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SHOCK-SHOCK INTERACTION STUDIES FOR WEAK INCIDENT SHOCKS



H. E. HUDGINS, JR.

AND

E. M. FRIEDMAN

DECEMBER 1973

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Technical Report 4590

SHOCK-SHOCK INTERACTION STUDIES
FOR WEAK INCIDENT SHOCKS

by

H. E. Hudgins, Jr.
and
E. M. Friedman

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ABSTRACT

The shock-shock interaction problem for weak incident waves impinging on a supersonic cone has been examined. The purpose of this study was to establish methods for predicting surface pressures since existing methods have been found inadequate for practical problems with weak blast waves. It is shown in this study that one-dimensional theory, which works well for strong blast waves, fails when the components normal to the surface of the flight velocity and of the blast particle velocity become comparable. As a consequence, an axisymmetric two-dimensional solution method was developed using a "primary wave" approximation. This approach has been automated in the PRIMUS computer code. The predictions from the code have been checked against experiment and other theory. The comparisons are presented and the agreement is quite good. The code was also used to predict the cone pressures for DNA Sled Test experiments. The results are presented and compared with the experimental results and other theoretical predictions.

This study established that for weak blast waves the maximum pressure for regular reflection occurs at the Mach reflection limit, not at side-on intercept. The question of whether reflection pressures are even higher on the Mach reflection side of the boundary was examined, but existing prediction methods could not resolve this point. To answer this question, a two-dimensional finite-difference code was also developed for shock-interaction. The feasibility of the method was established, but sufficient calculations have not been conducted at this time to report. It is clear that this finite-difference code could resolve the question definitively upon full development.

CONCLUSIONS

1. The results from "primary wave" analytical approaches developed for both one and two-dimensional problems compare well with exact methods and with experiment within the regular reflection regime.

2. One-dimensional methods have proven insufficient for side-on intercept of conical bodies by weak incident waves at supersonic vehicle velocities.

3. The two-dimensional analytical method has been proven by comparison with experiment to give good estimates of reflection pressures on cones in the regular reflection regime. This method has been automated as the PRIMUS (PRimary Interaction Method for Understanding Shocks) computer program.

4. Regular reflection computations indicate a rapid rise in pressure as the Mach reflection limit is approached, reaching pressures that are about 10% higher than in the side-on situation. These few computations suggest that hypersonic similarity parameter correlation of pressure is still valid for side-on intercept in the weak blast case but that the correlation loses accuracy near the regular reflection pressure maximum which occurs at the regular-Mach reflection boundary.

5. Previously available analytical and numerical estimates of oblique Mach reflection are contradictory and insufficient to settle the question: is there a maximum in shock-shock induced pressure in the Mach reflection regime just before the transition to regular reflection.

6. A two-dimensional finite-difference method using the frozen cells technique has been demonstrated to be feasible. Additional effort and computer time is needed however to produce useful computations in both the Mach and regular reflection regimes to settle the above question.

RECOMMENDATIONS

It is recommended that:

1. the PRIMUS computer program, that was developed, be used for making shock-shock estimates for cones and wedges in the regular reflection regime,

2. an effort should be made to complete the two-dimensional finite-difference method since this seems to be the only computational method capable of settling, once and for all, the question of the magnitude of oblique Mach reflection pressures, .

3. should the completed two-dimensional finite-difference code demonstrate that the Mach reflection regime pressure peak is not the maximum, it should be used to check the PRIMUS code in the regular reflection regime,

4. if this check of the PRIMUS code indicates that it needs to be refined for a more exact calculation of the complete pressure-time history, an effort to make these refinements should be undertaken since PRIMUS requires 1/1000 (or less) of the computer time required by the finite-difference method in the regular reflection regime,

5. improvement of these prediction methods be made before or, at worst, in parallel with further experimental efforts in the shock-shock area.

INTRODUCTION

Shock-shock interaction is the phrase used to refer to the events initiated when the bow wave of a supersonic vehicle encounters an incident wave from an external source, such as a blast wave. It has been known since the early 1960's that such an interaction may result in a transient pressure rise on the vehicle just inside the incident wave front.

The concern of vehicle designers about the effect of this rapid loading and unloading was originally directed toward basic structural integrity. Thus, the mid-60's saw a number of development efforts intended to produce analytical and/or experimental evaluation of shock-shock loading for strong blast waves and hypersonic vehicle velocities. Picatinny Arsenal was actively involved under both DASA, DNA, and AMC sponsorship and produced analytical studies and computer codes in the shock-shock problem area, (Refs 1 to 5).

In order to meet designer's needs, the SLAN computer code was also developed at Picatinny (Ref 6). This code is not an analytical method but utilizes curve fits to the analytical results developed at Picatinny and elsewhere. Its purpose was to estimate shock-shock interaction loading at a blunt body stagnation point and for oblique regular and Mach reflection on cones while requiring a minimum of input and using a minimum of computer time.

In order to cover the wide range of intercept angles and vehicle geometries cited above, a great many assumptions had to be made and hypotheses accepted without adequate verification. This was clearly stated and experimental confirmation called for in the SLAN report. The development of a facility capable of obtaining the required experimental data had been initiated at Picatinny Arsenal. The feasibility study had been completed and a pilot facility was being tested for performance, (Ref 7), when all work on shock-shock interaction was stopped because there did not appear to be any structural damage problem.

Shock-shock interaction loading reappeared as a problem in a different area of vehicle damage in 1972. This time, the concern was with weak incident waves and lower flight Mach numbers. These conditions invalidated many of the assumptions of the SLAN code - warning messages to this effect are printed as part of its output. They also placed analytically based numerical approaches such as the PASS code (Ref 2) in regimes where the numerics did not converge. Some outside user's still persisted in using the SLAN code and in disseminating the results without including the warnings issued by the code itself (for an example, see Ref 8). This resulted in a decision to see what one and two-dimensional analyses could be quickly performed in order to produce valid answers in the weak wave regime now of interest. The results of this effort are presented in this report.

DISCUSSION

One-Dimensional Methods

The numerical difficulties encountered by the PASS code for weak incident shocks required that a different analytical/numerical approach for incident shock with less than a 4 to 1 pressure ratio be utilized. At the same time, it appeared desirable to use as much already available technology as possible.

Picatinny Arsenal had available a transonic unsteady finite-difference axisymmetric flow field computer program (Ref 9). Part of this code consisted of a subroutine to compute which types of wave forms will evolve from the juxtaposition of two states of a gas. Its analytical basis is taken directly from the analysis beginning on page 362 of Landau and Lifshitz (Ref 10) except that it has been specialized to the same gas on both sides. Other subroutines taken from the transonic program are used to iterate to the solution which matches the analytical jump conditions (Rankine-Hugoniot equations) across both waves and meets the required equality of pressure and velocity across the contact surface separating them.

The analytical simplifications made for the computation of shock-shock interaction in the weak wave case were that:

1. the gas is ideal,
2. the continuously varying vehicle flow field properties between the bow shock and the surface are replaced by a number of discontinuous steps with the properties evaluated as the average of the end point values of each strip across the shock layer; the exceptions being that the correct values are used at the shock and at the surface (see Fig 1),

3. when computing the interaction at each node only the primary wave transmitted toward the body is followed from node to node, secondary interactions and waves are ignored.

The heart of the method used lies in the second and third simplifications above. This means that the method used is essentially the method of Moeckel (Ref 11) extended to unsteady flow and it is also related to "shock-expansion" methods. The method developed will henceforth be referred to as the "primary wave" method. The bounds on validity imposed by the kinds of simplifications made in the primary wave method can only be determined by comparison with exact solutions or with experiments. The resulting new one-dimensional computer code using this method was given the acronym WISH (Weak Interaction of SHocks).

At the same time, a one-dimensional "shock-tube" unsteady finite-difference code using the linear method of Godunov (Ref 12) was modified to compute the one-dimensional shock interaction with the desired pre-interaction flow field. The usual difficulty with this approach is that the desired flow field does not remain constant in time because it does not satisfy the one-dimensional flow equations. It was found that this change occurred more rapidly than the shock-shock interaction and wall reflection did for the cases of interest. Thus, valid answers required a method of preserving the desired flow field for a sufficiently long time period. The technique developed here was a cell-by-cell "freezing" of the desired flow field imposed near the wall end of the "shock-tube." The criterion used for unfreezing a particular cell was a 1% change in the pressure of the adjacent up-stream cell due to shock-shock interaction.

