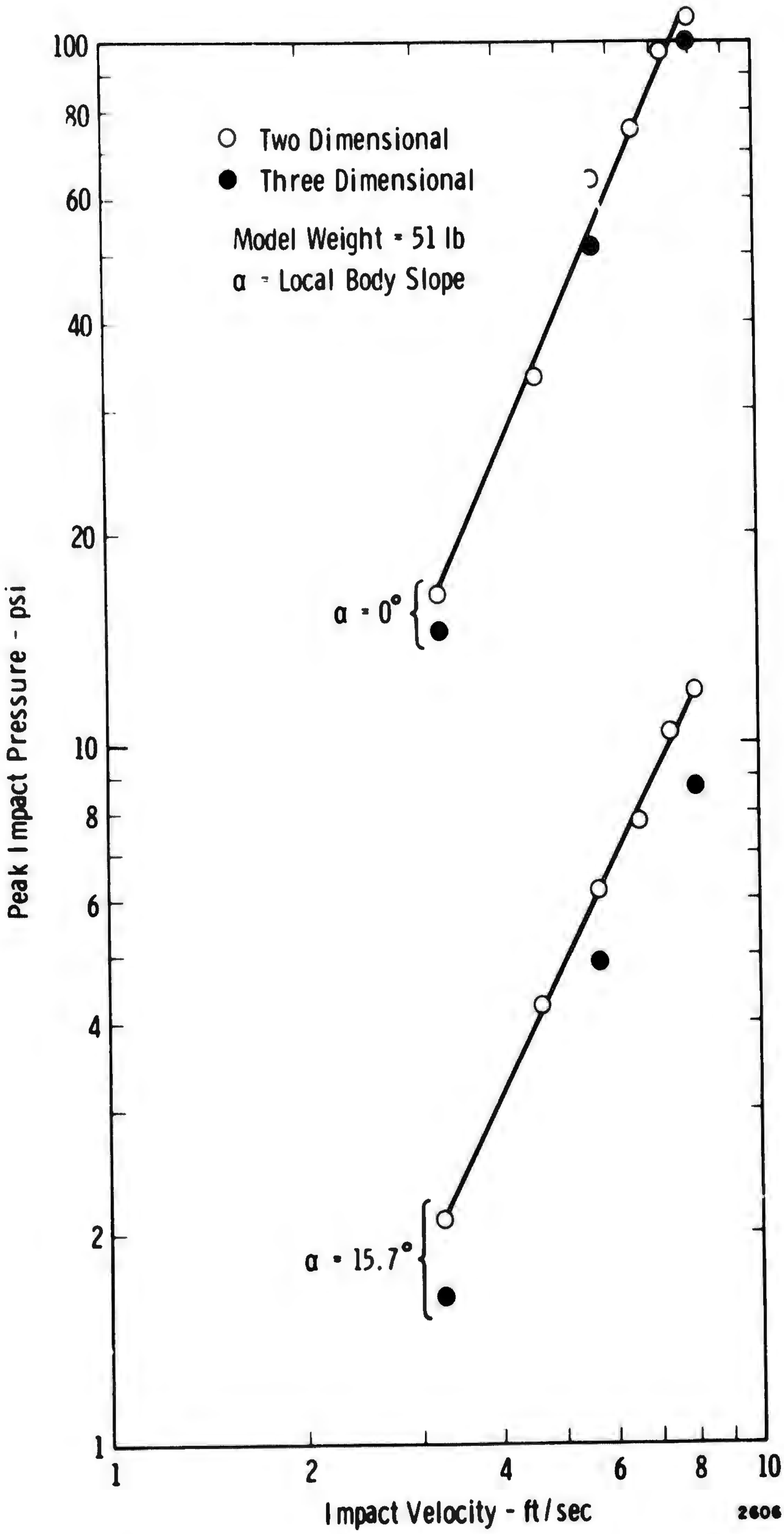


Figure 18. Comparison Of Peak Impact Pressure For Two And Three Dimensional Air Flow, V-1 Model In Still Water

3. Impact on a Disturbed Water Surface

a. Effect of Hull Form

All of the previously outlined combinations of hull form and mass loading were also drop tested on continuous, single frequency, head waves. The term, single frequency, represents the indicated frequency of the wave generator. Since the wave trains were periodic but not truly sinusoidal, a spectral analysis of the continuous wave would contain many frequency components distributed about the dominant generator frequency. In most cases each model was drop tested from 2, 6 and 12 inches with at least 20 impacts at each height. Intermediate heights of 4, 8 and 10 inches were not tested because there was no reason to believe that the pressure-velocity diagram on waves would be anything but log-linear.

The effect that waves have on impact pressure is highly pronounced, as was first discussed in References 4 and 5. In general, the presence of waves causes the pressure histories to be quite random in nature. Both the magnitude of the pulse, and the shape change with subsequent drops. Figure 19 illustrates typical traces for water impact on still water and on waves. Generally, but not always, the peak value is reduced, and the pulse width is increased. The degree of influence of the waves is dependent on the wave amplitude and the wave length. Therefore, in order to achieve realism, the test waves should be properly scaled relative to the model.

It should be mentioned at this point that some tests were performed in an effort to correlate the nature of the pressure pulse as a function of the manner in which the model impacted the disturbed surface. These tests amounted to simultaneously recording the peak impact pressure along with wave height obtained from two wave transducers mounted adjacent to the model. Careful examination of this data showed no good correlation which would tend to reduce the data scatter. But, neither did it prove conclusively that no such correlation exists. This should be a point for further study.

Initially, exploratory tests were conducted with wave frequencies of 1.0, 1.5 and 2.0 Hz, and the data in Figure 20 illustrates the effect of these various wave conditions on the impact pressures for the UV-O model. Because of the nature of the wave generator, the wave height and surface irregularity increased as the excitation frequency increased. Relative to the model scales, the 1.0 Hz waves represented rather gentle disturbance conditions, which did not seem realistic. The 2 Hz wave condition was used for all tests because it appeared to give a surface condition comparing most favorably with actual sea conditions.

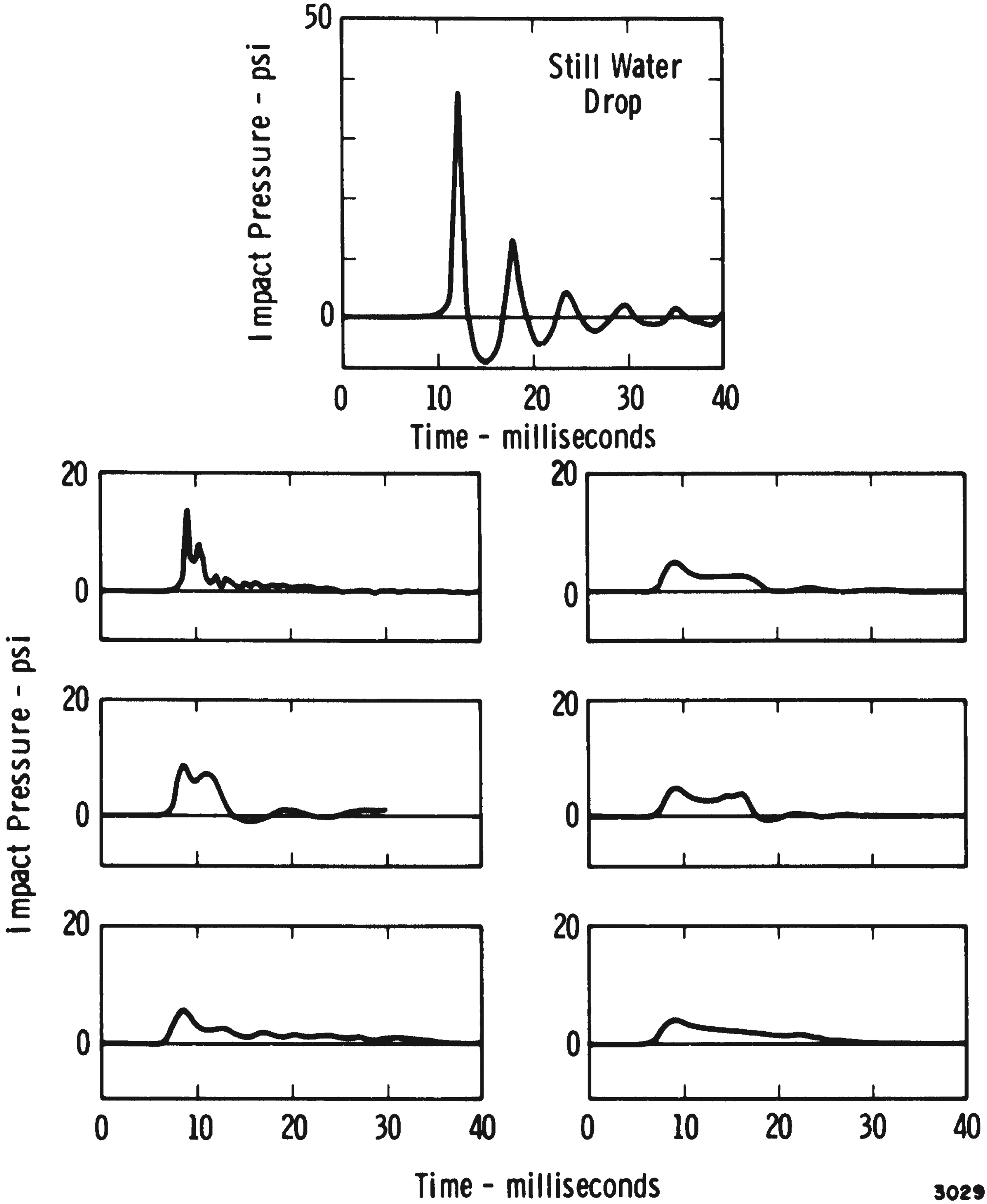


Figure 19. Typical Impact Pressure Histories For Model Drops On Waves Compared With Still Water

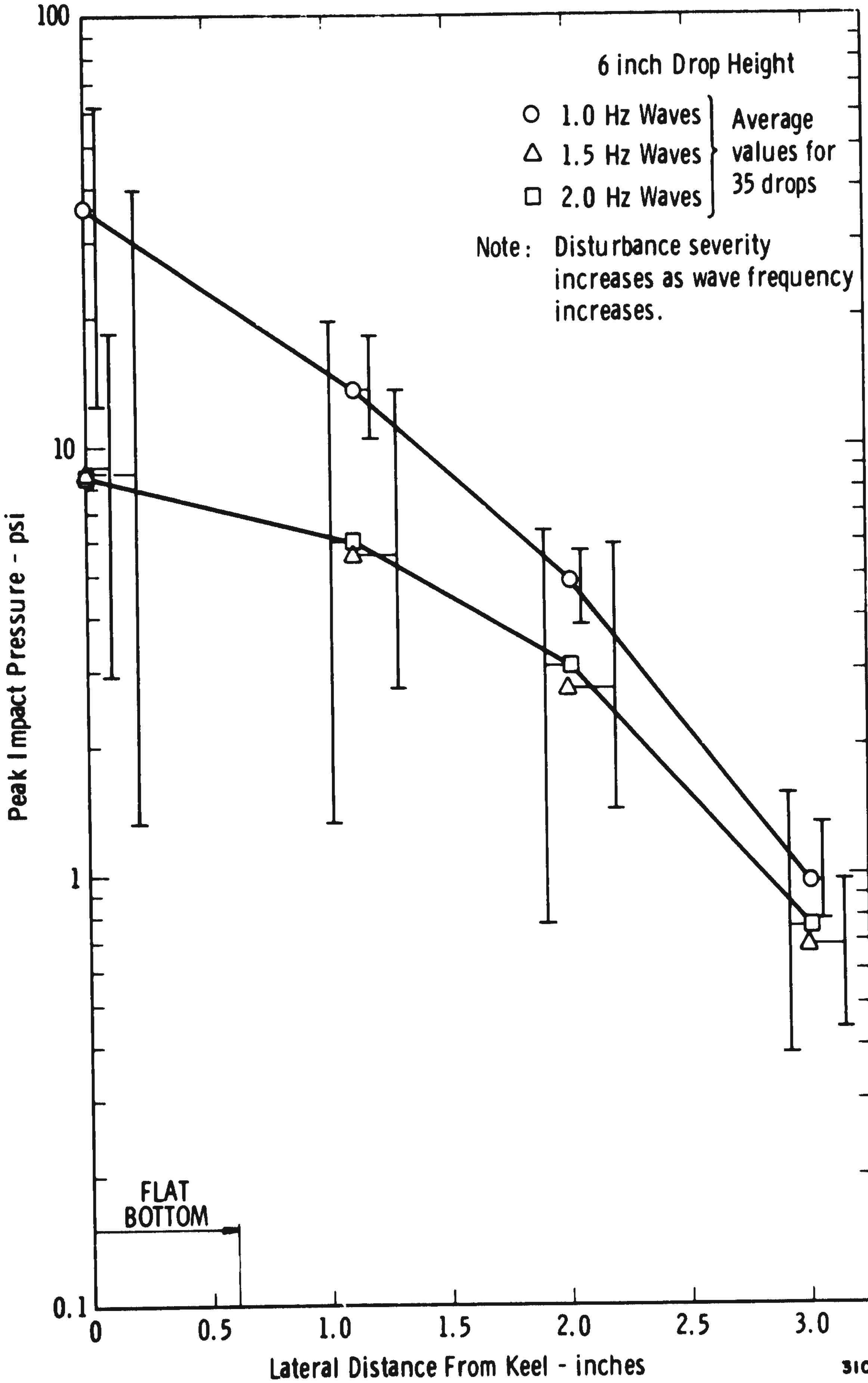


Figure 20. Effect Of Surface Disturbance Severity On Peak Impact Pressures For UV-0 Model (23 lb)

As will be discussed in a later section, these waves (2 Hz) appear to correspond to a condition of severe slam. The effect that the 2 Hz waves have on impact pressure for all of the test models was highly pronounced. Perhaps the best way of illustrating this effect is to compare pressure profiles on a given hull form in still water and on waves rather than present the standard pressure-velocity diagram. These profiles are presented in Figures 21 through 31 for the various hull forms. The UV-0 (50 lb), UV-1 (50 lb) and UV-2 (46 lb) data, not included with the above figures, will be presented in the next section which deals with the effect of flat bottom width on impact pressure profile.

It can be seen from the data at hand that there is almost an order of magnitude reduction in keel and near keel impact pressures. This effect diminishes rapidly with distance away from the keel until, at the outermost transducer locations (maximum local body slope), there is negligible difference between wave and still water impact pressure. In fact, at the 2-inch drop height, there were cases where the pressure levels were so insignificant as to be unrecordable. All of the data points represent arithmetic averages; the range of impact data is indicated for each transducer location.

Some interesting comments can be made regarding the range of wave impact pressures associated with a particular transducer location, particularly those near the keel. During the conduct of the experiments, no constraints were placed on the impacts, such as timing the drop to occur at the crest or trough of the wave. The drop was, therefore, initiated randomly. The data scatter is attributable to the fact that the impact pressure is an independent random variable and, as such, possesses a definable probability density distribution. A histogram can be constructed for the range of impact pressures at any transducer location. Figure 32 illustrates one such histogram which has been fitted with a truncated exponential function whose form has been suggested by M. K. Ochi. The fact that the analytic function does not exactly fit the data might be attributed to the size of the sample. M. K. Ochi suggests that approximately 200 data points are needed to adequately define the parameters λ and p_0; in this case 100 impacts were performed. Also, however, it appears that a different analytic probability density function, such as a Rayleigh distribution, might better fit the data.

A figure similar to Figure 16 was constructed for drop tests of the three basic hull forms in waves and is shown in Figure 33. Again the pressure is normalized with respect to the square of the theoretical impact velocity. The original V model data is presented here in lieu of data obtained

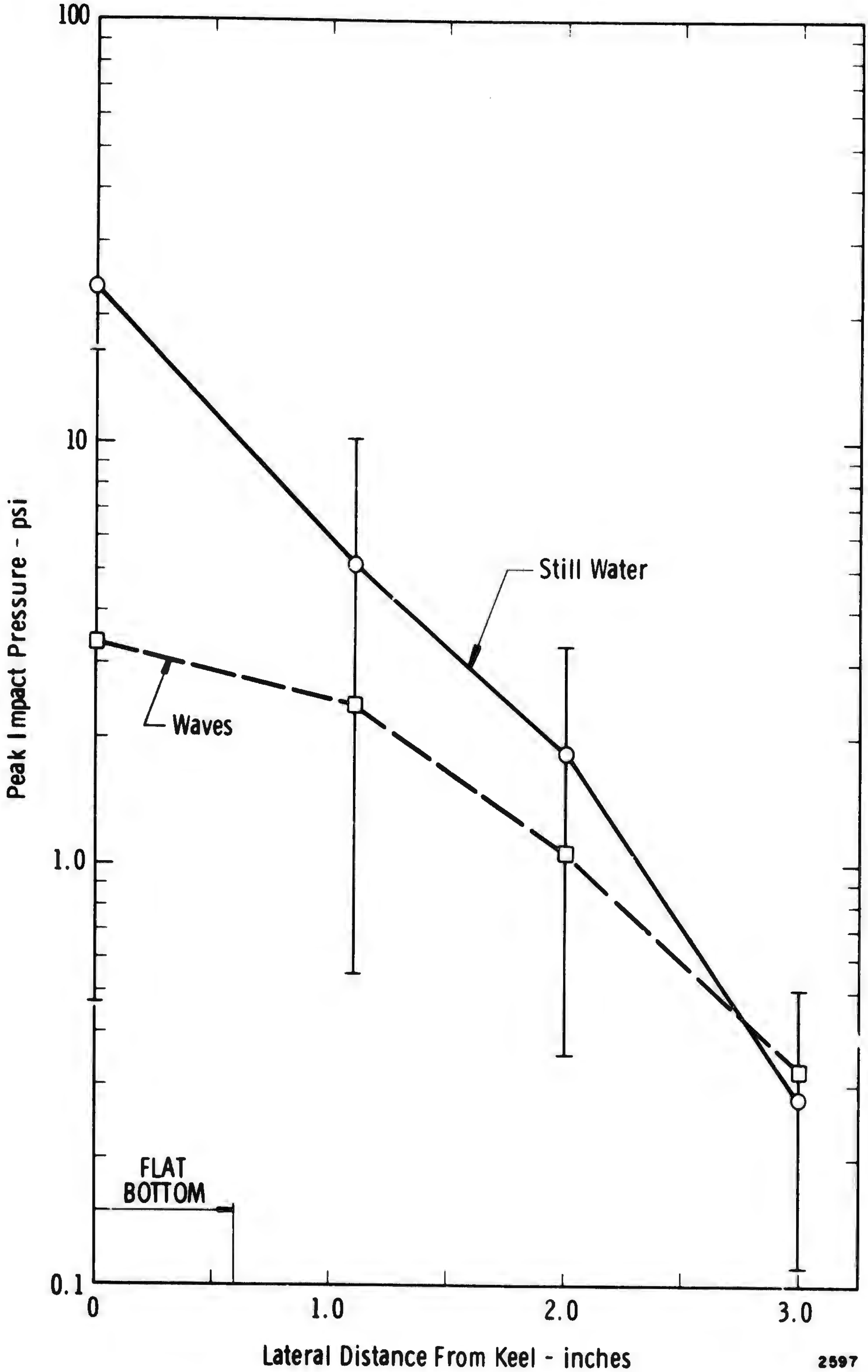


Figure 21. Breadthwise Variation Of Peak Impact Pressure For UV - 0 Model (23 lb) On Still Water And On Waves (2.0 Hz), 2 in. Drop Height