Both of the above methods were checked by comparing with other computations, an experiment, and with each other. The comparison cases used were:

1. NOL experiment: flight Mach number (M_∞) of 5.16, blast Mach number (M_b) of 4.89, head-on intercept of a sphere, (Ref 4);

2. PASS code result: side-on intercept of a 5° cone, $M_\infty = 10.0$, blast pressure ratio (P_b / P_∞) = 21, ideal air;

3. Analytical: shock of pressure ratio 1.5 propagating into still air and reflecting normally from a fixed wall.

These cases were all computed with the WISH code and with the one-dimensional finite-difference code, which was given the name 1-D. A comparison of results is given below:

Table 1

One-Dimensional Comparison

CASE NO.	1st REFLECTION PRESSURE (psf)				TIME TO 1st WALL REFLECTION (microseconds)		
	Exp/Theo	PASS	WISH	1-D	PASS	WISH	1-D
1	3,300 (Exp)	3,280	3,300	3,300	54.4	55.3	57.
2	--	42,360	41,940	41,800	9.88	10.0	10.
3	4,733 (Theo)	--	4,730	4,730	--	74.6	75.

All results are seen to be in good agreement with each other for both pressure and time. It would also appear that any limitations due to the neglect of secondary wave interactions and real gas effects in WISH do not manifest themselves for nearly equal

strength shocks, each with a pressure ratio of about 30 to 1, (Case 1) nor for two very different shock strengths of pressure ratios 21 and 5 (Case 2).

The next step was to see if one-dimensional methods could produce usable results for the side-on intercept of cones with weak blast waves and significant non-parallelism of body and body shock. The case selected for analysis was based on the DNA Shock-Shock Test Program utilizing a rocket sled (Ref 8). An 11.2° cone at Mach 5 was intercepted by a blast wave of pressure ratio 1.6 parallel to the bow shock of the cone (16.6° from the horizontal). The reflected pressures predicted are compared below and can be seen to be in good agreement with each other.

Table 2

Sled Test Pressure Comparison

CODE	1st REFLECTED PRESSURE
WISH	148 psia
1-D	143 psia

The questioning of the validity of a one-dimensional analysis in the weak blast conical case basically arises from one point. Any one-dimensional analysis assumes (among other things) that the incident wave, bow shock, and body surface are parallel. The calculations above made the incident shock and the bow shock parallel and let the cone surface become non-parallel. Next the WISH code was used to compute the case where the incident shock and the cone surface were parallel but the bow shock was not. The result was a wall reflection pressure of 95 pounds per square inch. This large difference indicates that one-dimensional analysis is not adequate.

The question then becomes why was a one-dimensional analysis adequate for stronger incident waves (pressure ratios of 5 to 201) and thin vehicle shock layers (Ref4)? The answer seems to lie in the relative values of the blast particle velocity and the component of cone flight velocity normal to the blast front and, hence, in momentum and energy. When, for example, Check Case #2 and the Sled Test input conditions to the WISH code are compared, the numbers are those given below.

Table 3

SIDE-ON INPUT CONDITIONS COMPARISONS

CASE	CHECK CASE #2	DNA SLED TEST
Vehicle Mach No.	10.0	5.0
Blast Pressure Ratio	21.0	1.6
Blast Particle Velocity	3274 fps	388 fps
Cone Half-Angle	5.0°	11.2°
Cone Shock Angle	7.7°	16.6°
Flight Velocity ⌊ Bow Shock	1296 fps	1588 fps
Flight Velocity ⌊ Cone Surface	843 fps	1080 fps

It is clear that the major difference between the cases is that in the strong wave case the blast particle velocity is 70 to 80% of the sum of normal vehicle

velocity and blast particle velocity, while in the weak wave case the proportions are just about reversed and the vehicle velocity component dominates. In the latter situation the choice of whether the blast wave is parallel to the body surface or parallel to the body shock has a substantial effect upon the resulting total velocity in body-fixed coordinates. Conversely, in the strong incident shock case, the total velocity is relatively insensitive to whether the blast is aligned with the body surface or with the body shock since so much of the total velocity is due to the blast particle velocity. It is also clear that the thicker the shock layer, the greater the difference between the component of the flight velocity normal to the body surface and the component normal to the body shock.

As a result the use of one-dimensional analyses for the weak wave case, which is dominated by a two-dimensional flow, is not appropriate.

Two-Dimensional Methods (Planar and Axisymmetric)

It is well established from experiment (Ref 13 to 15) that the initial interaction between a conical shock and an incident wave can be treated as a planar two-dimensional problem. This interaction can be solved exactly by the SWIVEL code available at Picatinny Arsenal. The SWIVEL code is also capable of computing the regular reflection pressure and duration of the transient due to the transmitted incident wave when the wave propagates through a constant property layer after the shock-shock interaction, i.e., the case of a wedge, (See Fig 2 for the basic wave diagram and designation of regions).

The non-uniform shock layer of a cone was treated by the same basic method of using a step-wise approximation of a non-uniform shock layer with which the transmitted incident wave interacts and ignoring the secondary interactions. The SWIVEL code's analytical basis is the computation of the 4-shock intersection that can result when 2 co-planar waves interact. Thus in the new analysis, the isentropic compression between shock and surface

on a cone was modeled by a series of weak shock compressions since, as is well known, weak shocks are very nearly isentropic.

During the development of the new computer code, it was found that a single interior shock compression to the cone surface conditions gave essentially the same reflection pressure as a multi-shock compression. It was also found that for the cone flight conditions of interest, that the entropy jump across a single interior shock was still small enough that the flow was nearly isentropic. Therefore, in the interest of simplicity of coding, getting results sooner, and ease of setting up cases a single shock compression was used. The new computer code was given the acronym PRIMUS (Primary Inter-action Method of Understanding Shocks). PRIMUS also retains the wedge case capability of the SWIVEL code.

Another change that had to be made in SWIVEL to produce PRIMUS was the addition of the ability to compute the quasi-steady conditions on a cone at an angle of attack. The wedge conditions can be, and still are, computed in closed form but the cone conditions at angle of attack can not. Windward ray cone surface pressures at angle of attack are estimated from experimental data collected and correlated by one of the authors in the form of the ratio of actual pressure coefficient to the Newtonian pressure coefficient vs the hypersonic similarity parameter defined by $M_\infty \sin(\theta_c + \alpha)$, where M_∞ is the flight Mach number, θ_c is the cone semi-angle, and α is the angle of attack. Other properties required were taken from Sims' tabulation for cones at small angles of attack (Ref 16) and curve fitted. The curve fits are restricted to the range of parameters currently expected to be required and they have not been checked for accuracy at flight Mach numbers less than 3, or cone half-angles greater than 15° . Furthermore, Sims' angle of attack data is only valid at small angles of attack.

The original SWIVEL code estimated the duration of the pressure transient by assuming that: the reflected

• wave was not deflected or altered in strength by its interaction with the contact surface, the expansion wave resulting from the interaction of the reflected wave and the deflected blow wave also propagated back to the body through uniform conditions, and that this expansion was the primary pressure relief mechanism. The duration was defined so that the decay time due to the width of the expansion fan was excluded. This analysis has not been altered at this time in PRIMUS. Thus, the times predicted for the conical case have been computed using the same basic assumptions. Of course the uniform conditions used are the true cone surface conditions. A desirable future effort would be to incorporate the complete non-uniform layer including interaction with the contact surface.

In parallel with this development, an effort was made to modify a two-dimensional, unsteady finite-difference blunt body flow field program (Ref 17), developed with DNA funding, to compute shock-shock interaction of a plane shock wave with a conical flow field. This approach allows the realistic approximation of two-dimensional effects by allowing for non-parallel body surface, bow shock and blast wave and for the non-uniform shock layer, which is the main flow difference between wedges and cones. This is modeled by the "freezing" of the imposed conical flow just as has been discussed for the one-dimensional finite difference code.

This approach is the only one to date which offers hope for answering certain questions that have been asked in the technical community as to where the maximum wall pressure occurs as a function of intercept angle: is there a maximum on the Mach reflection side of the transition intercept angle from Mach to regular reflection and is it greater than the rise in pressure on the regular reflection side of the transition. The finite difference method is expected to compute both with equal facility. Its one serious drawback would seem to be long running times (about one hour on a CDC 6500 which would make it a candidate for answering certain questions about phenomenology rather than a code to be used for each case of

interest. The "frozen flow field" used in the one-dimensional finite-difference code and now incorporated into the two-dimensional code does not affect the propagation rate of discontinuities nor reflected pressures. All the unsteady finite-difference methods of lower dimensionality than the real problem do share one difficulty: they compute the final quasi-steady-state solution of the lower-dimensionality problem rather than that of the problem they are being used to approximate. This is not an insuperable problem and it can be resolved by the same non-numerical method used in the PASS code; one estimates the width of the final expansion wave and its strength by simple closed form methods (page 78 of Ref 18) and patches this onto the finite difference solution beginning at the first predicted pressure relief at the body surface.

This study was carried to the point of showing feasibility. The code was modified to planar two-dimensional form, the boundary conditions suitably modified and initial conditions for the shock-shock interaction problem coded and debugged. A true wedge case for regular reflection was set up (as the correct result was known) and the computation begun. The initial interaction of the bow and blast waves proceeded normally and the transmitted blast wave was propagated toward the body surface; then the body surface pressure near the nose began to rise as it should. Unfortunately, at this time development work had to cease. The method appears to be verified as to feasibility and a small effort would determine its accuracy for wedge regular reflection, cone side-on at high Mach number, and Mach reflection for cones or wedges, both head-on and oblique.

Mach Reflection

The question has arisen, provoked by some predictions of Gardner (Ref 20) and two experimental points in Ref 19, as to where the maximum shock-shock interaction surface pressure as a function of intercept angle actually occurs. Gardner at McDonnell-Douglas suggests that it lies at the boundary between Mach and regular reflection on the Mach

reflection side and may exceed any regular reflection pressure. To illustrate this, the results from Ref 20 has been redrawn as Fig 3 of this report.

The experimental pressure ratios in Ref 19 are for a 90° half-angle cone at Mach 3.1 and a blast pressure ratio of 5. The PRIMUS code predicts the result for HARTS Round 7 (40° intercept angle) to within the indicated uncertainty and predicts the limit for regular reflection to be between 39.5° and 39.0° . It is HARTS Round 9, which was supposedly at a 41° angle of intercept, which gave an 80% higher value of reflected pressure. Since the angle of attack of the cone and angle of intercept of the blast are both subject to some uncertainty, this may be evidence for a maximum in pressure just on the Mach reflection side of the limit if the combined effect was to reduce the effective angle of intercept below about 39° . On the other hand, it may be evidence for an error in data acquisition or reduction.

A brief survey of existing analytical work that applies to oblique Mach reflection reveals very little of direct applicability to the cases of interest. Blankenship and Busemann (Ref 21) present some calculations for cones with very small intercept angles (1° or less away from head-on). These results apply to a wave pattern which occurs only at very high vehicle Mach numbers ($M_\infty \gg 10$) for the blast strengths of interest. These calculations can only give an initial slope, which certainly does not remain constant, for the variation with intercept angle while the intercept angles of interest are 20 to 30 degrees. Most fundamentally, the assumed wave pattern does not apply to the flight and blast Mach numbers of current interest.

The wedge analysis and results by Inger (Ref 22) appears, at first glance, to be applicable. His assumption of a weak blast wave is consistent with the current problem and the same method is used for intercept angles from 0° (head-on) to 60° . The assumption of a wedge need

not disqualify this method for useful cone computations, (see the comparison in Fig 4). However, Inger's method also requires a strong bow wave and he appears unwilling to extend his method below a value of the hypersonic similarity parameter of about 2 (see Fig 7 of Ref 22). Upon closer examination, one finds that the restrictions are even more severe. Not only must the hypersonic similarity parameter be large but this must be achieved while keeping the wedge and wedge shock essentially parallel. This implies small wedge angles and high Mach numbers. Thus the range of proposed validity seems to be at too high Mach numbers and for too slender wedges to be of use in the current problem area. Nevertheless, one might hope to at least answer the important question of the trend of peak pressure with intercept angle as it increases from head-on. Inger's method shows a smooth steady increase in peak pressure with increasing obliquity of intercept.

The stated range of validity is that the original wedge shock angle (θ) minus the wedge angle (δ), (all in radians, see also Fig 2) is much less than 1. However, the results seem erroneous, at least for large intercept angles, even in this proposed range of validity. The PRIMUS code computes the exact solutions for shock-shock interactions on wedges which result in regular reflection from the surface. A check case of a 6° wedge at Mach 20 (for which the angular difference is 0.04 radians) with a blast wave of Mach number 1.2 was computed with PRIMUS for intercept angles from 60° to 22° . Results for this case were also computed using the correlations plots in Ref 22. A comparison of reflection pressure/ambient pressure is shown below and plotted in Fig 5.

Table 4

Oblique Intercept Comparison for Wedges

INTERCEPT ANGLE (0° = head-on)	$\left(\frac{P_{refl}}{P_{\infty}}\right)$ Inger	$\left(\frac{P_{refl}}{P_{\infty}}\right)$ PRIMUS (Exact)
10°	12.60	Mach Reflection
20°	13.10	Mach Reflection
25°	13.38	16.11
30°	13.68	15.89
40°	14.41	16.01
50°	15.45	16.24
60°	17.11	16.45

Since the same pre-intercept and quasi-steady pressures were used for both methods for each case, it seems that the difference must be attributed to the value of maximum pressure computed by Inger's method. That method does not predict the minimum in pressure followed by a strong rise with decreasing intercept angle just before the Mach reflection limit that is characteristic of weak incident wave regular reflection. Either Inger's method cannot be applied to as large intercept angles as he believed in 1966 or 0.04 is not $\ll 1$ for his method at $M_{\infty} = 20$. Since the small perturbation theory used is only valid in the limit as $\delta \rightarrow 0$, this could be the case. Whether or not it is adequate for small intercept angles (Mach reflection) is not well established at this time.

A rather risky extrapolation of cone experimental results in Ref 23 to lower blast strengths and assuming that the hypersonic similarity parameter is a correlating quantity indicates that Inger's results for head-on intercept in this case are in good agreement (see Fig 5). If this is a valid check, and if Inger predicts the correct trend, it indicates that there is no reflection pressure maximum due to Mach reflection. Any rise in pressure near the Mach-regular reflection limit would then be due to the rise which occurs in the regular regime. However, there are too many unconfirmed assumptions to consider the matter settled.

The work of Smyrl (Ref 24) is similar to that of Inger and is applicable to lower flight Mach numbers but it is a linearized analysis which requires that the wedge angle (or wedge angle plus the intercept angle) be small enough that linearization is valid at the desired Mach number. Thus, this method can only give the initial slope of the pressure-intercept angle function for wedges that are intercepted obliquely.

RESULTS

The one-dimensional "primary wave" (WISH code) and finite-difference methods developed (1-D code) were found to be in good agreement with each other and with a number of other exact and experimental results for one-dimensional flow. One-dimensional computations of the DNA Sled Test conditions at a Mach number of 5, an 11.2° half-angle cone with a 16.6° bow wave angle, and a blast pressure ratio of 1.6 indicated that there was a 55% increase in reflected surface pressure in going from a blast wave parallel to the cone surface to a blast wave parallel to the bow shock. Reasons for this difference are detailed in the Discussion and the essential result is that the one-dimensional approximation breaks down at some difference in angle when the three surfaces (blast wave, bow wave, and body) are not parallel. The breakdown occurs at small angles when the vehicle velocity normal to the blast wave dominates the blast particle velocity in the sum of the two terms.

The two-dimensional "primary wave" analytical approximation was automated in a form appropriate for cones in the PRIMUS computer program. Suitable experimental or independent analytical methods to check against are harder to obtain for the oblique intercept of cones. The most suitable predictions available were those by Gardner and Lenertz (MDAC and MMC, respectively, on Fig 2-15 of Ref 8) for the DNA Sled Test. The PRIMUS results are in good agreement with Gardner for pressure and in fair agreement for duration in this case with the blast front nearly parallel to the cone surface. This is shown in Figure 6. Lenertz does not predict durations and the pressure predicted is lower than the other methods. The peak pressure predicted by PRIMUS is 73 to 79 psia, depending on the experimental uncertainty in blast strength and orientation.