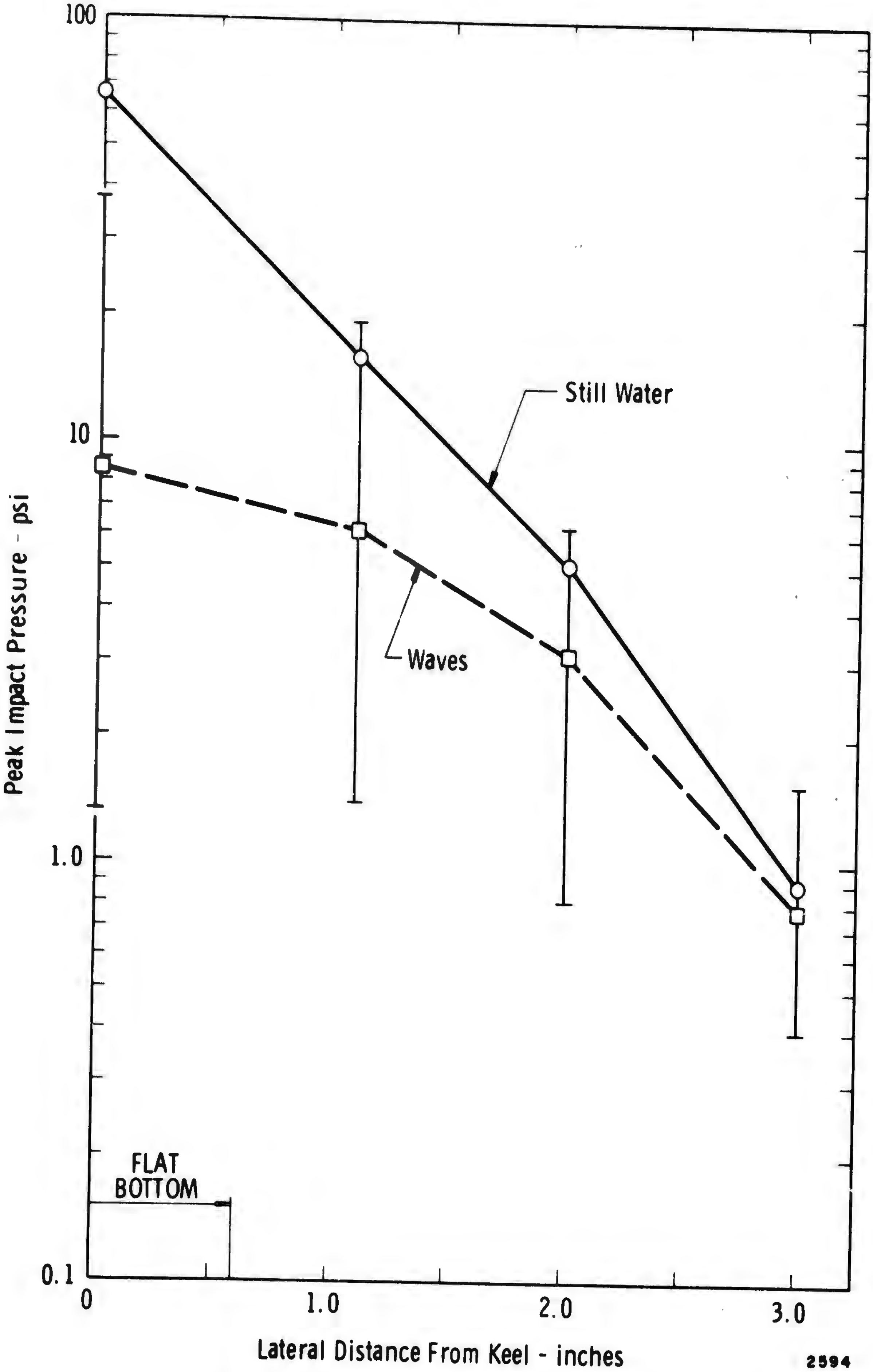


Figure 22. Breadthwise Variation Of Peak Impact Pressure For UV-0 Model (23 lb) On Still Water And On Waves (2.0 Hz), 6 in. Drop Height

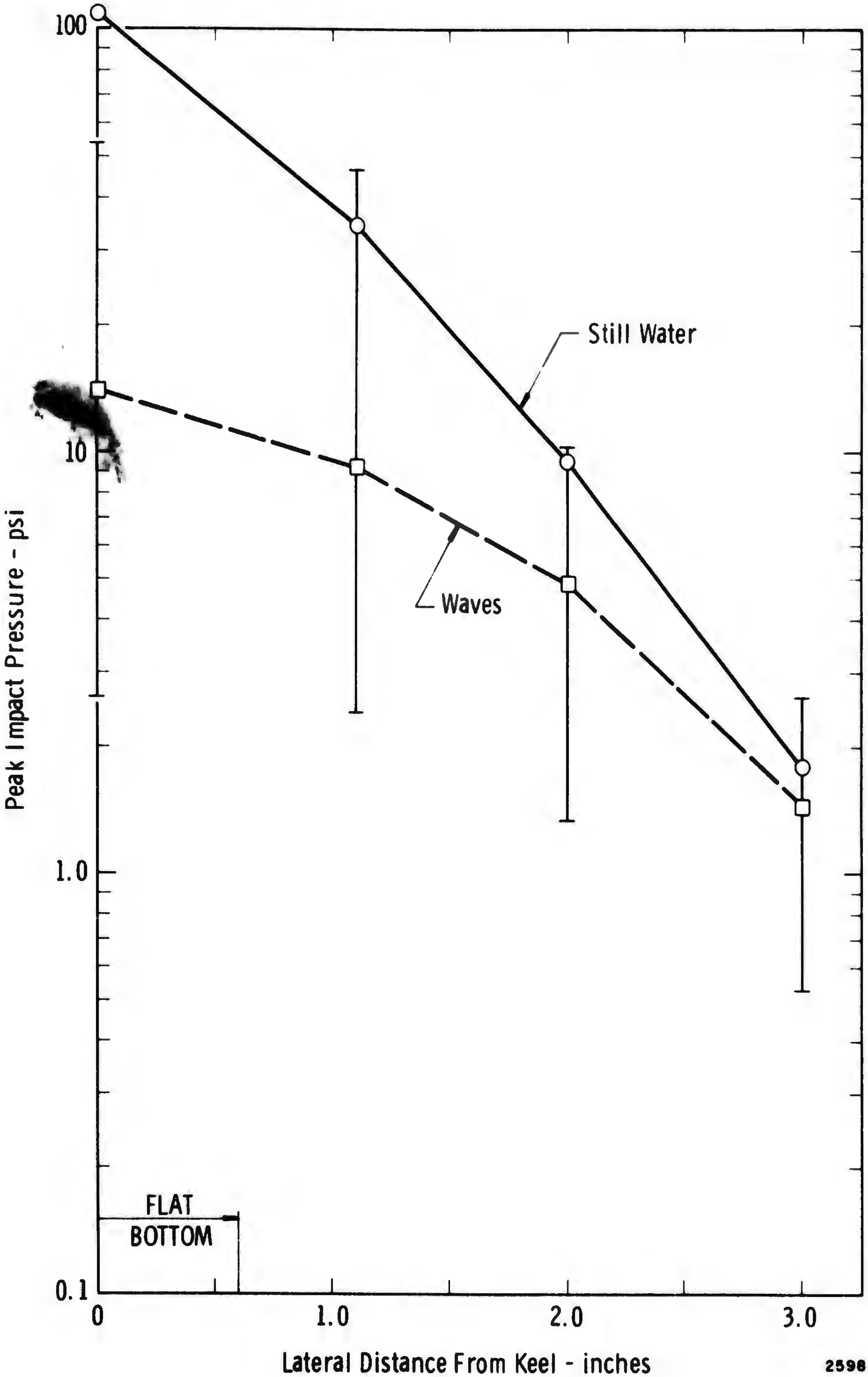


Figure 23. Breadthwise Variation Of Peak Impact Pressure For UV - 0 Model (23 lb) On Still Water And On Waves (2.0 Hz), 12 in. Drop Height

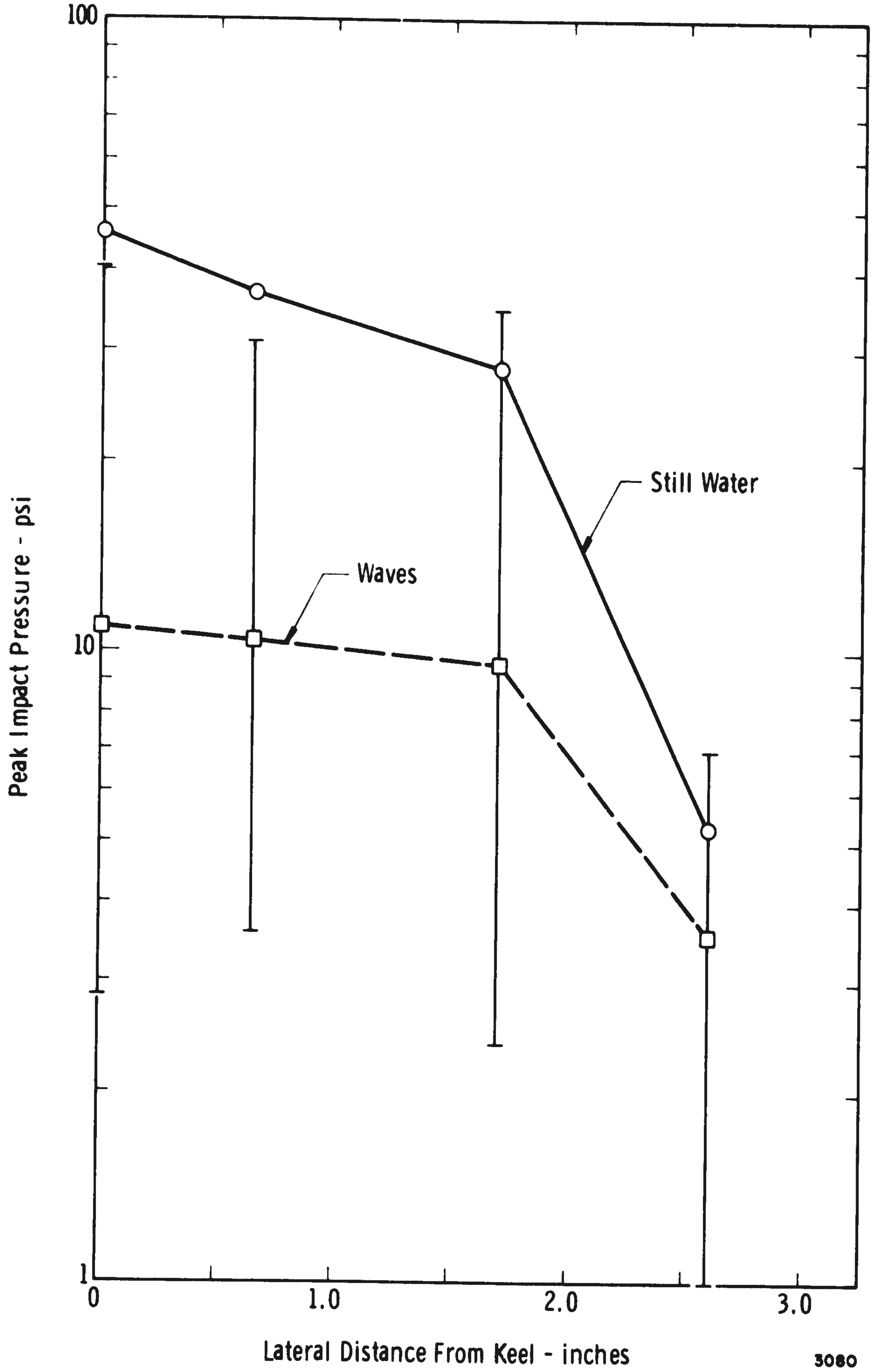


Figure 24. Breadthwise Variation Of Peak Impact Pressure For The UV - 1 Model (25 lb) On Still Water And On Waves (2.0 Hz), 6 in. Drop Height

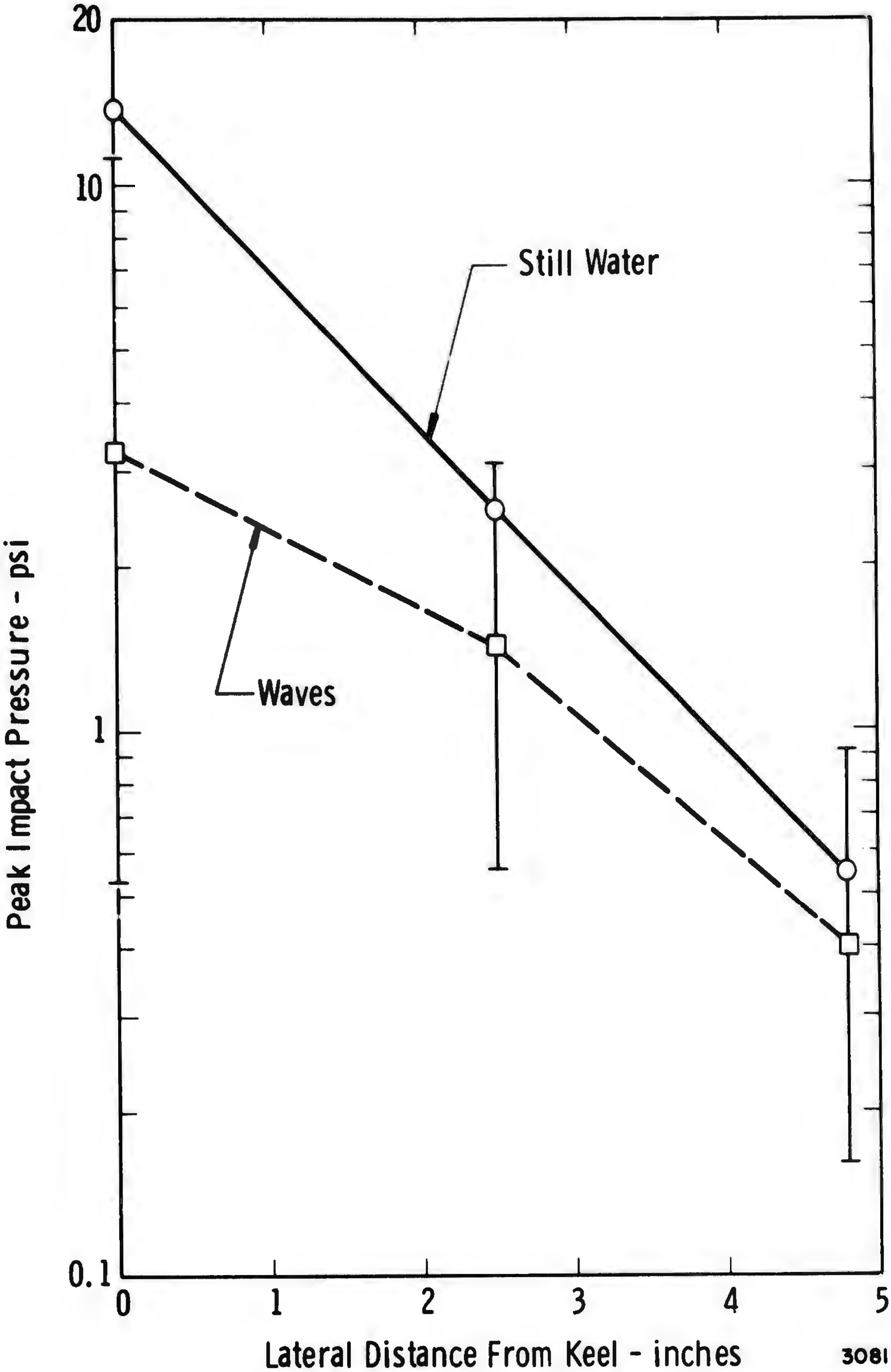


Figure 25. Breadthwise Variation Of Peak Impact Pressure For The V - 0 Model (36 lb) On Still Water And On Waves (2.0 Hz), 2 in. Drop Height

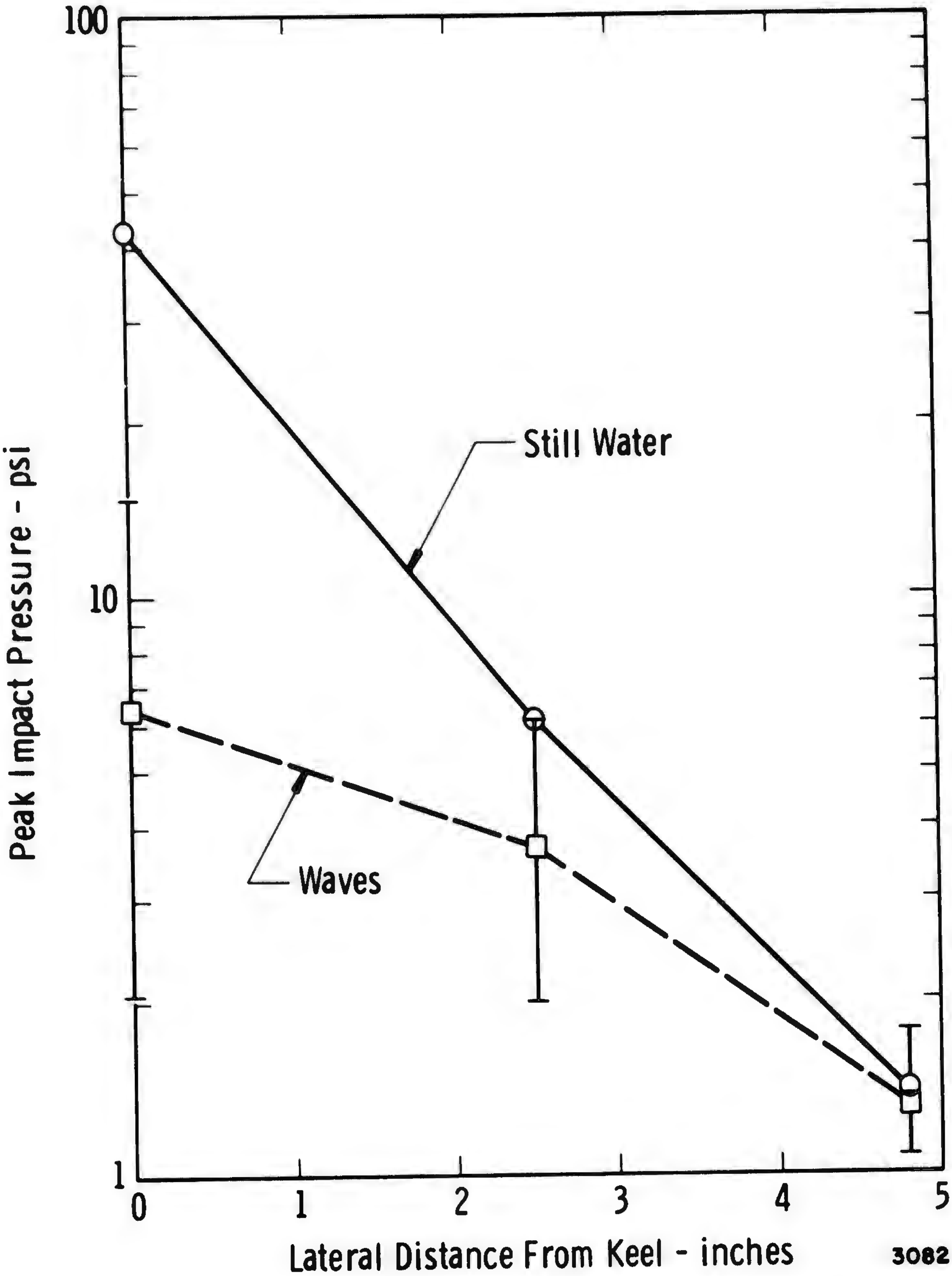


Figure 26. Breadthwise Variation Of Peak Impact Pressure For The V-0 Model (36 lb) On Still Water And On Waves (2.0 Hz), 6 in. Drop Height

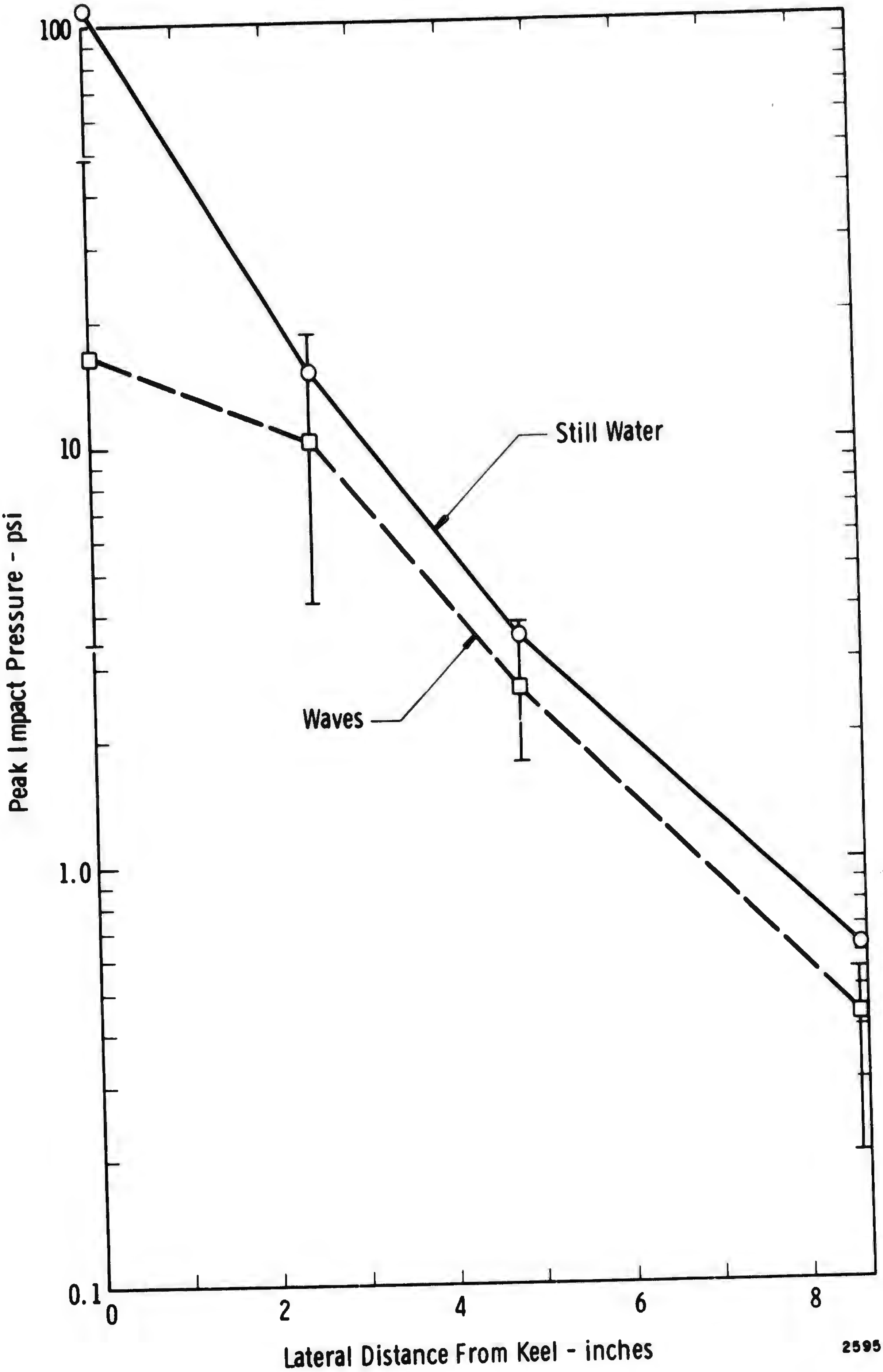


Figure 27. Breadthwise Variation Of Peak Impact Pressure For V - 0 Model (36 lb) On Still Water And On Waves (2.0 Hz), 12 in. Drop Height

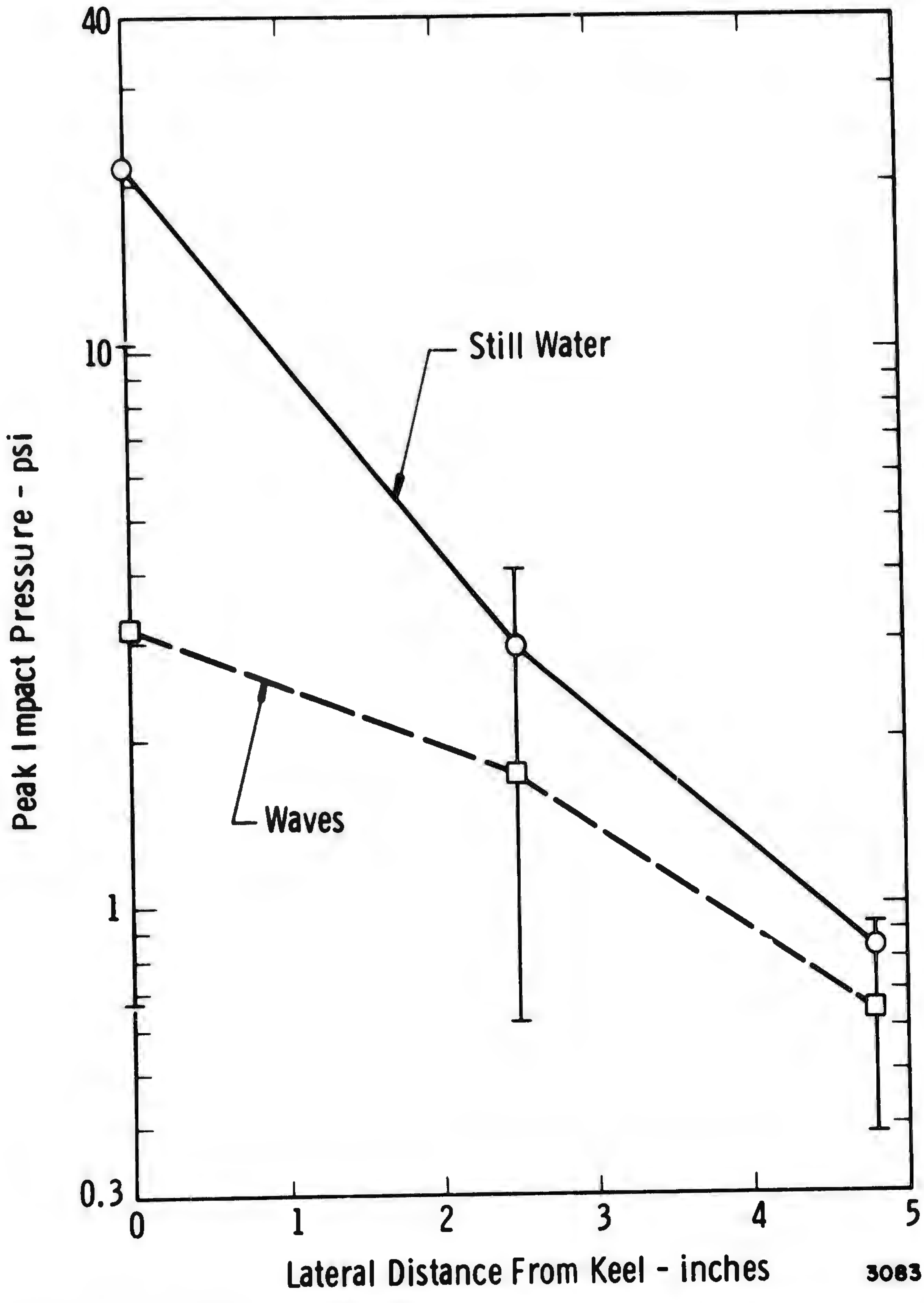


Figure 28. Breadthwise Variation Of Peak Impact Pressure For The V-0 Model (104 lb) On Still Water And On Waves (2.0 Hz), 2 in. Drop Height

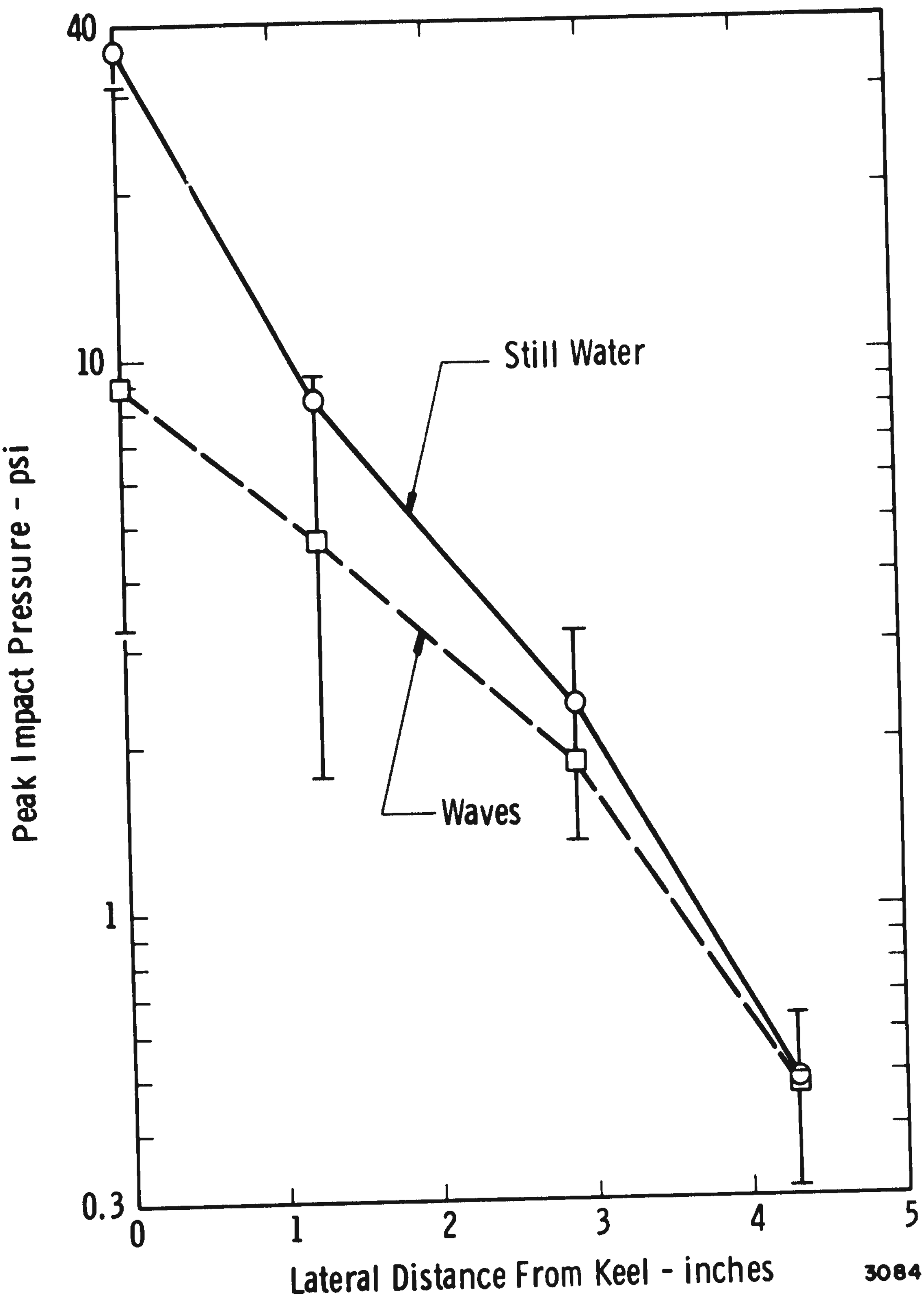


Figure 29. Breadthwise Variation Of Peak Impact Pressure For The V-0 Model (104 lb) On Still Water And On Waves (2.0 Hz), 6 in. Drop Height

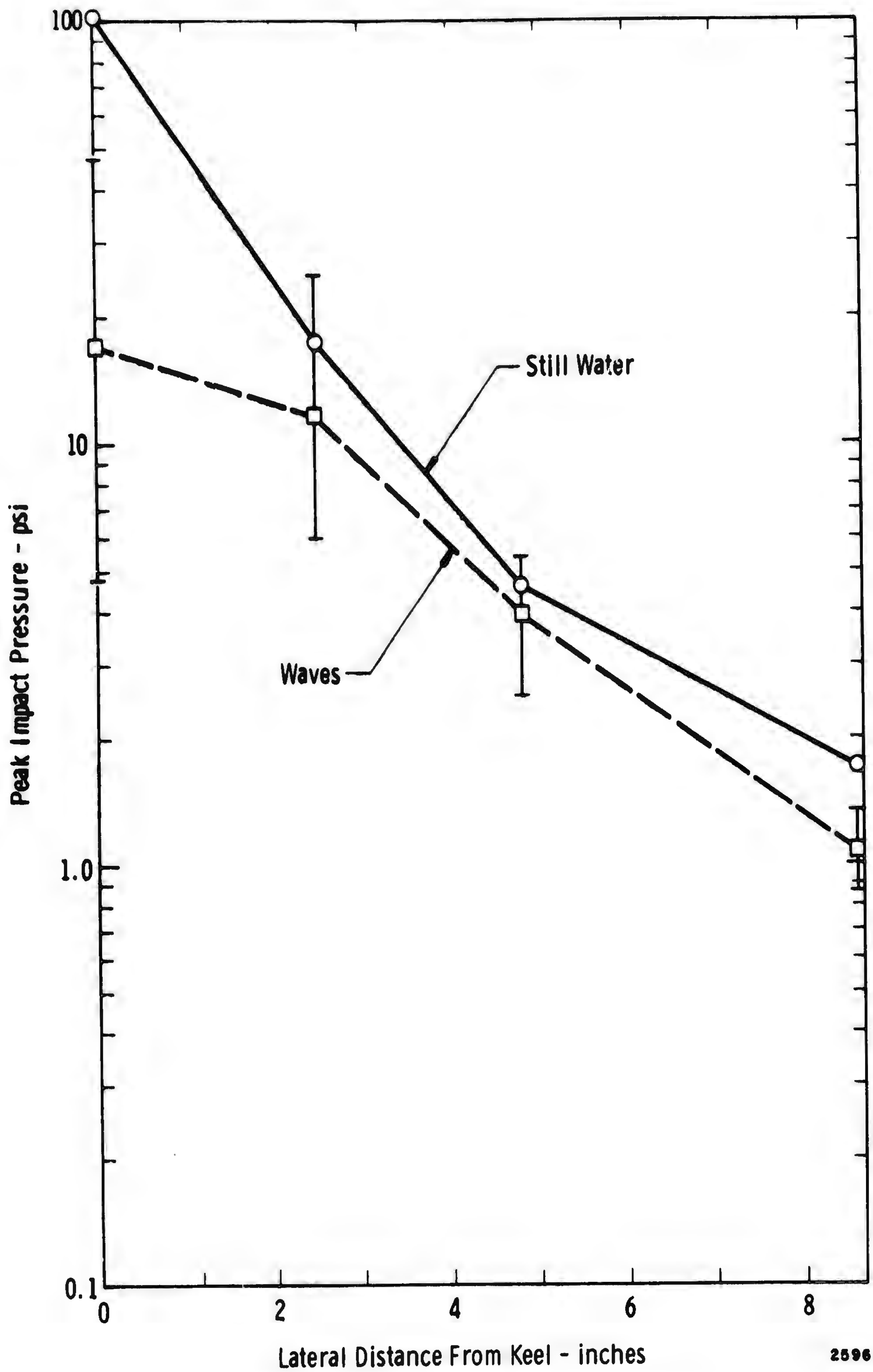


Figure 30. Breadthwise Variation Of Peak Impact Pressure For The V-0 Model (104 lb) On Still Water And On Waves (2.0 Hz), 12 in. Drop Height