The experimental results for the Sled Test are reported in Reference 8. The data in which the most confidence is placed is from the test designated 4B-B3. However, the fact that the high temperature pressure gauges used had too slow a response time and the regular gauges were subjected to a high temperature environment had necessitated a great deal of processing of the raw data. The basic technique was to calibrate the gauges with a shock-tube and use convolution techniques to predict the actual pressures sensed during the rise time of the slower response gauges. Figure 2-15 of Ref 8 shows both the preliminary estimate band and the final estimate of the shock-shock reflection pressure after processing the raw data. The final estimate results in a peak reflected pressure of about 100 psia. This is 32% above the mean estimates of any of the two-dimensional theories including PRIMUS. The final reduced data from the experiment, as taken from Ref 8, are compared with the theoretical predictions on Fig 6. It should be noted however that the gauge in question read the theoretical pre-interaction surface pressure (33 psia) exactly while it read 23% high for the quasi-steady post-interaction pressure. This suggests that the gauge had changed calibration during the shock-shock transient. The PRIMUS predictions and an analytical approximation

from Reference 14 are compared next with a different experiment (Ref 14) which did not depend upon pressure gauges. Since good agreement was achieved with this other experiment, and several theories are in essential agreement for the DNA Sled Test, it would seem that the gauge response problem is the major cause of the disagreement between theory and experiment in that test. Certainly, the experiment was not as definitive as one would have liked. It is understood that a Phase II experiment will be conducted in which it is hoped to eliminate some of the problems mentioned.

The only oblique regular reflection on cones experimental results are those of Ref 14 where pressures are predicted from photographs of shock patterns observed on cone models launched through an oblique shock at 40° from the normal to the cone axis. The incident shock strengths tested are higher than those of interest to the current problem but the cone angles and cone Mach numbers are in the desired range.

The PRIMUS predictions and these experimental results for the ratio of reflected pressure to initial cone pressure are compared in Figures 7 to 10. Only the mean value of the experimental shock wave Mach numbers actually achieved was used at each nominal experimental value for the incident wave strength in the PRIMUS computations. Quite good agreement was found for the variation of the ratio of reflected to initial pressure with shock wave Mach number for both 9° and 15° half-angle cones (see Fig 7 and 8). The PRIMUS predictions of the variation with cone Mach number shows a somewhat stronger dependence on cone Mach number than the experimental data indicates for both 9° and 15° cones, at the higher blast strengths. As the blast strength is reduced, the agreement with experiment becomes better and better and is excellent at the lowest strength tested and should be excellent at the even lower strengths of interest, (see also Fig 9 and 10).

The Two-dimensional theory used in Ref 14 computes the 2-shock interaction exactly but ignores the effect of the non-uniform shock layer on the strength and orientation of the transmitted shock and then computes the reflection at the surface using actual cone surface conditions. The 'primary wave' approach in PRIMUS does consider the non-uniformity of the shock layer. The improvement made by accounting for the change in transmitted wave strength and inclination is discussed below. The predictions of the theory of Ref 14 are always higher than the PRIMUS code predictions. The PRIMUS predictions are clearly in better agreement with experiment for the 9° cones (Fig 9); while in the case of the 15° cones, the data scatter is too great to permit a choice between the two theories (Fig 10). The pressure trends with shock wave Mach number of the two methods can be seen by comparing Fig 7 with 11 and Fig 8 with Fig 12. Again the method used in PRIMUS compares more favorably with experiment for the 9° cones and also appears superior for the 15° cones.

The PRIMUS code achieved this agreement even though various messages-warning of the violation of assumptions-were printed out for some of the required cases. However, these were related to the small angles of attack limit inherent in using Sims' results (Ref 16) for the quasi-steady state or to the duration calculation, which is known to be an approximation. It is hoped that this will not lead to the wholesale neglect of such messages by users as it did with the SLAN code.

The two-dimensional finite difference computer code using a method of "freezing" the imposed preinteraction flow field was brought to the point of proving feasibility of the basic method in two dimensions. The necessity of stopping work prevented checking it against exact solutions for wedges and comparing it with the PRIMUS results for cones. This computer code is the only one which currently has the potential of computing the oblique Mach reflection case and, hence, resolving the uncertainties in this regime dealt with in detail in the Discussion.

In order to permit the ready computation of oblique intercept of cones and wedges in the regular reflection regime, Appendix A of this report contains a brief user's guide to input and output of the PRIMUS code, a listing of PRIMUS, and a wedge and a cone check case.

The PRIMUS code has been used to compute shock-shock results for a cone of semi-angle 11.2° and a blast Mach number of 1.234 at intercept angles from 90° down to the Mach reflection boundary for flight Mach numbers of 3, 5, and 7. The variation of the maximum in surface pressure over ambient pressure with intercept angle and flight Mach number is shown in Fig 13. The maximum reflected pressure ratio at each Mach number is plotted versus flight Mach number on Fig 14. The pressure ratio at an intercept angle of 78.8° (blast wave parallel to cone surface) is also plotted against Mach number on the same figure. This shows that the maximum pressure in the regular reflection regime always occurred at the boundary between Mach and regular reflection, not at the "side-on" conditions, for weak blast waves. At the same blast strength and cone semi-angle, the regular reflection boundary moves to lower intercept angles (more nearly head-on) as the flight Mach number increases. This is due to the stronger bow wave resulting in greater weakening of the transmitted wave. At the same time, however, the reflected pressure over ambient pressure ratio rises with Mach number since the surface pressure rises more strongly with flight Mach number.

The rapid rise in reflection pressure with small changes in intercept angle near the Mach-regular reflection boundary can result in significant errors if the computational angular increment is too large in this region. For example in the above computations at $M_\infty = 5$, if calculations are made at one degree intervals, a ratio of reflection pressure to ambient of 6.02 at $\beta = 25^\circ$ and Mach reflection at 24° is obtained. But when increments of 0.1° are used the pressure ratio becomes 6.36 at 24.2° , with Mach reflection at 24.1° .

When increments of 0.01° are used, the maximum pressure ratio increases still further to 6.44 at 24.18° with Mach reflection at 24.17° (see also Fig 15).

Earlier side-on results for strong blast waves had correlated well with the hypersonic similarity parameter, (Ref 4). In order to see if this remained true for weak blasts, the Sled Test case and a case at twice the Mach number but the same value of the hypersonic similarity parameter were computed with PRIMUS. The results are compared on Fig 15 for the same blast strength at various intercept angles. The side-on ratios of reflection pressure to ambient are nearly equal, however, the Mach 10 results first undershoot then overshoot the Mach 5 results as the intercept angle decreases. The maximum error, at the same angle, occurs near the Mach reflection limits and is about 10%.

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APPENDIX A

PRIMUS INPUT DESCRIPTION

<u>COLUMN</u>	<u>NAME</u>	<u>FORMAT</u>	<u>EXPLANATION</u>
1-10	M1	F	Flight Mach number
11-20	XIB	F	Blast pressure/ambient pressure ¹
21-30	BETA	F	Blast intercept angle (0° = head-on)
31-40	DELTA	F	Wedge case = wedge angle; deg. Need not be specified if XI1 is specified. Cone case = flow deflection angle at conical shock, deg. need not be specified if XIS is specified.
41-50	XI1	F	Pressure ratio across wedge shock. Need not be specified if DELTA is specified for wedge. Surface pressure ratio for cone case.
51-60	CONE	F	Cone half-angle, deg. Blank for wedge case
61-70	XIS	F	Cone shock pressure ratio. Need not be specified if DELTA, conical flow deflec- tion angle, is specified. Blank for wedge case.

¹Analysis currently scaled to ambient pressure = 1, am-
bient sound speed = 1, ambient density = ratio of specific
heats = 1.4.

PRIMUS KEY OUTPUT QUANTITIES¹

MSUB1	flight Mach number
XISUBB	blast pressure/ambient pressure
BETA	incident wave intercept angle (0° = head-on) deg.
GAMMA	ratio of specific heats (constant)
DELTA	wedge angle, or flow deflection angle at conical shock, deg.
ASUB1	ambient sound speed (scaled to 1)
PSUB1	ambient pressure (scaled to 1)
MSUBB	blast wave Mach number
LAMBDA	final state angle of attack, deg.
THETAF	final state <u>wedge</u> shock angle, deg.
XISUBWF	final state <u>wedge</u> pressure/blast pressure
PSUB3F	final state <u>wedge</u> pressure/ambient pressure
P6/P3F	final state <u>wedge</u> reflection pressure/ambient pressure
PSUBF	cone or <u>wedge</u> reflection pressure/ambient pressure
MSUBF	final state <u>cone</u> surface Mach number
THETAC	final state <u>cone</u> shock angle, windward ray, deg.
ALPHAC	final state <u>cone</u> angle of attack, deg.
CONANGL	<u>cone</u> half angle, deg.