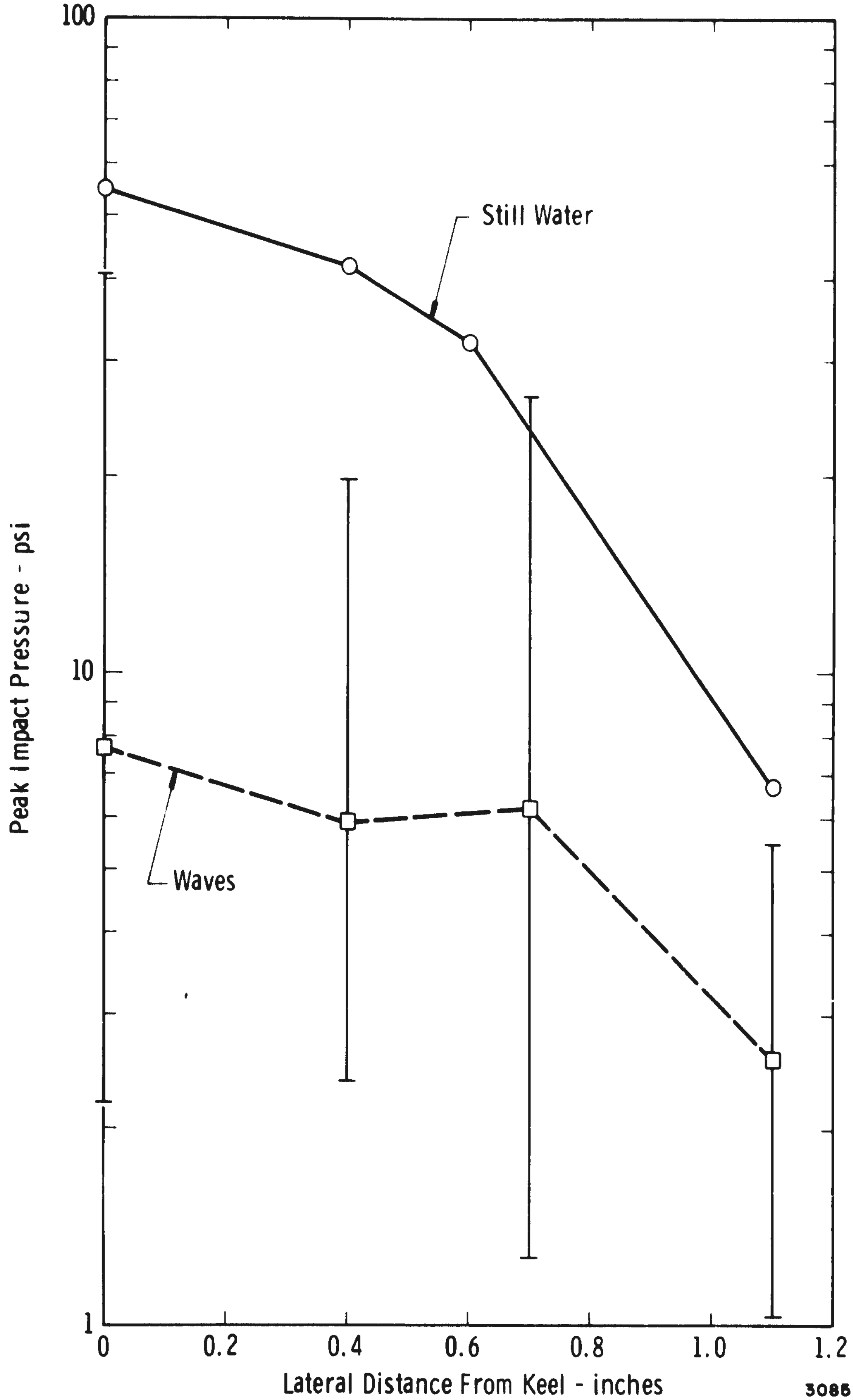


Figure 31. Breadthwise Variation Of Peak Impact Pressure For The U Model (20 lb) On Still Water And On Waves (2.0 Hz), 6 in. Drop Height

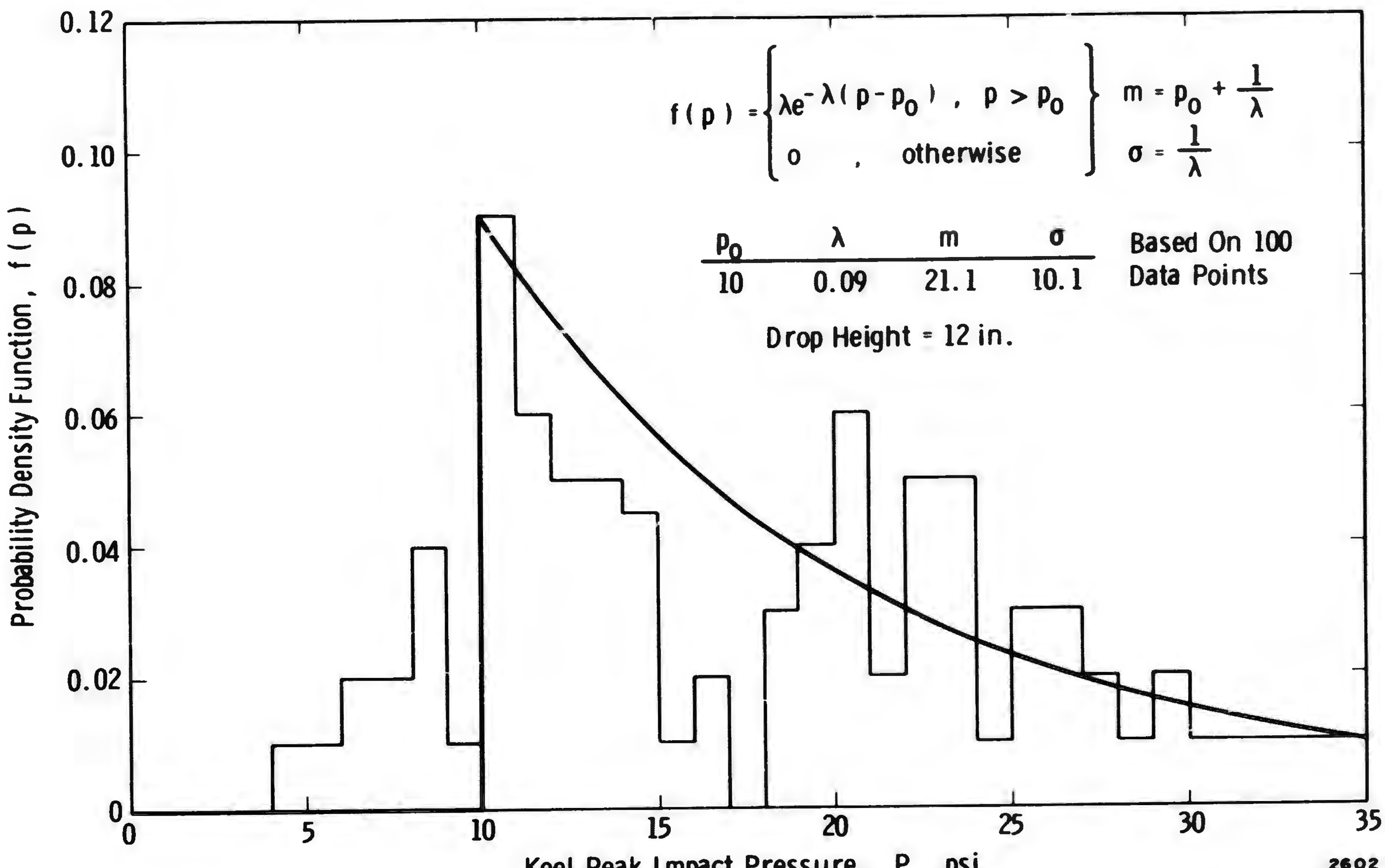


Figure 32. Typical Probability Density Function For The Peak Keel Impact Pressure On The UV-2 Model In Waves (2.0 Hz)

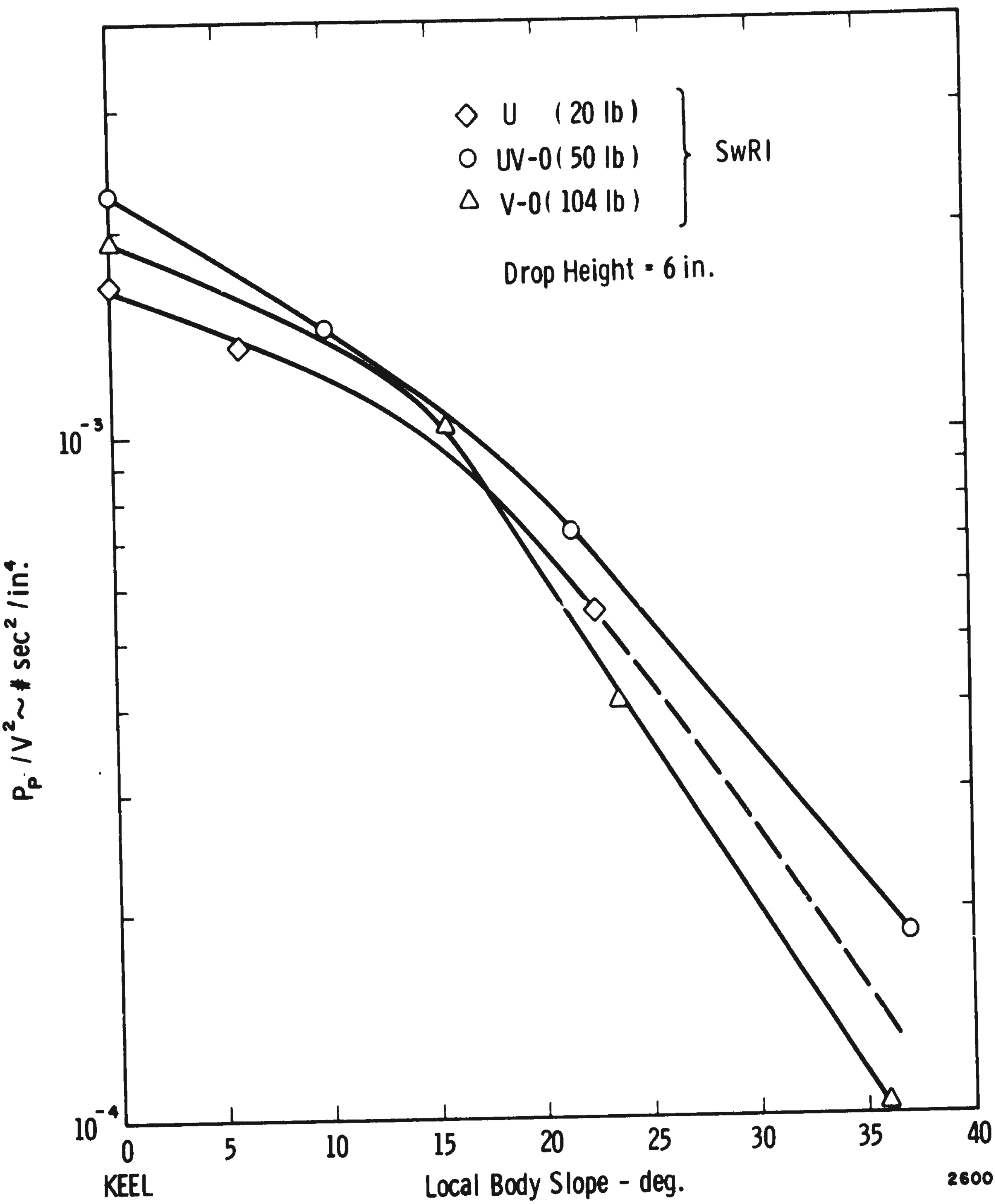


Figure 33. Comparison Of Peak Impact Pressure Distribution On Three Basic Hull Profiles Impacting On Waves (2.0 Hz)

by reducing model length in order to increase mass loading. The impact data from the V-1 version in waves was not realistic because of the extremely short model length which introduced undesirable end effects onto the impact pressure. It appears that, had the U and V-0 models been closer to mass saturation, then the pressure profile would have approximated the UV-0 profile.

Earlier it was mentioned that the pressure-velocity diagram in waves was log-linear. An illustration of this behavior is given in Figure 34. Each curve was fitted to an equation of the form $P = kV^n$, and the values of k and n are as indicated. The exponent, n, which represents the curve slope is essentially constant. For the 6-inch drop condition (5.68 ft/sec) values of k were calculated assuming that the curves had a slope equal to two, and they are presented for comparison purposes only.

b. Effect of Extent of Flat Bottom

The effect of extent of the flat bottom on the peak impact pressure resulting from drops on waves can be derived in a manner analogous to Figure 17. Experimental pressure profiles for the heaviest versions of the UV-0 and -2 are presented in Figures 35 and 36. Tests were conducted on the UV-1 model only for the 6-inch drop height; the drop data for that condition will be presented subsequently. Note that, with the exception of the profile for the UV-2 model dropped from 12 inches, all pressure profiles are monotonically decreasing functions of the beamwise location of the transducers. All data points represent an arithmetic average of the pressures obtained from at least 20 impacts. Therefore, the behavior of the UV-2 model, which was impacted 100 times at the 12-inch drop height, must represent more than a casual artifact caused by insufficient impacts. The approximate doubling of the shoulder ($x = 0$) pressure relative to the keel pressure might suggest a reduction in the cushioning effect near the shoulder.

Figure 37 illustrates an interesting result obtained by combining the pressure profiles for the three UV forms at a drop height of 6 inches. For that particular drop height, the impact pressure is apparently independent of extent of flat bottom, and can be described by a single continuous function of the transverse coordinates, x and α. Compare this result with the three curves in Figure 17 that are required for still water impact. The radical change in profile requirements strongly suggests that a different mechanism controls the generation of pressure on waves. Note, also, that there is roughly an order of magnitude reduction in keel pressure in the presence of waves. This pressure reduction due to waves is present for body slopes less than 10 degrees; beyond 10 degrees waves seem to have a negligible effect on pressure.

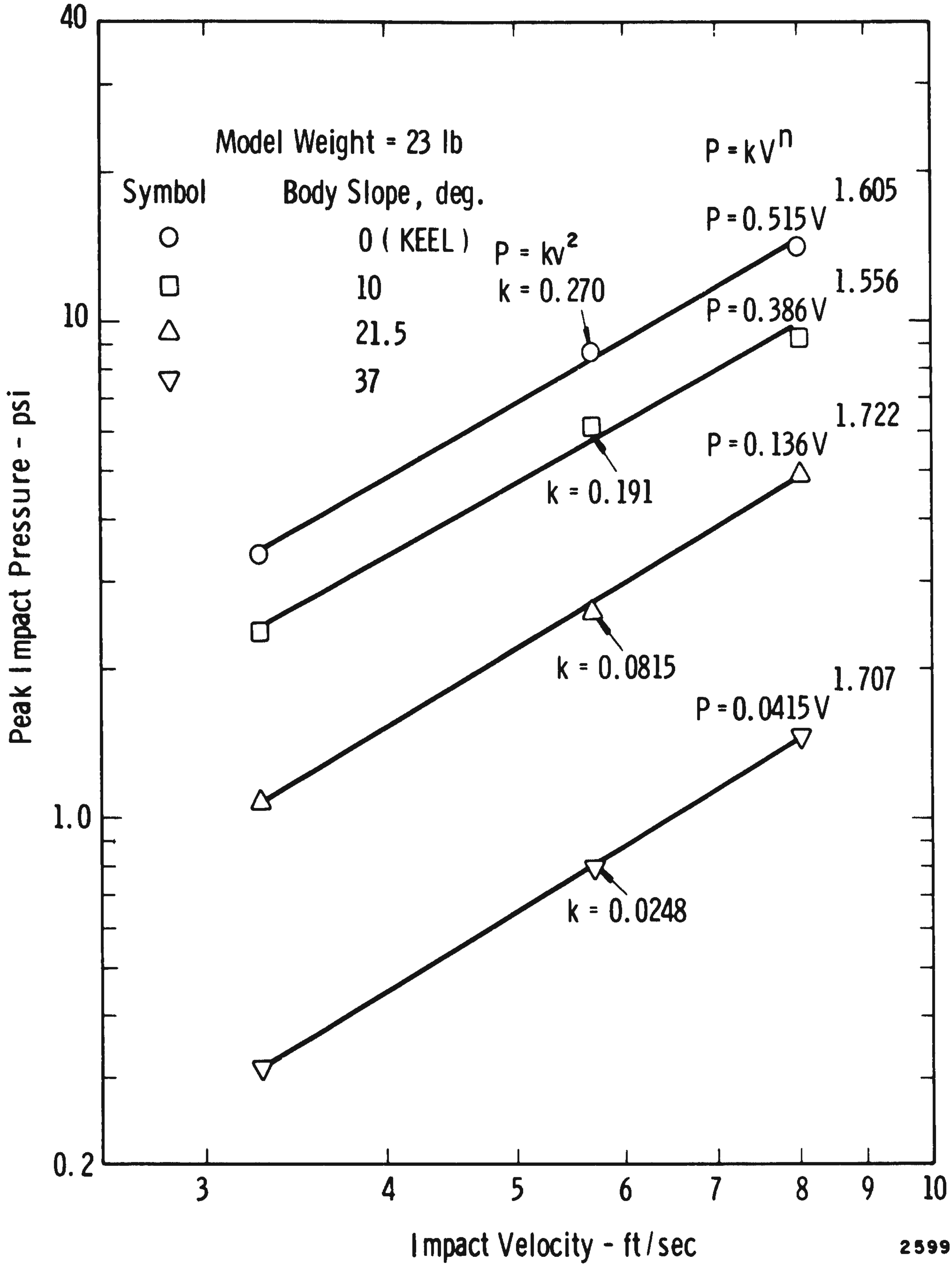


Figure 34. Variation Of Peak Impact Pressure With Impact Velocity For UV - 0 Model On Waves (2.0 Hz)

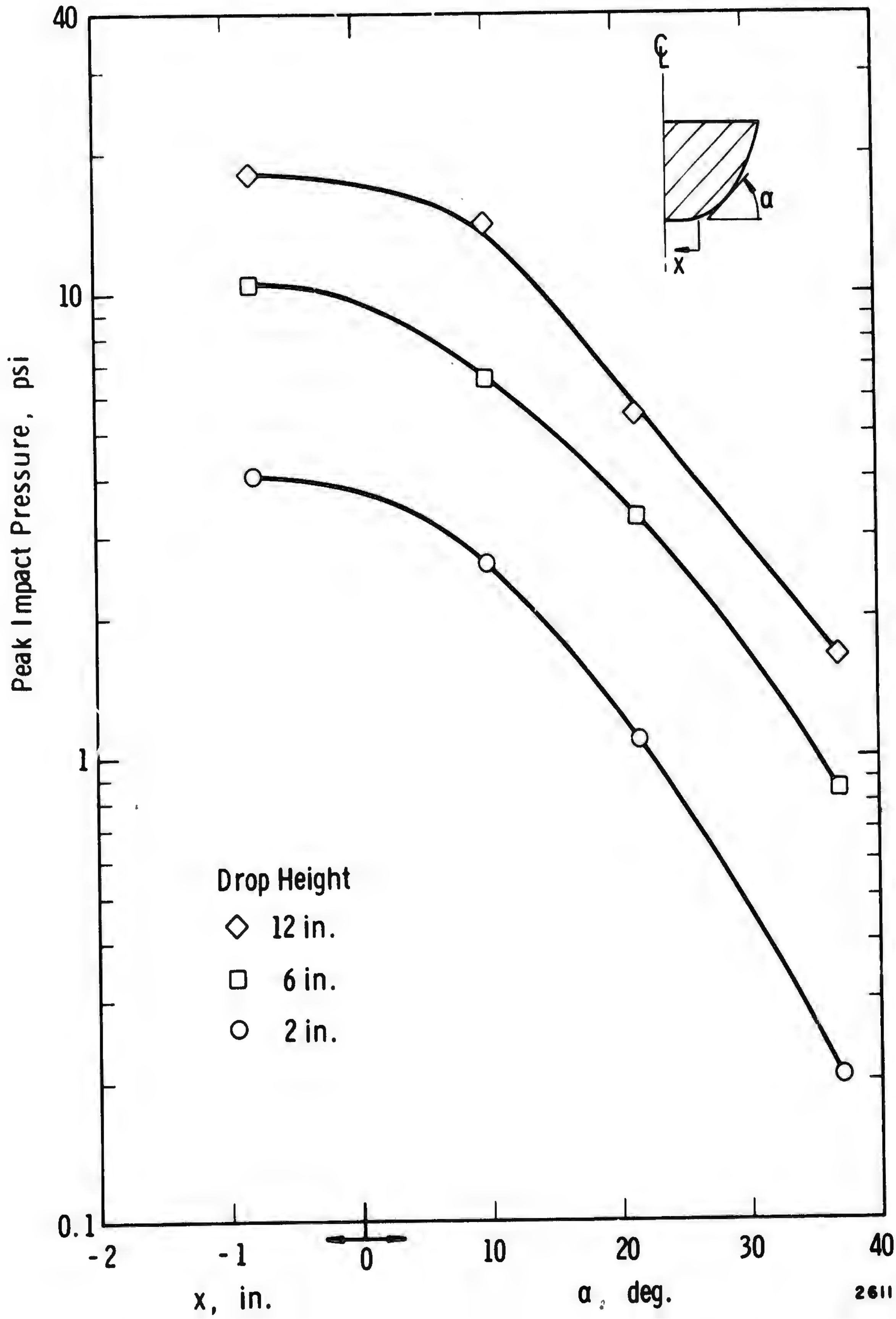


Figure 35. The Effect Of Drop Height On The Peak Impact Pressure Distribution On The UV-0 Model (50 lb) In Waves (2.0 Hz)

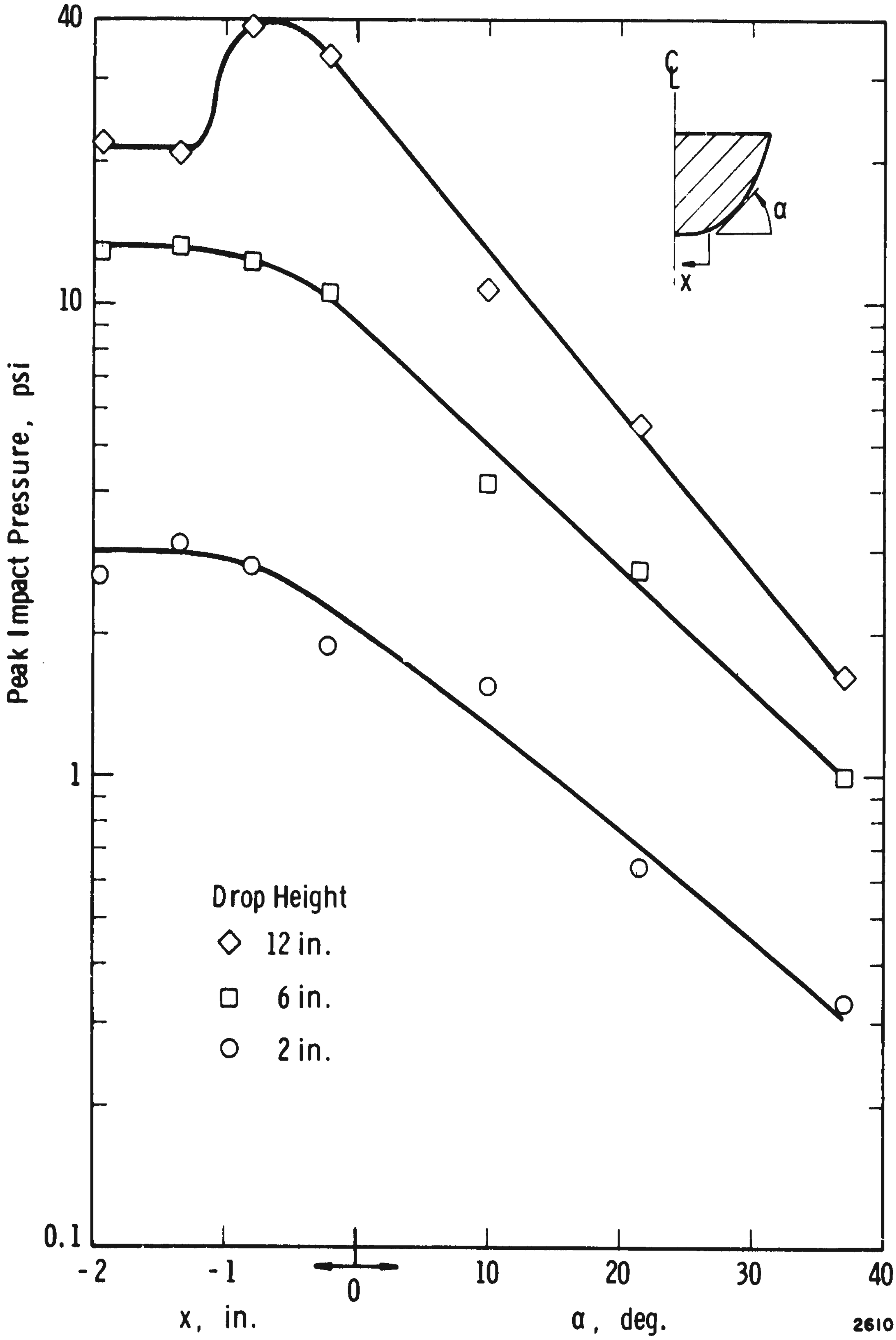


Figure 36. The Effect Of Drop Height On The Peak Impact Pressure Distribution On The UV-2 Model (46 lb) In Waves (2.0 Hz)

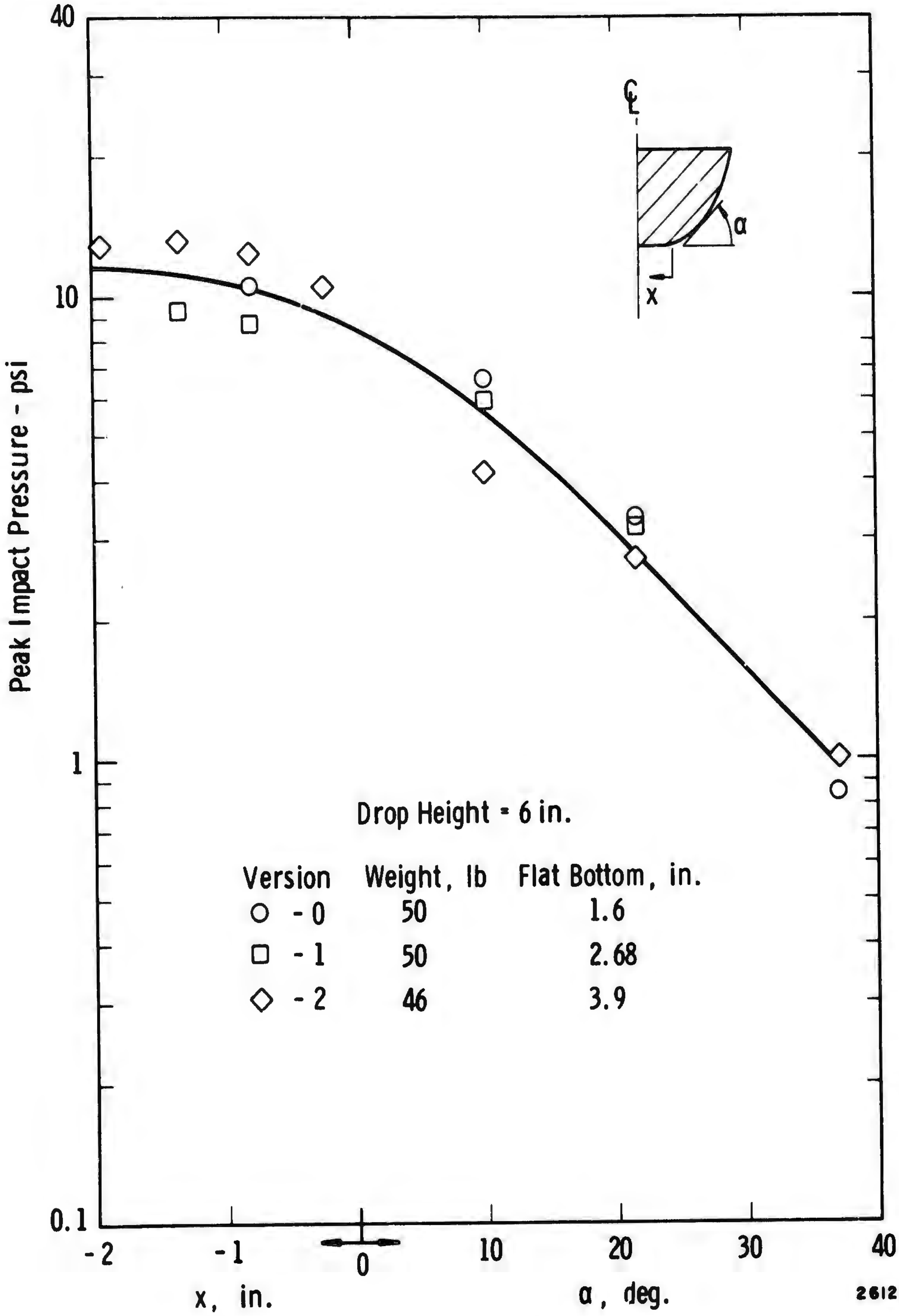


Figure 37. The Effect Of Flat Bottom Width On The Peak Impact Pressure Distribution For The UV Model In Waves (2.0 Hz)

c. Two-Dimensional Drop Tests Versus Model Seaworthiness Tests

As stated previously, the ultimate goal of two-dimensional impact testing is to generate an inexpensive experimental technique which will corroborate full-scale slamming results in an open sea of arbitrary sea state. Recently an excellent agreement was reached between model seaworthiness tests on a Gopher vessel and its full-scale counterpart. Thus, if the two-dimensional tests can be constructed so as to yield results that are in agreement with the model seaworthiness tests, then a solution to the problem will have been found.

In Figure 38 the keel impact pressure for the UV-0 (23 lb) model is compared with the impact pressure for Station 3-1/2 on a model Mariner vessel. Station 3-1/2 is geometrically similar to the two-dimensional hull form under consideration. As is evident, the presence of waves brings the agreement much closer. The arithmetic average of our drop peak pressure data is now only 1-1/2 to 2 times the reported values for these model seaworthiness results.

It must be emphasized that there are two very good reasons why some discrepancy might still exist. First, the wave conditions for our two-dimensional model drop tests were not identical to those employed in the referenced seaworthiness tests. Second, the effective mass loadings for the two model conditions may have been different.

Let's now consider in more detail the possible effect of differences in surface wave conditions. Figure 39 illustrates the effect that varying the degree of water surface disturbance in the experimental tank had on impact pressure. Severity of the surface disturbance, expressed in arbitrary units, is a combined measure of wave frequency and amplitude. Even though it does not show the independent effect of wave frequency and amplitude on impact pressure, it does indicate quite conclusively that if we were to increase the severity of the surface disturbance using the present wave generator we would anticipate lower keel peak impact pressures and therefore, much better agreement between two-dimensional drop tests and model seaworthiness results.

For the sake of completeness the wave amplitude and wave length corresponding to a disturbance number of two (used for our tests) was scaled up by the model scale factor, 40:1, and superimposed on Figure 40, which was modified from Ochi[2]. It is apparent that we have simulated waves of an extremely short wave length, but severe height. Thus, the wave test conditions might be termed non-typical.

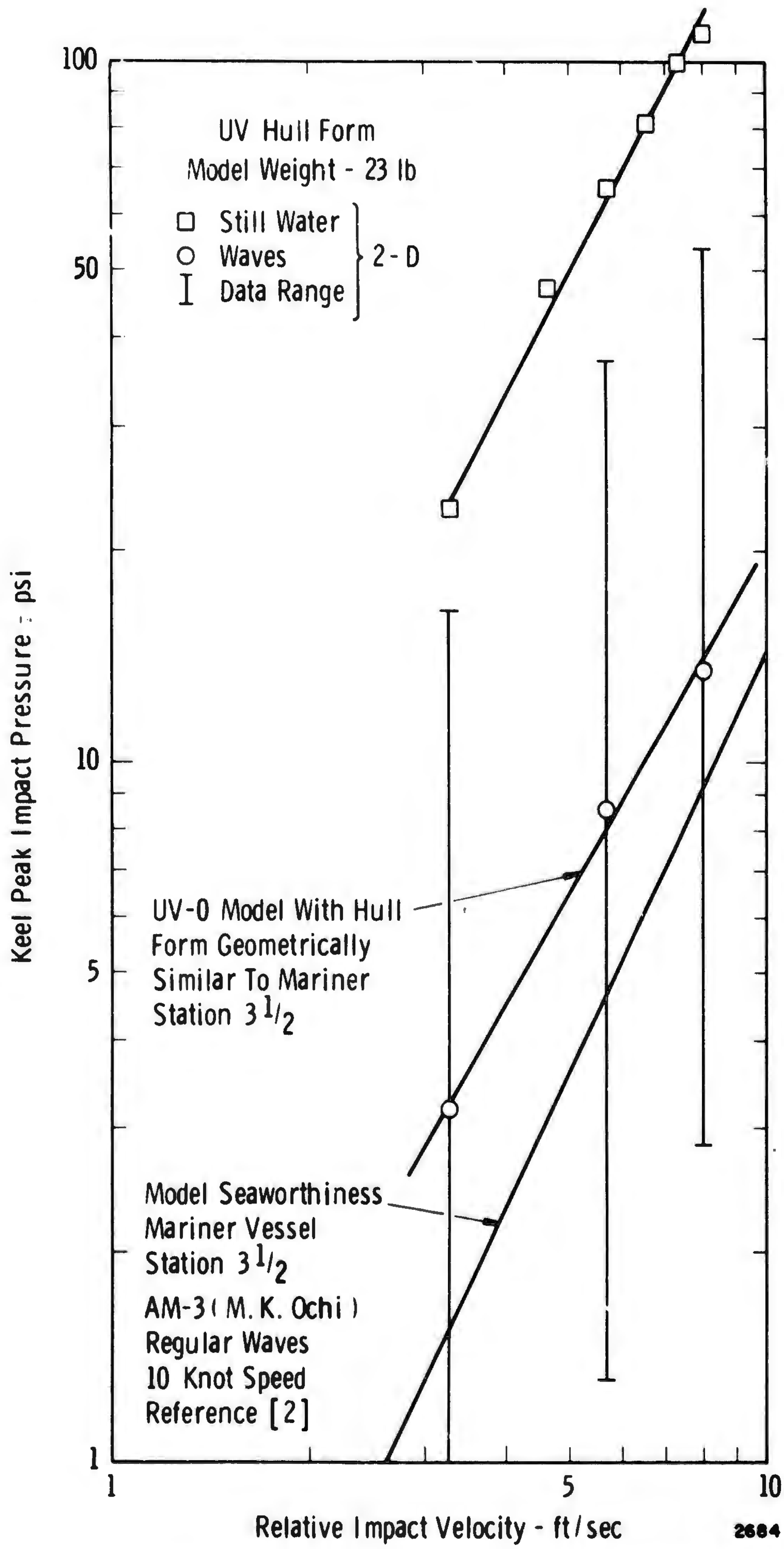


Figure 38. Comparison Of Two-Dimensional And Model Seaworthiness Impact Pressures