PC/P1	<u>cone</u> initial surface pressure/ambient pressure
P6/PC	<u>cone</u> reflection pressure/initial <u>cone</u> surface pressure
TAU	cone or wedge dimensionless duration of reflection pressure, ta_1/b , where t is the actual time and b is the axial distance from the wedge or cone tip to the point of interest. ¹

¹) See also Fig 2 for designation of regions and points.

LISTING OF PRIMUS

PROGRAM	PRIMUS	INPUT	TAPES	INPUT	OUTPUT	TAPES	OUTPUT
1	RENAME	1					
2	RENAME	2					
3	RENAME	3					
4	RENAME	4					
5	NEGATE	5					
6	NEGATE	6					
7	NEGATE	7					
8	NEGATE	8					
9	NEGATE	9					
10	CONC3	10					
11	CONC3	11					
12	CONC3	12					
13	CONC3	13					
14	CONC3	14					
15	CONC3	15					
16	CONC3	16					
17	CONC3	17					
18	CONC3	18					
19	CONC3	19					
20	CONC3	20					
21	CONC3	21					
22	CONC3	22					
23	CONC3	23					
24	CONC3	24					
25	CONC3	25					
26	CONC3	26					
27	CONC3	27					
28	CONC3	28					
29	CONC3	29					
30	CONC3	30					
31	CONC3	31					
32	CONC3	32					
33	CONC3	33					
34	CONC3	34					
35	CONC3	35					
36	CONC3	36					
37	CONC3	37					
38	CONC3	38					
39	CONC3	39					
40	CONC3	40					
41	CONC3	41					
42	CONC3	42					
43	CONC3	43					
44	CONC3	44					
45	CONC3	45					
46	CONC3	46					
47	CONC3	47					
48	CONC3	48					
49	CONC3	49					
50	CONC3	50					
51	CONC3	51					
52	CONC3	52					
53	CONC3	53					
54	CONC3	54					
55	CONC3	55					

[illegible]

LINE	CODE	TEXT	START	END
115	C	IF CONE CASE IS TO BE COMPUTED, DELTA IS FLOW DEFLECTION ANGLE AT CONICAL SHOCK, XI1 IS THE CONE SURFACE PRESSURE RATIO, AND CONE IS THE CONE HALF-ANGLE. ALL ANGLES INPUT IN DEGREES.	78	111
120	C	THE PRESSURE RATIO ACROSS THE CONICAL SHOCK, XIS, MAY BE INPUT INSTEAD OF THE FLOW DEFLECTION ANGLE, DELTA.	111	117
125	C	READ 1000, M1, XIB, BETA, DELTA, XI1, CONE, XIS	117	120
130	C	IF (EOF(5) .NE. 0.) STOP	120	121
135	C	IF (XIS .NE. 0.) GO TO 21	121	122
140	C	IF (DELTA .NE. 0.) GO TO 20	122	123
145	C	CALL WEDGE(XI1, M1, DELTA, THETA)	123	124
150	C	GO TO 20	124	125
155	C	21 CALL WEDGE(XIS, M1, DELTA, THETA)	125	126
160	C	20 IF (M .EQ. 1) GO TO 270	126	127
165	C	PRINT 1010	127	128
170	C	PRINT 1020	128	129
175	C	PRINT 1030, M1, XIB, BETA, DELTA	129	130
180	C	PRINT 1040	130	131
185	C	PRINT 1030, G, A1, P1	131	132
190	C	PRINT 1050	132	133
195	C	270 CALL BLSTW	133	134
200	C	IF (M .EQ. 1) GO TO 271	134	135
205	C	PRINT 1030, MB, VRN, ETAB, A2, UB, U2, M2	135	136
210	C	IF (NALL .EQ. 1) GO TO 271	136	137
215	C	SAVE INITIAL INTERACTION CONDITIONS FOR BLAST	137	138
220	C	BM=MB	138	139
225	C	SVRN=VRN	139	140
230	C	ETAB=ETAB	140	141
235	C	SA2=A2	141	142
240	C	SUR=UB	142	143
245	C	SU2=U2	143	144
250	C	SH2=M2	144	145
255	C	BETAS=BETA	145	146
260	C	271 CALL FINAL(NERR)	146	147
265	C	IF (NERR) 30, 30, 40	147	148
270	C	30 IF (M .EQ. 1) GO TO 50	148	149
275	C	PRINT 1060	149	150
280	C	PRINT 1030, LAMBDA, DELTA, THETA, XI1, ETAB, A3, P3, U3	150	151
285	C	GO TO 50	151	152
290	C	DETACHED SHOCK FOR WEDGE COMPUTATION NEED NOT APPLY IN CONE CASE	152	153
295	C	40 IF (CONE .NE. 0.) GO TO 30	153	154
300	C	GO TO 10	154	155
305	C	50 CALL BOWAVE(NERR)	155	156
310	C	IF (NERR) 70, 70, 60	156	157

170	60 PRINT 1080 GO TO 10 70 IF (M.EQ. 1) GO TO 71 PRINT 1090 PRINT 1030,THETA,XIW,ETAW,A3,AM3 PRINT 1100 71 CALL POINTA(ICASE)- GO TO (M0,90),ICASE 80 IF (M.EQ. 1) GO TO 81 PRINT 1110 GO TO 100 90 IF (M.EQ. 1) GO TO 81 PRINT 1120 100 PRINT 1030,VA,VI,V2,V3,EPS,ANG1,ANG2,ANG3 81 CALL FORFIV(NERR) IF (NERR) 120,120,110 110 PRINT 1130 GO TO 10 120 CONTINUE IF (M.EQ. 1) GO TO 122 PRINT 1140 GO TO (130,140), ICASE 130 PRINT 1150 GO TO 150 140 PRINT 1160 150 PRINT 1030,THETA1,THETA0,XI1,XI0,ANG4,ANG5,ANGT,ANGD,ETAT,A4A3 122 IF (CONE.EQ. 0.) GO TO 121 IF (M.EQ. 0) PRINT 1280 C C C COMPUTE 1-STEP COMPRESSION TO CONE SURFACE ALFA=LAMBDA ALSAVE=LAMBDA SAVE=M2 OLSV=DELTA OELTA=CONE XSAVE=XIW CSAVE=A3/A1 IF (INWALL.EQ. 1) GO TO 25 N4ALL=1 XI=XI1/XSAVE ETAW=XIW*(-GINV) A3=SORT(XIW*ETAW) M1=M1 M1=AM3 THETA=ASIN(SORT((0.5*GP*(XI1W-1.)/G)+1.)/M1) SUMN=(SIN(THETA)*M1)**2 DELTA=ATAN((12.*(SUMN-1.))/((M1*M1)*(G*COS(2.*THETA))+2.)*TAN(THETA) 1)) THETA=THETA/CUN C C C SAVE COMPRESSION SHOCK ANGLE TH0LO=THETA DELTA=DELTA/CON C C C	SWIVEL 98 SWIVEL 99 NOPRINT 7 NOPRINT 8 JUMP 12 SWIVEL 102 NOPRINT 9 SWIVEL 104 NOPRINT 10 NOPRINT 11 SWIVEL 106 NOPRINT 12 NOPRINT 13 SWIVEL 108 NOPRINT 14 SWIVEL 110 SWIVEL 111 SWIVEL 112 CONEFIX 2 CONEFIX 3 NOPRINT 16 SWIVEL 114 SWIVEL 115 SWIVEL 116 SWIVEL 117 SWIVEL 118 CONEFIX 4 CONEFIX 5 NUCONE 15 NUCONE 16 NUCONE 17 JUMP 13 JUMP 14 JUMP 15 INTERP 2 CONE 14 CONE 15 NUCONE 18 JUMP 16 JUMP 17 JUMP 18 JUMP 19 JUMP 20 NUCONE 19 JUMP 21 JUMP 22 JUMP 23 JUMP 24 JUMP 25 JUMP 26 NUCONE 20 NUCONE 21 NUCONE 22 JUMP 27 JUMP 28
175		
180		
185		
190		
195		
200		
205		
210		
215		
220		

```

DELSON=(GP/(12.*0.0))*(XIW-1.)*.3
M1=AM3
XIRS=XIB
XIR=XIT
PSCALE=XSAVE
ASCALE=CSAVE
GO TO (500,510)*ICASE
500 BETA=ANGT
GO TO 520
510 BETA=90.-ANGT
520 PRINT 1400
PRINT 1410,XIW,M1,THETA,DELTA,DELSON,BETA
GO TO 20
25 AMF=SAVE
ALFA=ALSAVE
123 CALL FCONC(CONE,XIBS,MIS)
CM=U3F/A3F
IF(M.EQ.1) GO TO 330
PRINT 1060
PRINT 1030,LAMBDA,DELTA,F,THETA,F,XIW,ETAF,A3F,P3F,U3F
CONVERTING FINAL CONE VALUES TO COMPRESSION VALUES
330 CONTINUE
XIWF=XIW/PSCALE
ETAF=ETAF/(PSCALE*(1./G))
A3F=A3F/ASCALE
P3F=P3F/PSCALE
U3F=U3F/ASCALE
ALFA=LAMBDA
121 CALL REGRFL(ICASE,NERR)
IF(NERR)170,170,160
160 PRINT 1170
NERR=9
GO TO 10
170 IF(M.EQ.1) GO TO 171
PRINT 1180
PRINT 1030,OMEGA1,DELTA,V4P,M4P,THETA,R,OMEGA,XIR,P6,P6P3,P6P3F
171 GO TO(180,190),ICASE
180 CALL TIMEA(NERR)
IF(NERR.EQ.1) GO TO 6969
IF(CONE.EQ.0.) GO TO 210
181 IF(M.EQ.1) GO TO 211
XI=XIW*PSCALE
P6=XIW*P6P3
TSCALE=ASCALE
TAU=TAU*ASCALE
TAUX=TAUX*ASCALE
PRINT 1290
PRINT 1300, CM,THETA,F,ALFA,DELTA,XIW,P6P3,P6C,PSCALE,TSCALE,TAU
GO TO 10
190 CALL TIMEH(NERR)
IF(N.EQ.4.AND. NERR.GT.0) GO TO 440
IF(NERR.LE.0) GO TO 220
M=1
275