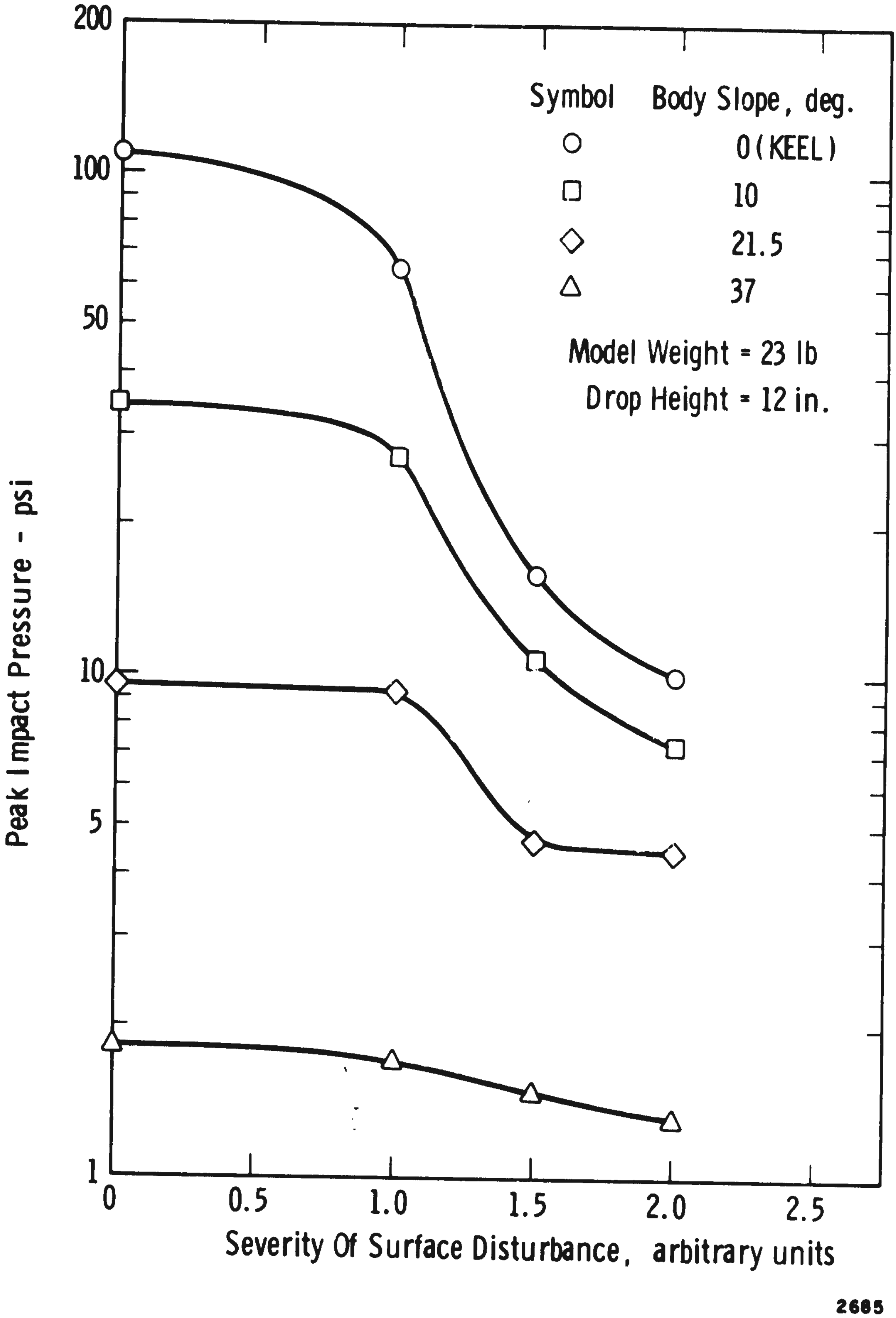


Figure 39. The Effect Of Surface Disturbance On Peak Impact Pressures For The UV-0 Model

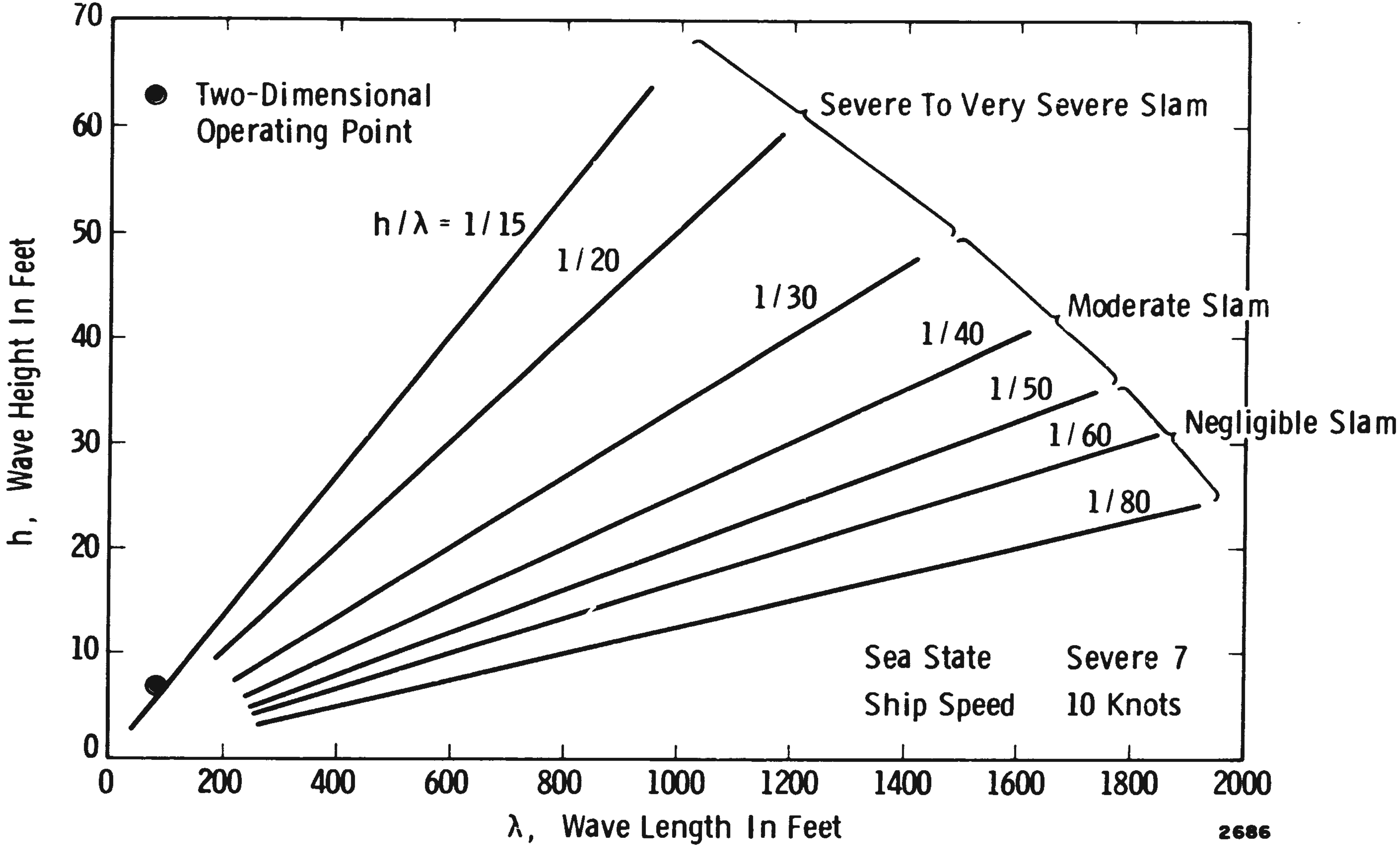


Figure 40. Observed Dimensions Of Wave Components And Relation With Severity of Slam (Modified From Ochi [12])

In conclusion, we believe that these results prove that good correlation between simple two-dimensional drop tests and model seaworthiness tests can be obtained. The key points in making such a simulation are (a) using a properly scaled disturbed surface, and (b) employing the proper effect mass loading.

d. Analogy of Balloon Drop

Some insight into the type of mechanism involved during impact with a wavy surface is afforded by the following analogy. During the initial stage of impact, the large body of water may be considered to be a semi-infinite elastic medium, and the slamming force a concentrated point load on its surface. The theory of elasticity predicts that the zone of influence of a concentrated load on the boundary of a semi-infinite solid is confined to a spherical region beneath the load. By assuming that this spherical region is bounded by a membrane, and that impact occurs at the terminal velocity for a given drop height, then a Gallilean transformation can be made, and the analogous problem of a fluid-filled, spherical membrane impacting vertically onto a rigid, flat surface (analog of ship bottom) can be studied.

To verify this idea, tests were conducted in the laboratory wherein water-filled balloons were dropped on a rigid flat plate. A pressure transducer was mounted in the plate at the point of impact. In Figure 41 the maximum contact pressure generated by the water-filled balloons falling from 6, 12, 24 and 36-inches onto the plate is compared with drop data of the UV form model in waves. The vertical polar axis of the balloon was impacted normally, as nearly as possible, onto the flush-mounted transducer in the plate. The comparison is quite striking, especially in the region extrapolated beyond the UV data.

The only major discrepancy in the above data occurs at the lower drop heights, but might be explained as follows: The act of releasing a balloon causes waves to travel through the fluid interior as well as around the circumference of the membrane. These waves oscillate and decay with time during the drop (for example, the 12, 24 and 36-inch drops). However, when the drop time does not permit these waves to decay sufficiently, the impact compression wave might reinforce the oscillatory waves at the pole, and the result is an increased pressure corresponding to the lower 6-inch (5.8 fps) drop condition. Another possible explanation of the above noted discrepancy would be the stiffness effect of the membrane or balloon wall. At the higher impact velocities this stiffness would tend to be negligible, while at the lower impact velocities it could cause undue restraint of the liquid, hence an increase in initial impact pressure.

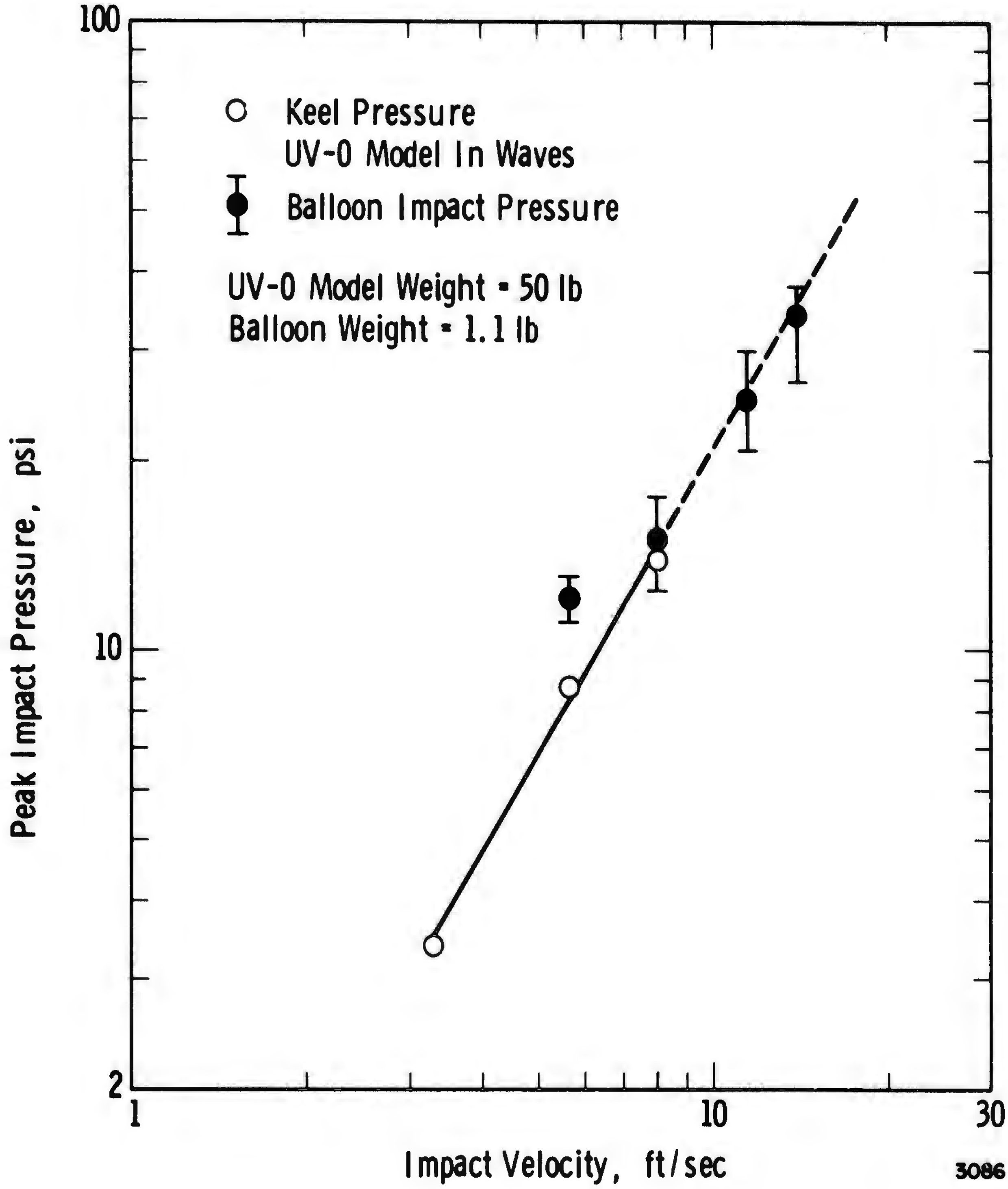


Figure 41. Comparison Of Balloon Impact Pressure With Peak Keel Impact Pressures On The UV-0 Model In Head Waves (2.0 Hz)

EXPERIMENTAL RESULTS - ELASTICITY OF IMPACTING SURFACE

1. Experimental Plan

Ship structures, and in particular hull panels, respond dynamically to transient pressures generated during water impact. This response is characterized by either:

a. Dynamic, linearly elastic deformations of the hull for impacts in moderate sea states, or

b. Plastic deformation (work hardening) of panel materials caused by impact in severe seas.

Regardless of the response mode, it should be expected that the presence of structural deformation will likely result in impact pressures which deviate from the pressures obtained when the structure is considered to be infinitely rigid. This deviation has been termed "interaction pressure" by Chuang.

To investigate the nature of this interaction, a series of water impact tests were conducted using the flexible bottom model described on page 12. The objectives of these tests were to determine:

a. The dependence of peak impact pressure on plate thickness or alternately bending rigidity,

b. The extent of panel work hardening on peak impact pressure as a result of repeated impacts, and

c. The combined effect of elastic bottom and surface waves.

It was initially planned that, following the drop tests with the simple flexible bottom model, the UV-0 model described earlier would be modified to include a typical elastic bottom section, and suitable pressure transducers. As it turned out, this was not attempted for the following reason. The simple model tests required more time than had been anticipated because of the need to continually replace the bottom plates, including remounting the transducer. We had quickly learned that satisfactory data, showing no influence of plate deformation or work hardening, could only be obtained if questionable bottom plates were replaced. This suggested also, that tests on a more elaborate model should also involve continual replacement of bottom panels.

The experimental procedure used with the flexible bottom model was essentially the same as before, except that a continual check was made for permanent bottom deformation and evidence of poor repeatability from drop to drop, suggesting work hardening.

2. Impact On a Quiescent Water Surface

a. Effect of Plate Thickness

The experimental pressure-impact velocity relationship for several plate thicknesses is shown in Figure 42. Rigid body impact data from Reference 5 is also presented to allow a measure of the interaction effect. As can be seen, there is an orderly reduction in peak impact pressure as plate thickness decreases for all drop heights. This behavior could have been postulated a priori on the basis that a thinner plate has less bending rigidity than a thick plate, and a larger deflection which entrains more cushioning air, thus lowering the impact pressure.

Early in the testing sequence it was evident that the oscillatory response of the plate to impact contained frequencies that could possibly have been induced by an acceleration sensitive transducer. To determine the possible effect of the plate acceleration, a compensation scheme described on page 15 was investigated. The result of this investigation was that the pressures recorded without any acceleration compensation adequately represented the true phenomena.

Figure 43 consists of a normalized cross plot of Figure 42. The points bearing symbols are actual data points, and the solid line is an approximate representation of the functional dependency. For the limited range of plate thicknesses, these data suggest that peak impact pressure can be represented analytically as the product of a function describing the variation of pressure with plate thickness and a function which varies linearly with drop height. This observation is based on the fact that, for any plate thickness, the ratio of impact pressures at any two drop heights remains nearly constant. Thus, within the realm of the present study, the elasto-hydrodynamic process governing the generation of impact pressure is essentially a linear one.

b. Effect of Work Hardening

A very interesting observation was made from a series of impacts on a 0.090-inch plate on still water. Figure 44 illustrates the effect of work hardening or permanent set on the peak impact pressure. The curve labeled Run II (identical to the data on the previous figure) was obtained by dropping the model at progressively larger drop heights. The curve labeled

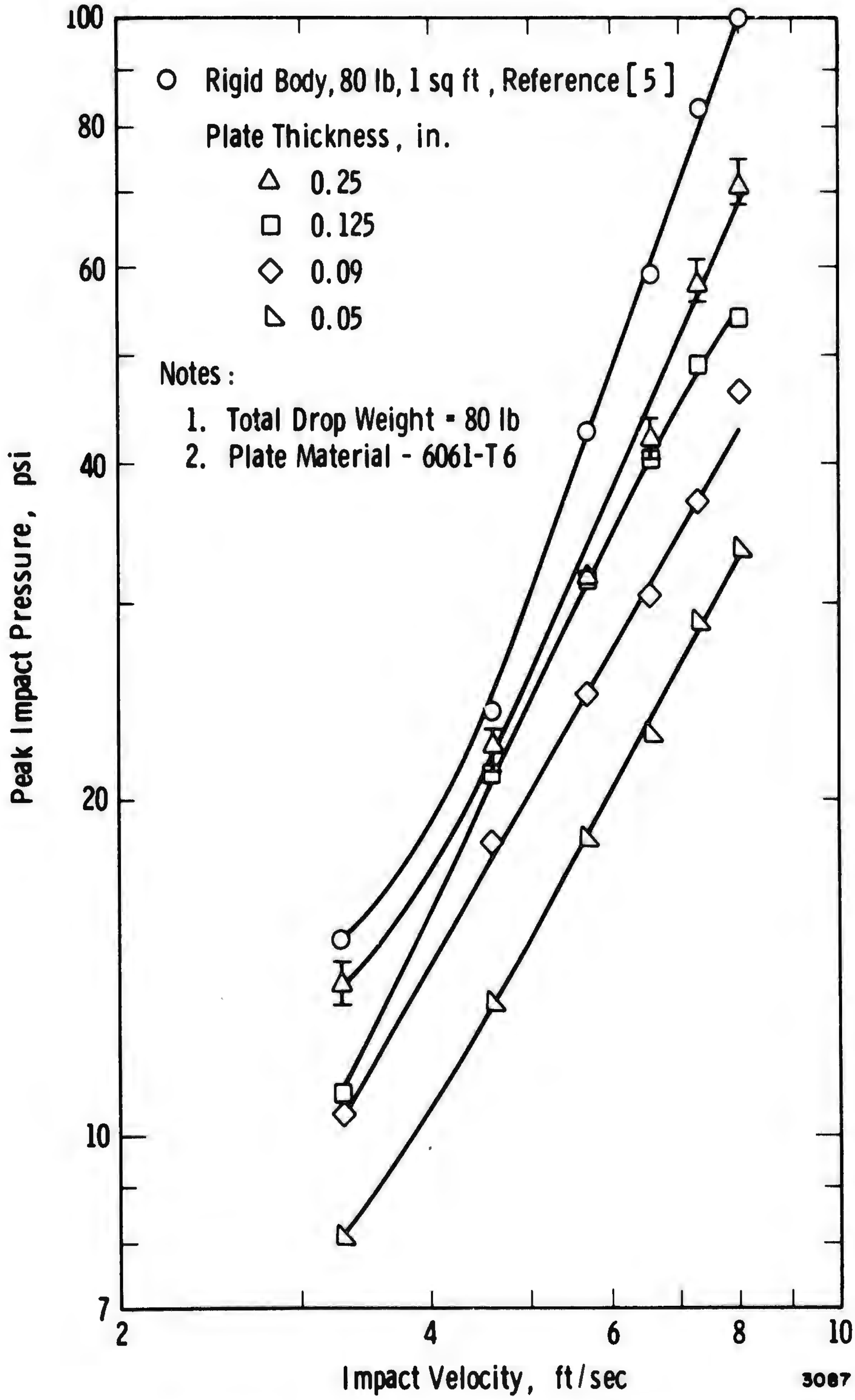


Figure 42. Effect Of Plate Thickness On Still Water Impact Pressure

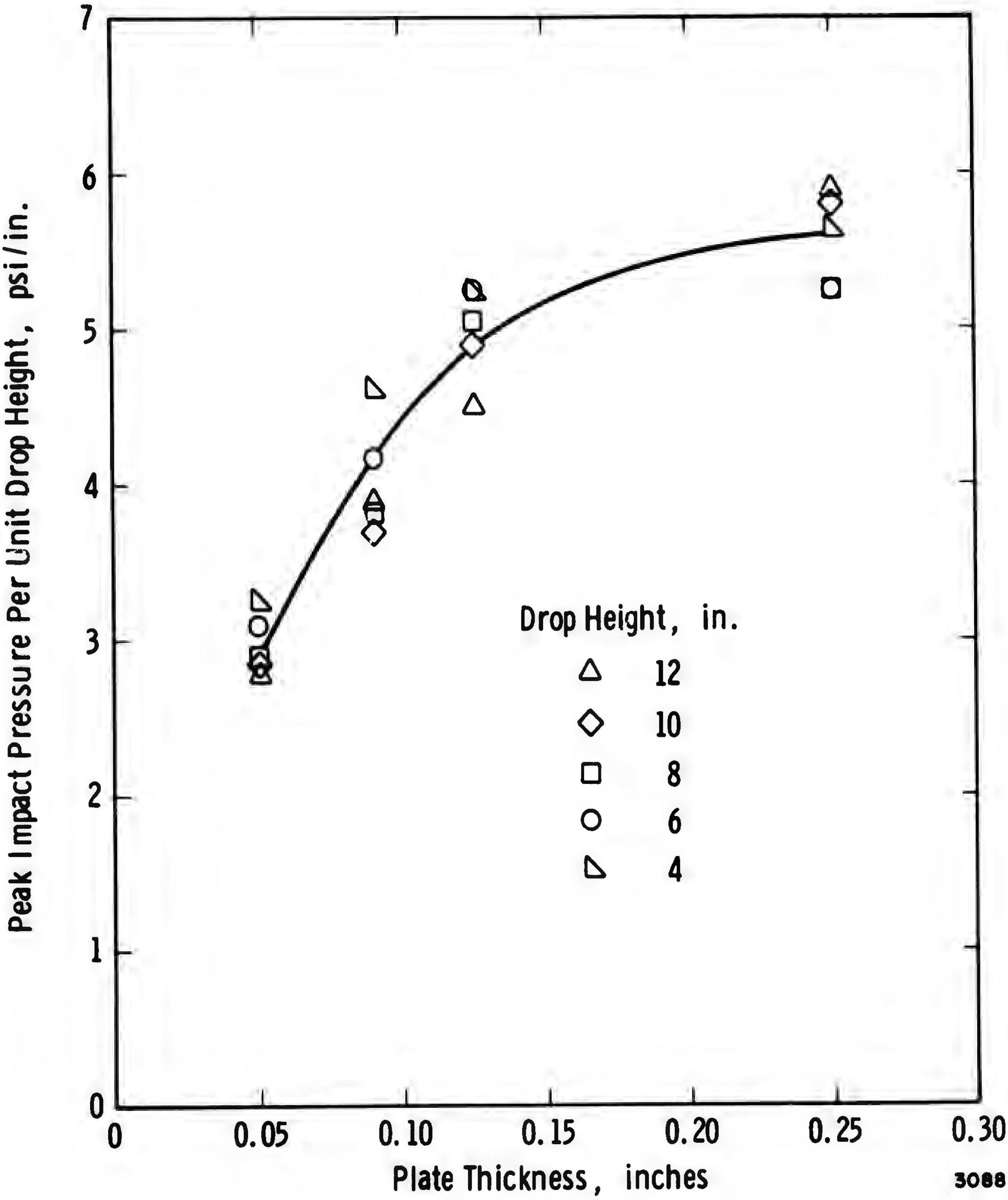


Figure 43. Normalized Impact Pressure As A Function Of Plate Thickness

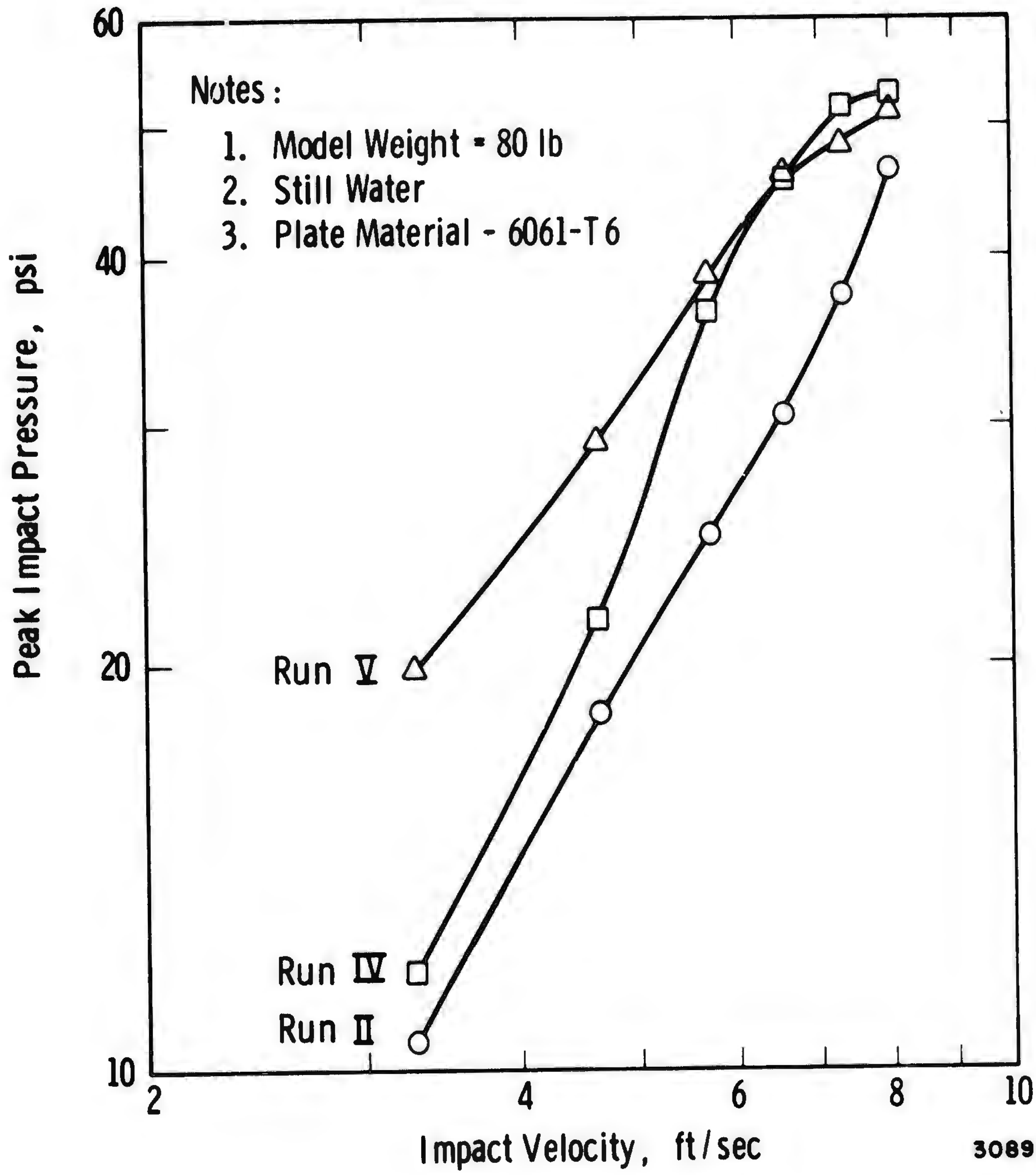


Figure 44. Indicated Strain Hardening Of A 0.09 in. Plate As A Result Of Consecutive Sequences Of Drop Tests

Run IV was a repeat of Run II with the same plate, again beginning the drops at 2 inches and increasing to 12 inches. Run V was generated by repeating the above procedure. These results imply that, through work hardening, the plate became more rigid, thereby probably reducing the amount of deflection available for entrainment of cushioning air and hence, increasing the impact pressure.

c. Oscillatory Nature of the Impact Pressure History

Figure 45 shows a few typical impact pressure-time histories for the 0.25-inch and 0.05-inch-thick plates. It is interesting to note that for the thicker plates the impact trace is dominated by the long period oscillations of the entrapped air bubble with no apparent excitation of the plate vibrational modes. However, for a significant decrease in the plate bending rigidity (two orders of magnitude for the 0.05-inch plate as compared to the 0.25-inch plate) it was observed that the hydroelastic impact process excites the plate bending modes, which show up as high frequency pressure fluctuations superimposed on the bubble oscillation pressure. It was generally observed that on plates thinner than 0.125 inches, these structurally-induced pressure fluctuations were not of a single frequency throughout pressure-time history. This fact suggests that several bending modes may have been excited either individually or jointly at various stages of the impact event.

For plates thicker than 0.125 inch, it was possible to construct a graphical representation of the relation of peak impact pressure and the entrapped bubble frequency. This representation is shown in Figure 46. Interestingly, the pressure-frequency curves appear to have an inverse power law functional relationship. In fact, the 0.25 inch plate has a calculated exponent of -2.56. Remembering that impact pressure varies roughly as the square of the impact velocity leads to the conclusion that bubble frequency and impact velocity are related by a function of the form $V^m f^n =$ constant where $m \neq n$ and $m, n > 1$. The fact that bubble frequency decreases as drop height increases suggests that a larger mass of air is being trapped by larger plate deflections; thus, by analogy with a simple harmonic oscillator, the vibrational frequency must decline. It was not feasible to construct pressure-frequency curves for plates thinner than 0.125 inch because the pressure induced by excitation of plate bending modes obscured the dominant bubble frequency.

In select cases, it was possible to detect a dominant bending mode frequency during the decline in pressure immediately following the peak impact pressure. These frequencies were scaled from the pressure trace

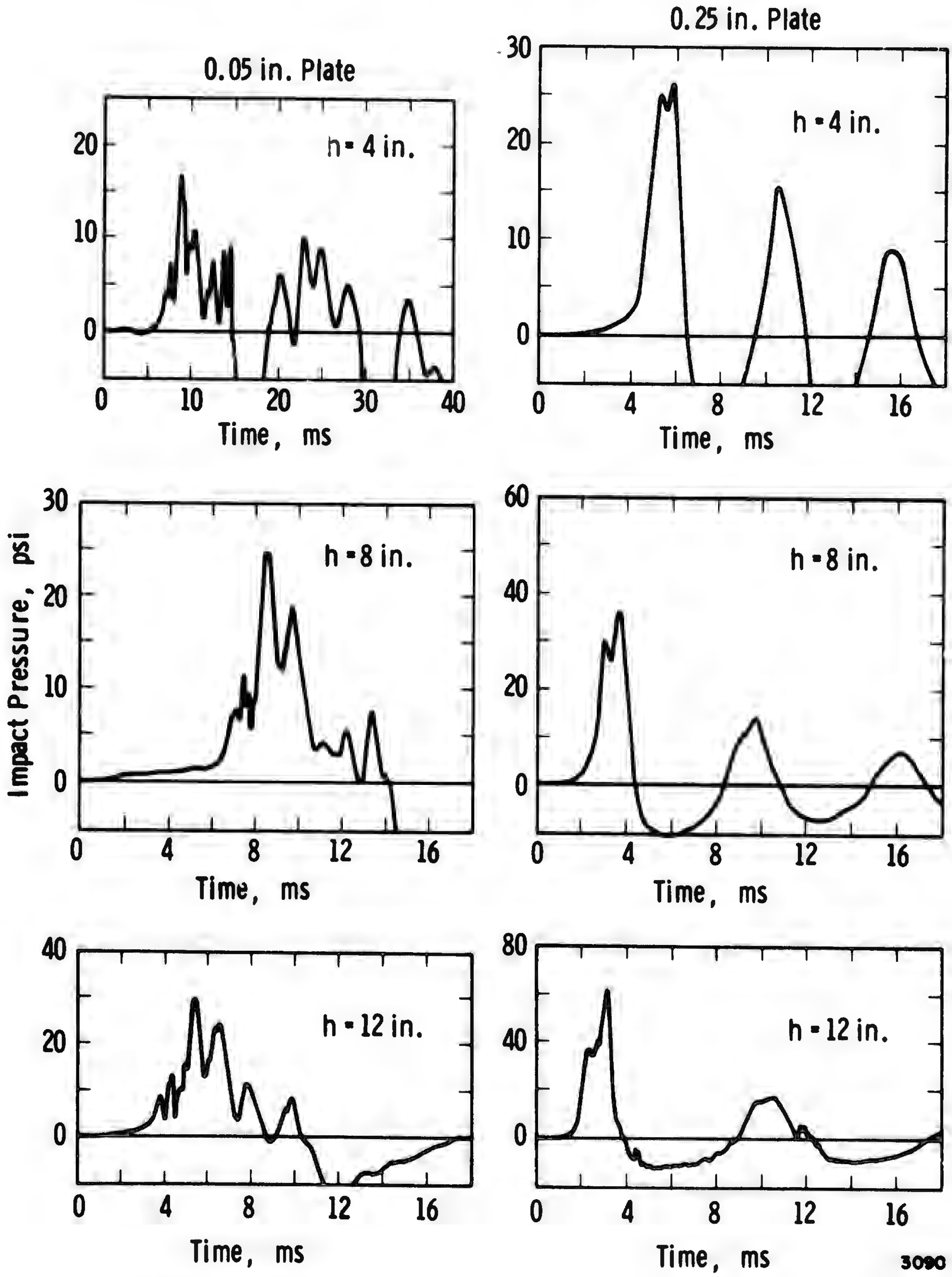


Figure 45. Typical Impact Pressure-Time Histories For The 0.05 and 0.25 in. Thick Plates On Still Water

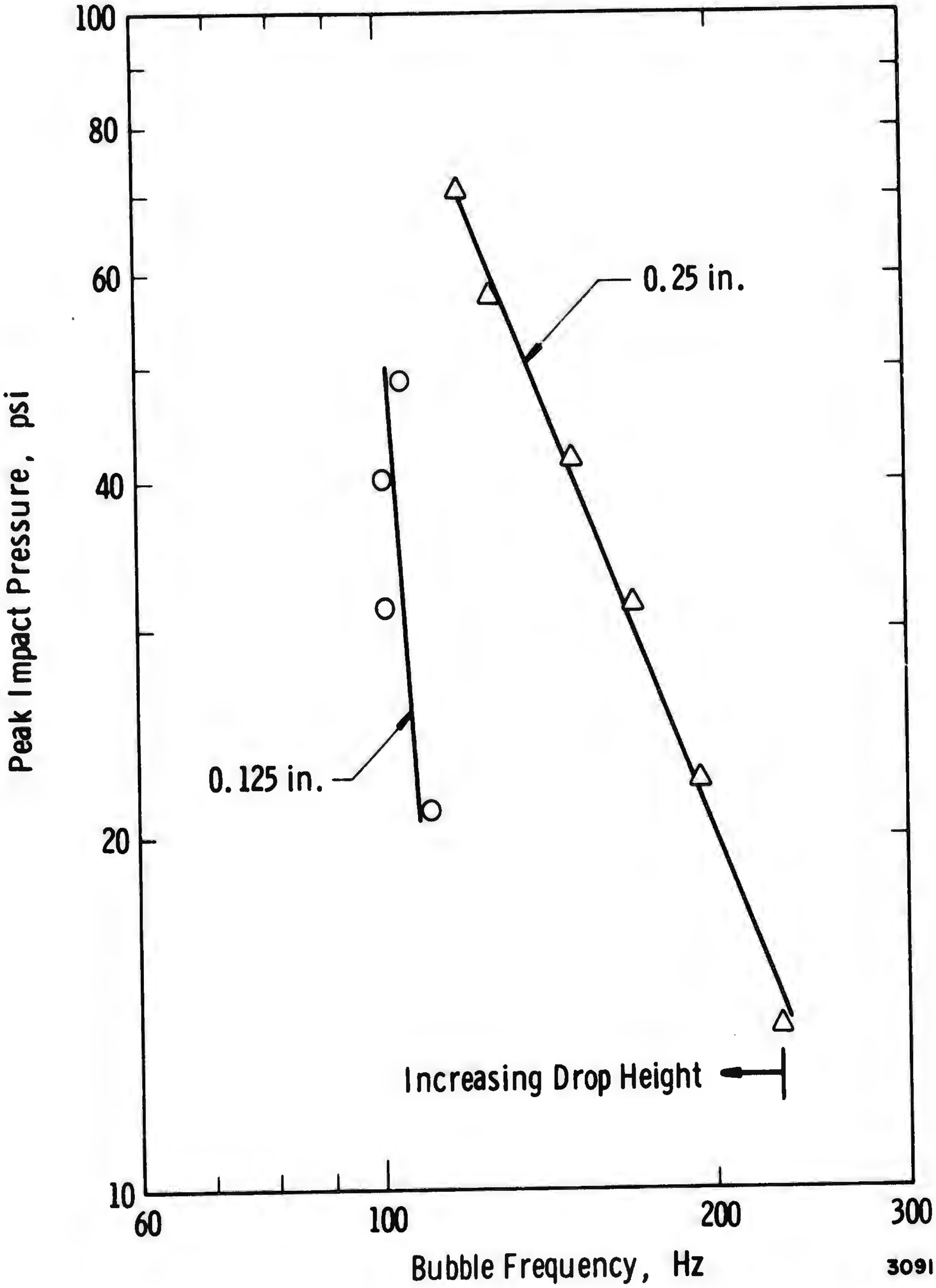


Figure 46. Relationship Between Still Water Peak Impact Pressure And Entrapped Air Bubble Frequency

and appear in Figure 47 as a function of drop height. The general trend for the two thickest plates suggests that the forcing function (impact velocity) excited the same bending mode or combination of modes. The thinnest plate simply responded differently.