```

JUMP 29
JUMP 30
NUCONE 23
JUMP 31
NUCONE 24
NUCONE 25
JUMP 34
JUMP 35
JUMP 36
JUMP 37
JUMP 38
JUMP 39
JUMP 40
JUMP 41
JUMP 42
NUCONE 26
NEGATE 8
NEGATE 9
NUCONE 28
NUCONE 29
NUCONE 30
NUCONE 31
NUCONE 32
NEGATE 10
NUCONE 33
NUCONE 34
NUCONE 35
NUCONE 36
NUCONE 37
NUCONE 38
NOPRINT 17
SWIVEL 120
SWIVEL 121
SWIVEL 122
SWIVEL 123
NOPRINT 18
NOPRINT 19
SPELL 1
NOPRINT 20
SWIVEL 127
SWIVEL 128
CONE3 14
INTERP 7
JUMP 43
HEALP2 4
JUMP 45
JUMP 46
JUMP 47
CONE 25
REALP2 5
CONE 27
DOPRINT 6
TAUB-1 6
SWIVEL 131
NOPRINT 21

```

280 PRINT 1250
    BI=BETA
    IF (CONE .NE. 0.) THETA=THOLD
    IF (THETA-DELTA .GT. 5.) GO TO 250
    BETA=190.-THETA*.999
    NERR=0
    PA=P6P3
    IF (CONE .EQ. 0.) GO TO 261
    ASAVE=AMF
    THSAVE=THETAS
    ALSAVE=ALFA
    OSAVE=DELTA
    XTSAVE=XIM
    XTSAVE=EXIT
    TSAVE=TSSCALE
    DELTA=DLSVE
    261 CONTINUE
    N=2
    B2=BETA
    GO TO 20
    200 PRINT 1190
    GO TO 10
    210 IF (M .EQ. 1) GO TO 211
    PRINT 1200
    PRINT 1030,APOR,CPOR,OCOR,EOPOR,OPOR
    PRINT 1210
    PRINT 1030, CHI,PSI7,MU7,PSIM
    PRINT 1220
    PRINT 1030, VC,U7,V7,VE,TAU
    211 IF (N .EQ. 2) GO TO 290
    IF (N .EQ. 3) GO TO 300
    IF (N .EQ. 4) GO TO 420
    GO TO 10
    220 IF (M .EQ. 1) GO TO 221
    IF (CONE .NE. 0.) GO TO 222
    PRINT 1230
    PRINT 1030, APOR,CPOR,OCOR
    PRINT 1210
    PRINT 1030, CHI,PSI7,MU7,PSIM
    PRINT 1240
    PRINT 1030,VC,U7,V7,TAU
    221 IF (N .EQ. 4) GO TO 420
    GO TO 10
    222 CONTINUE
    XIW=XIW*PSCALE
    P6C=XIW*P6P3
    TSCALE=ASCALE
    TAU=TAU*ASCALE
    TAU=X=TAU*ASCALE
    PRINT 1290
    PRINT 1300, CM,THETAF,ALFA,DELTA,XIW,P6P3,P6C,PSCALE,TSSCALE,TAU
    GO TO 10
    250 IF (THETA-DELTA .GT. 15.) GO TO 200
    WRITE(6,1260)
    GO TO 260
    295 GO TO 20
    300 PRINT 1030,APOR,CPOR,OCOR,EOPOR,OPOR
    PRINT 1210
    PRINT 1030, CHI,PSI7,MU7,PSIM
    PRINT 1220
    PRINT 1030, VC,U7,V7,VE,TAU
    305 IF (N .EQ. 2) GO TO 290
    IF (N .EQ. 3) GO TO 300
    IF (N .EQ. 4) GO TO 420
    GO TO 10
    310 IF (M .EQ. 1) GO TO 221
    IF (CONE .NE. 0.) GO TO 222
    PRINT 1230
    PRINT 1030, APOR,CPOR,OCOR
    PRINT 1210
    PRINT 1030, CHI,PSI7,MU7,PSIM
    PRINT 1240
    PRINT 1030,VC,U7,V7,TAU
    315 IF (N .EQ. 4) GO TO 420
    GO TO 10
    320 XIW=XIW*PSCALE
    P6C=XIW*P6P3
    TSCALE=ASCALE
    TAU=TAU*ASCALE
    TAU=X=TAU*ASCALE
    PRINT 1290
    PRINT 1300, CM,THETAF,ALFA,DELTA,XIW,P6P3,P6C,PSCALE,TSSCALE,TAU
    GO TO 10
    325 IF (THETA-DELTA .GT. 15.) GO TO 200
    WRITE(6,1260)
    GO TO 260
    330

```

```

290 T2=TAU
    NERR=0
    N=3
    BETA=B2-5.
    B3=BETA
    IF (CONE .NE. 0.) THETA=THOLD
    IF (CONE .NE. 0.) DELTA=DLSVE
    GO TO 20

300 T3=TAU
    NERR=0
    N=4
    BETA=B3.
    IF (CONE .NE. 0.) THETA=THOLD
    IF (CONE .NE. 0.) DELTA=DLSVE
    B4=BETA
    GO TO 20

420 T4=TAU
    BETA=B4
    CALL PARA-(T2,T3,T4,B2,B3,B4,C11,C12,C13)
    TAU=CT1+CT2*BETA+CT3*BETA*BETA
    TAU=ABS(TAU)
    P6P3=PA
    IF (CONE .NE. 0.) GO TO 421
    PRINT 1270,TAU,P6P3
    GO TO 10

421 ANF=ASAVE
    THFTAS=THSAVE
    ALFA=ALSAVE
    DELTA=DSAVE
    XIW=XISAVE
    XII=XISAVE
    XIW=XIW*PSCALE
    XII=XIW*PSCALE
    P6C=XIW*P6P3
    TSCALE=ASCALE
    TAU=TAU*ASCALE
    TAU=TAU*ASCALE
    PRINT 1290
    PRINT 1300, CM,THETAF,ALFA,DELTA,XIW,P6P3,P6C,PSCALE,TSCALE,TAU
    GO TO 10

440 N=4
    BETA=B3-2.
    IF (CONE .NE. 0.) THETA=THOLD
    IF (CONE .NE. 0.) DELTA=DLSVE
    B4=BETA
    NERR=0
    GO TO 20

320 GO TO 10
6969 WHITE(6,1420)
    TAU=ABS(TAU)
    GO TO 181
END