In those cases where the impact excited the plate vibrational modes, it was observed that the high frequency oscillations immediately after the peak pressure gave way to longer period structural vibrations as the gross pressure level decayed with time.

3. Impact On a Disturbed Water Surface

In conjunction with the still water impact tests, flexible plates were selectively drop tested on a disturbed water surface. Figures 48 and 49 present the results of dropping 0.09- and 0.05 inch plates, respectively, from heights of 2 inches and 6 inches onto two-dimensional regular waves having an indicated frequency of 2 Hz. Each data point for wave impact represents an arithmetic average of 20 drops. Rigid body and flexible plate impact pressures on still water have been included on these figures for discussion purposes.

In Figure 48 it can be seen that the presence of waves significantly reduces the average peak impact pressure relative to the still water counterpart. This result is consistent with the trend that was observed during the hull form study. It should be noted that the still water impact data for the 0.09-inch plate corresponds to maximum indicated work hardening (see Figure 44). Interestingly, the average wave impact pressure on the work hardened plate also falls below the still water data for a non-work hardened plate.

A somewhat different situation occurs in Figure 49 for the 0.05-inch plate. For this case it appears that the presence of waves has a negative effect on impact pressure. However, this apparent anomaly can be resolved on the basis that the sample size (20 impacts) was not large enough to be statistically significant. Therefore, neither a true average nor mean was achieved for the results in either Figure 48 or 49. It is postulated that an increase in the sample size would result in a reduction in the wave impact pressure below both the still water data for the 0.05-inch plate and the wave data for the 0.09-inch plate.

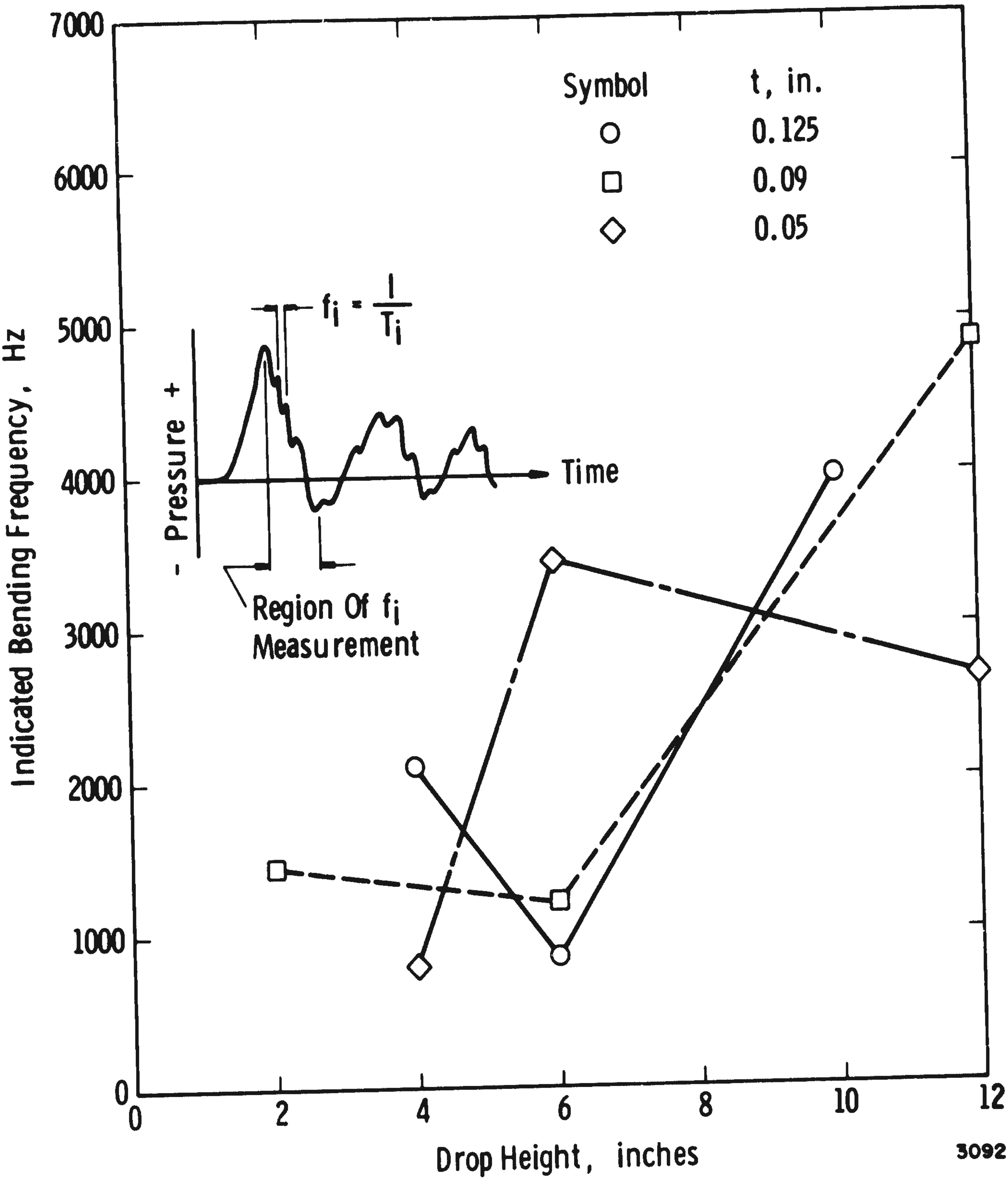


Figure 47. Post Impact Plate Bending Frequencies

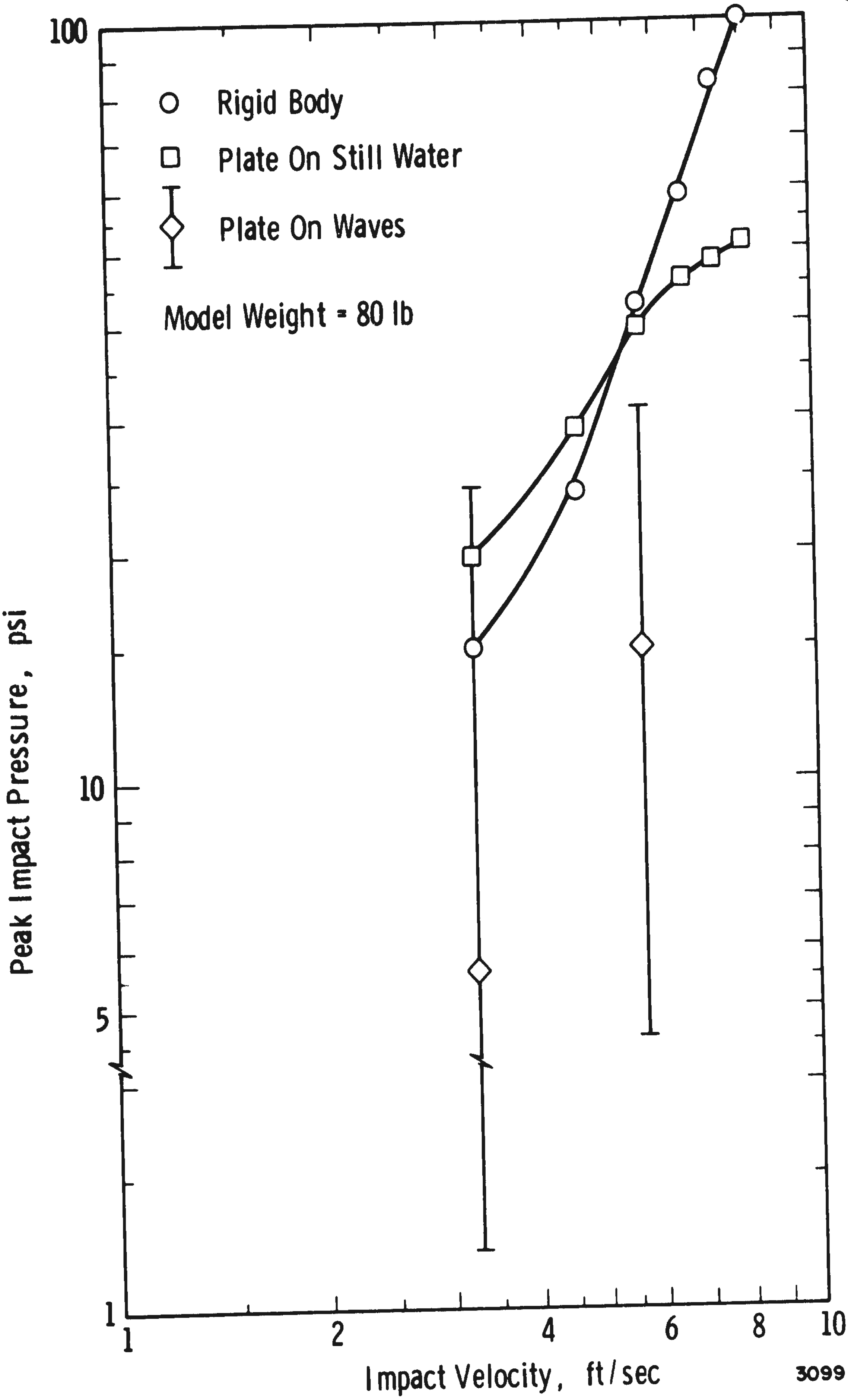


Figure 48. Effect Of Waves On Peak Impact Pressure For The 0.09 in. Plate

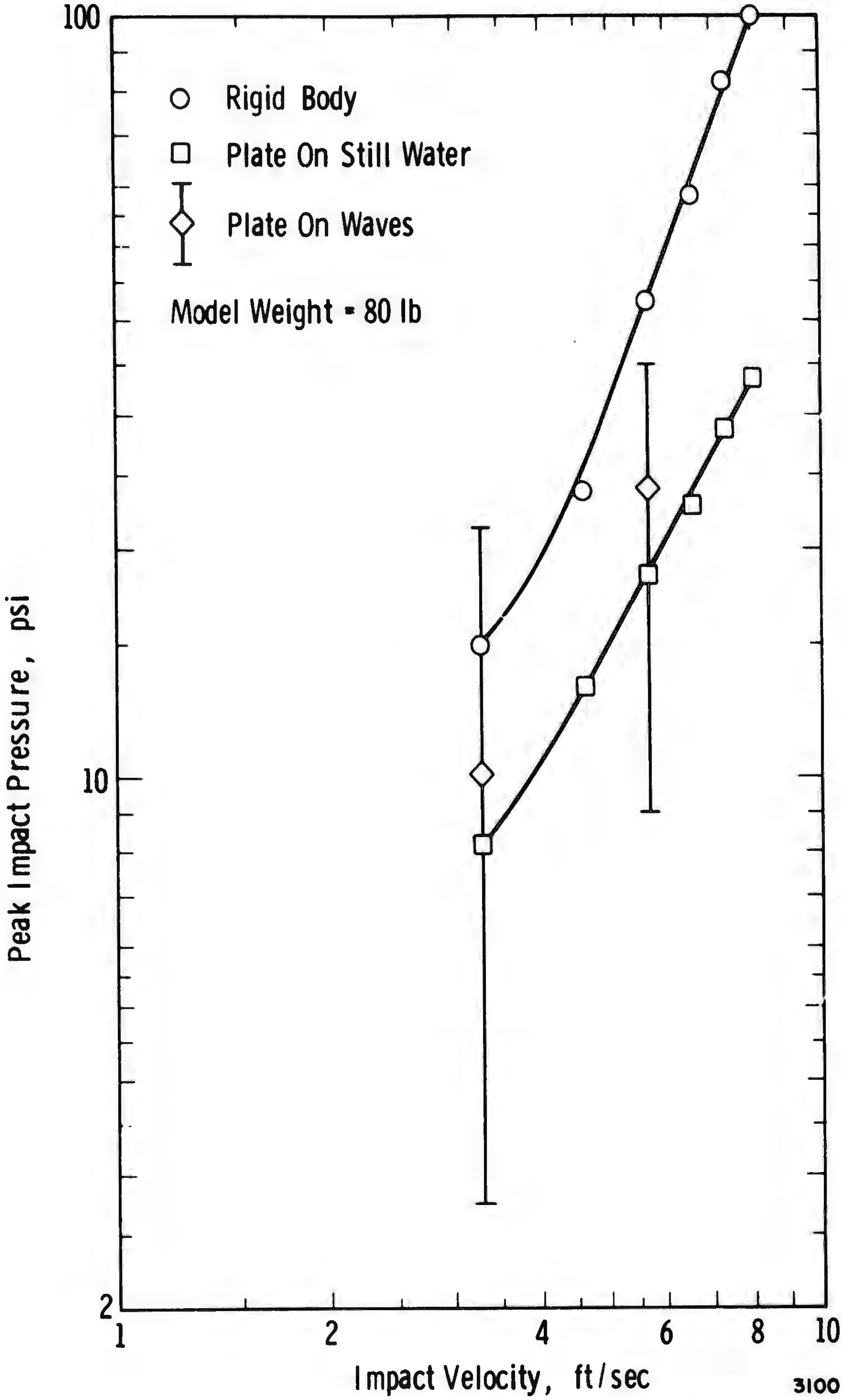


Figure 49. Effect Of Waves On Peak Impact Pressure For The 0.05 in. Plate

DISCUSSION AND CONCLUSIONS

The results of the model water impact experiments reported herein clearly show that (a) the shape of the model cross-section, and mass loading, (b) the nature of the water surface prior to impact, and (c) bottom elasticity effects all have an important bearing on the pressure transients experienced during impact.

The primary conclusions derived from the still water impacts of the various hull forms are:

(1) The peak impact pressures over the bottom of a model vary in a complex fashion as a function of basic shape, mass loading, and extent of flat bottom. Away from the keel for a given local body slope, the impact pressures generally decrease as the model becomes more V like.

(2) At the keel, the peak pressures are influenced mostly by the extent of flat bottom. The greater the flat bottom, the lower the peak pressure. The three basic models (U, UV, and V) had the same flat bottom, and approximately the same peak keel impact pressure. Increasing the flat bottom on the UV model caused a reduction in the peak keel pressure. In general, the variation of peak keel pressure with changes in flat bottom is in accordance with the scale effect results reported in Reference 5.

(3) Our U, UV, and V form data generally substantiates the results obtained by M. D. Ochi[3]; the differences observed may be explained by variations in model construction and experimental technique.

For impacts of the various models on waves, the following statements apply:

(1) For impacts on waves, the peak pressure is a random quantity, and the average value for a large number of successive drops is greatly reduced from the still water value.

(2) The greatest reduction in peak pressure occurs at the keel, and the scatter in the data is such that even the highest pressure observed from a large number of drops is lower than the still water value.

(3) The reduction in the average peak pressure becomes progressively less as the observation point is moved away from the keel. Also, away from the keel, peak pressures higher than the still water value are occasionally observed.

(4) For drops on waves, the effect of hull form and extent of flat bottom is much less pronounced than for drops on still water. To a first approximation, the average peak impact pressure, for a given drop height, appears to be only a function of the local body slope, and extending the flat bottom has little effect.

(5) The above behavior suggests strongly that the physical mechanisms for drops on waves compared with still water are quite different. One possible elementary analogy for the wave problem is the impact of a water-filled balloon on a rigid flat plate.

(6) When performed with realistic surface wave conditions, and proper mass loading conditions, two-dimensional drop tests should show good agreement with model seaworthiness test results. Even without proper waves or mass loading, our test results showed surprisingly good agreement with seaworthiness data.

When a flexible flat plate with clamped boundary conditions on all edges is impacted on a quiescent surface, the following observations apply:

(1) For a given drop height (impact velocity) and plate material, a systematic reduction in peak impact pressure accompanies a reduction in plate thickness (bending rigidity), the upper bound being the rigid body pressure. Increased plate deflections accompanied by entrainment of larger quantities of cushioning air are given as the mechanism for the pressure reduction.

(2) The effects of work hardening of the plate material are clearly visible after repeated sequences of drops. Plate stiffness appears to increase giving rise to larger impact pressures, especially at the lower drop heights.

(3) Bending induced pressure fluctuations are superimposed on the gross impact pressure variations. Maximum bending mode frequencies are observed during the initial rise in impact pressure and immediately thereafter. Increasing time (decreasing gross pressure) is accompanied by a decrease in bending frequencies. Therefore, several modes may be excited during a single impact.

(4) For the thicker plates, those for which the impact forcing function does not excite bending frequencies, the impact pressure is inversely proportional to the frequency of oscillation of the entrapped air bubble. This relationship suggests that the impact velocity and bubble frequency can be described by $V^m f^n$ = constant.

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