```

```

SUBROUTINE-BLSTW
REAL M1,M2,M2
COMMON/HREG/M2,VBN,ETAB,A2,UB,U2,M2
COMMON/CONST/G,GP,GM,CON,A1,P1
COMMON/INPUT/M1,X1B,HEIA,DELTA
5  B=CON*HEIA
    MB=SQRT ((GP*X1B*GM)/(2.*G))
    VBN=MB
    ETAB=(GM*X1B*GP)/(GP*X1B*GM)
10  A2=SQRT (X1B*ETAB)
    UB=VBN*M1*COS (H)
    U2=SQRT ((M1*SIN (H))*2*(UB-ETAB*VBN)**2)
    M2=U2/A2
RETURN
END
15

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```

SUBROUTINE ROWANG(M,DELTA,THETA,NERR)
  REAL M
  COMMON/CNST/G,GP,GM,CON,AI,PI
  C
  C SHOCK ANGLE EQUATION IS OF THE FORM OF A BI-CUBIC
  C
  C
  C DEFINE CONSTANTS AND COEFFICIENTS OF BI-CUBIC
  C
  5 NERR=0
    OO=CON*DELTA
    SEN=SIN (OO)
    CUS=COS (OO)
    C2=(M**2*2.01/M**2-0*SEN**2
    D=(2.0*M**2*1.01/M**4*(GP**2/4.0*GM/M**2)*SEN**2
    E=-CUS**2/M**4
    P=-C*C/3.*0
    Q=2.*(C/3.)***3 -C*0/3.*E
  6 H=-0/(2.*(SORT ((-P/3.)***3)))
  7 HANS=ABS (H)
    IF (HANS.GT. 1.) GO TO 140
    OMEGA=ACOS (H)
    CC=2.*SINT (-P/3.)
  C
  C TRIGONOMETRIC SOLUTION TO ROOTS OF CUBIC
  C
  RT1=CC*CUS (OMEGA/3.) -C/3.
  RT2= CC*COS (OMEGA/3. +120.*CON ) -C/3.
  RT3= CC*COS (OMEGA/3. -120.*CON ) -C/3.
  C
  C DETERMINE MIDDLE ROOT - THE PHYSICALLY CORRECT ONE
  C
  C SMALLEST ROOT RESULTS IN AN ENTROPY DECREASE
  C
  C LARGEST ROOT IS STRONG SHOCK SOLUTION
  C
  X=AMAX1(RT1,RT2,RT3)
  Y=AMIN1(RT1,RT2,RT3)
  IF (RT1.LT. X.AND. RT1.GT. Y) GO TO 1
  IF (RT2.LT. X.AND. RT2.GT. Y) GO TO 2
  IF (RT3.LT. X.AND. RT3.GT. Y) GO TO 3
  NERR=1
  RETURN
  3 RT=RT3
  GO TO 4
  1 RT=RT1
  GO TO 4
  2 RT=RT2
  C
  C SOLUTION FOR SHOCK ANGLE
  C
  C
  4 THETA=(ASIN ((SINT-(ABS-(RT)))))/CON
  130 IF (THETA-90.0) 150,150,140
  140 NERR=1
  150 CONTINUE
  RETURN
  END

```

	SURROUTINE BOWAVE(NERR)	SWIVEL	222
	REAL M1,M2,M2	SWIVEL	223
	COMMON/HREG/MB,VBN,ETAB,A2,UB,U2,M2	SWIVEL	224
	COMMON/CONST/G,GP,GM,CON,A1,P1	SWIVEL	225
5	COMMON/INPUT/M1,X1B,HEITA,DELTA	SWIVEL	226
	COMMON/WREG/THETA,X1W,ETA,A3,AM3	JUMP	65
	CALL BOWANG(M1,DELTA,HEITA,NERR)	SWIVEL	228
	IF (NERR) 10,10,20	SWIVEL	229
10	T=CON*THETA	SWIVEL	230
	U=CON*DELTA	JUMP	66
	AMNS=(M1*SIN(T))*2	JUMP	67
	X1W=(2.*G*AMNS-GM)/GP	JUMP	68
	AM3=SURT((1.-0.5*GM*AMNS)/(G*AMNS-0.5*GM))*SIN(T-D)	JUMP	69
15	ETAW=(GM*X1W*GP)/(GP*X1W*GM)	SWIVEL	232
	A3=SURT(X1W*ETAW)	SWIVEL	233
	20 CONTINUE	SWIVEL	234
	RETURN	SWIVEL	235
	END	SWIVEL	236

	SUBROUTINE FINAL (NERR)	SWIVEL	237
	REAL M1,M2,M3,LAMBDA	SWIVEL	238
	COMMON/REG/M2,VBN,ETAB,A2,UB,U2,M2	SWIVEL	239
	COMMON/CONST/G,GP,GM,CUN,A1,PI	SWIVEL	240
5	COMMON/FREG/LAMBDA,DELTA,THEIAF,XIWF,ETAWF,A3F,P3F,U3F	SWIVEL	241
	COMMON/INPUT/M1,XIB,HETA,DELTA	SWIVEL	242
	B=CON*BETA	SWIVEL	243
	LAMBDA=BETA-ATAN (M1*SIN (R))/(UB-ETAB*VBN))/CON	SWIVEL	244
	OELIAF=DELTA*LAMBDA	SWIVEL	245
10	CALL BOWANG(M2,DELTA,THEIAF,NERR)	SWIVEL	246
	IF (NERR) 10,10,20	SWIVEL	247
	10 I=CON*THEIAF	SWIVEL	248
	XIWF=(2.*G*M2*M2*SIN (I)*SIN (I)-GM)/GP	SWIVEL	249
	ETAWF=(GM*XIWF*GP)/(GP*XIWF*GM)	SWIVEL	250
15	A3F=SQRT (XIWF*ETAWF)*A2	SWIVEL	251
	P3F=XIWF*XIB	SWIVEL	252
	40 U3F=SQRT (U2*COS (I))*2.*(ETAWF*U2*SIN (I))*2)	SWIVEL	253
	20 CONTINUE	SWIVEL	254
	RETURN	SWIVEL	255
20	END	SWIVEL	256

```

SUBROUTINE FORFIV(NERR)
  REAL M1,MH,M2
  COMMON/APOINT/VA,V1,V2,V3,EPS,ANG1,ANG2,ANG3
  COMMON/HREG/MB,VBN,ETAB,A2,UB,U2,M2
  COMMON/CUNST/G,GP,GM,CON,A1,P1
  COMMON/INPUT/M1,X1B,BETA,DELTA
  COMMON/IDUEG/THETAT,THETAD,X1I,XID,ANG4,ANG5,ANGI,ANGD,ETAT,
    CA4A3
  COMMON/HREG/ THETA,X1W,ETAW,A3,AM3
  P4M=((2.0*G*(V3/A3)**2-GM)/GP)*X1W
  P5M=((2.0*G*(V2/A2)**2-GM)/GP)*X1B
  P3=X1W
  P2=X1B
  IF (P4M-PSM) 10,10,20
    GO TO 30
  20 PM=P4M
  30 IF (P3-P2) 40,40,50
  40 PL=P2
    ASL=ANG2
    PR=PL/P3
    CALL POINT(PR,V3,A3,DSIG,ANG)
    A4L=ANG3-DSIG
    GO TO 60
  50 PL=P3
    A4L=ANG3
    PR=PL/P2
    CALL POINT(PR,V2,A2,DSIG,ANG)
    ASL=ANG2-DSIG
  60 CALL INTSEC (P2,P3,ANG2,ANG3,PM,PL,A4L,ASL,V2,A2,V3,A3,NERR)
    IF (NERR) 70,70,80
  70 ANGI=ANG3-THETAT
    ANG2=ANG2-THETAD
    ETAT=(GM*X1I*GP)/(GP*X1I*GM)
  90 A4A3=SQRT (X1I*ETAT)
  80 CONTINUE
  RETURN
END
```

```

SWIVEL 257
SWIVEL 258
SWIVEL 259
SWIVEL 260
SWIVEL 261
SWIVEL 262
SWIVEL 263
SWIVEL 264
JUMP 70
SWIVEL 266
SWIVEL 267
SWIVEL 268
SWIVEL 269
SWIVEL 270
SWIVEL 271
SWIVEL 272
SWIVEL 273
SWIVEL 274
SWIVEL 275
SWIVEL 276
SWIVEL 277
SWIVEL 278
SWIVEL 279
SWIVEL 280
SWIVEL 281
SWIVEL 282
SWIVEL 283
SWIVEL 284
SWIVEL 285
SWIVEL 286
SWIVEL 287
SWIVEL 288
SWIVEL 289
SWIVEL 290
SWIVEL 291
SWIVEL 292
SWIVEL 293
SWIVEL 294
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SUBROUTINE INTSEC (P2,P3,S2,S3,PM,PL,S4L,S5L,V2,A2,V3,A3,NERH)
COMMON/IDHEG/THETAT,THETAD,X11,X1D,ANG4,ANG5,ANGT,ANGD,ETAT,
CA4A3
DEL=10.0
DO 10 I=1,50
DEL=DEL/10.0
PU=PL*DEL
PRT=PU/P3
PRD=PU/P2
CALL POINT (PRD,V2,A2,DS,THETAD)
S5U=S2*DS
CALL POINT (PRT,V3,A3,DS,THETAT)
S4U=S3*DS
CALL SLIPT (S5L,PL,S5U,PU,S4L,PL,S4U,PU,S0,P0)
IF (P0-PU) 10,30,40
10 CONTINUE
20 NERR=1
GO TO 90
30 X11=PRT
X1D=PRD
ANG4=S4U
ANG5=S5U
NERR=0
GO TO 90
40 DO 70 I=1,1000
PL=PU
PU=P0
S4L=S4U
S5L=S5U
PRT=PU/P3
PRD=PU/P2
CALL POINT (PRD,V2,A2,DS,THD)
S5U=S2*DS
CALL POINT (PRT,V3,A3,DS,THT)
S4U=S3*DS
CALL SLIPT (S5L,PL,S5U,PU,S4L,PL,S4U,PU,S0,P0)
IF (P0-PU) 50,20,20
50 IF (P0-PU) 20,30,60
60 IF (ARS (PU-PU)-0.0001) 80,80,70
70 CONTINUE
GO TO 20
80 X11=PU/P3
X1D=P0/P2
CALL POINT (X1D,V2,A2,DS,THETAD)
ANG5=S2*DS
CALL POINT (X1T,V3,A3,DS,THETAT)
ANG4=S3*DS
NERR=0
GO TO 90
90 CONTINUE
RETURN
END

```

	SUBROUTINE POINT (X1,V1X,DEL,ANG)	SWIVEL	346
	COMMON/CONST/G,GP,GM,CON,AL,PI	SWIVEL	347
	AA=2.*G*((V/A)*((V/A)-1.))/GP	SWIVEL	348
	BB=X1-1.	SWIVEL	349
5	CC=X1*GM/GP	SWIVEL	350
	PWH=(AA-BB)/CC	SWIVEL	351
	PWH=ABS (PWH)	SWIVEL	352
	1 COANG=SUPT (PWH)	SWIVEL	353
	AA=G*(V/A)*((V/A)	SWIVEL	354
10	DEL=ATAN (HH*COANG/(AA-BB))/CON	SWIVEL	355
	ANG=ATAN (1./COANG)/CON	SWIVEL	356
	RETURN	SWIVEL	357
	END	SWIVEL	358

```

SUBROUTINE-POINTA(ICASE)
REAL MI,MB,M2
COMMON/APOINT/VA,VI,V2,V3,EPS,ANG1,ANG2,ANG3
COMMON/BREG/MH,VBN,ETAB,A2,UB,U2,M2
COMMON/CONST/G,GP,GM,CUN,A1,PI
COMMON/INPUT/MI,XIB,ETA,DELTA
COMMON/WREG/ THETA,XIW,ETA,A3,AM3
B=CUN*THETA
T=CON*THETA
ANG=90.-THETA
IF (BETA-ANG)10,10,20
10 ICASE=1
VA=UB/COS (B*PI)
40 VI=SUMT ((MI*SIN (T))**2*(VA-MI*COS (T))**2)
V2=SUMT ((ETAB*VBN)**2*(VA*SIN (B*PI)-MI*SIN (B))**2)
V3=SUMT ((ETA*MI*SIN (T))**2*(VA-MI*COS (T))**2)
EPS=ATAN (MI*SIN (T)/(VA-MI*COS (T)))/CON
ANG1=90.-THETA-EPS
A=CON*(90.-THETA-THETA-EPS)
ANG2=BETA+ATAN (ETA*TAN (A))/CON
E=CON*EPS
ANG3=90.-THETA-ATAN (ETA*TAN (E))/CON
GO TO 30
20 ICASE=2
VA=-UB/COS (B*PI)
50 VI=SUMT ((MI*SIN (T))**2*(VA-MI*COS (T))**2)
V2=SUMT ((ETAB*VBN)**2*(VA*SIN (B*PI)-MI*SIN (B))**2)
V3=SUMT ((ETA*MI*SIN (T))**2*(VA-MI*COS (T))**2)
EPS=ATAN (MI*SIN (T)/(VA-MI*COS (T)))/CON
ANG1=THETA-EPS
A=CON*(BETA+THETA-EPS-90.)
ANG2=90.-BETA+ATAN (ETAB*TAN (A))/CON
E=CON*EPS
ANG3=THETA-ATAN (ETA*TAN (E))/CON
30 CONTINUE
RETURN
END
```

```
10 SUBROUTINE REGFL(ICASE,NERR)
   REAL M1,M4P,LAMRDA
   COMMON/APOINT/VA,V1,V2,V3,EP5,ANG1,ANG2,ANG3
   COMMON/CONST/G,GP,GM,CON,A1,P1
   COMMON/FNEG/LAMHDA,DELTA,THETA,XIWF,ETAWF,A3F,P3F,U3F
   COMMON/INPUT/M1,XIB,BETA,DELTA
   COMMON/HREFG/OMEGAI,DELTAI,V4P,M4P,THETAI,OMEGAR,XIR,P6,P6P3,P6P3F
   COMMON/TDREG/THETAI,THEIAU,XII,XID,ANG4,ANG5,ANGI,ANGD,ETAT,
      CA4A3
   COMMON/WNEG/ THETA,XIW,ETAW,A3,AM3
1  GO TO (10,20),ICASE
10 OMEGAI=90.-DELTA-ANGT
   GO TO 30
20 OMEGAI=ABS (DELTA-ANGT)
30 O=CON*OMEGAI
   I=CON*THETAI
   DELTAI=OMEGAI-ATAN (ETAT*TAN (U))/CON
   V4P=V3*SIN (T)*SQRT (ETAT*2*(1./TAN (O)))**2)
   M4P=V4P/(A4A3*A3)
20 IF ((OMEGAI-.02) .LT. 0.) GO TO 70
   CALL BOWANG(M4P,DELTAI,THETAI,NERR)
   IF (NERR) 40,40,50
40 I=CON*THETAI
   OMEGAR=THETAI-DELTAI
   XIR=(2.*G*M4P*M4P*SIN (T)*SIN (T))-GM/7GP
80 CONTINUE
   P6=XIR*XIT*XIW
   P6P3=XIR*XIT
   P6P3F=P6/P3F
50 CONTINUE
   RETURN
70 PRINT 100
100 FOR:AT(1H0 *TRANSMITTED BLAST WAVE PARALLEL TO BODY - IGNORE -VE
   ILUCITY AND TIME OUTPUTS*,/)
   OMEGAR=0.00001
   OMEGAI=0.00001
   THETA=0.00001
   DELTA=0.00001
   XIW=((3.*G-1.)*XIT-GM)/(GM*XIT+GP)
   GO TO 80
   END
```

```

SURROUTINE SLIPT(X1,Y1,X2,Y2,X3,Y3,X4,Y4,X,Y)
A=(Y1-Y2)/(X1-X2)
B=0.5*(Y1+Y2-A*(X1+X2))
C=(Y3-Y4)/(X3-X4)
D=0.5*(Y3+Y4-C*(X3+X4))
X=(D-B)/(A-C)
Y=0.5*(B+D+A*(A-C))
RETURN
END

```

```

SWIVEL 426
SWIVEL 427
SWIVEL 428
SWIVEL 429
SWIVEL 430
SWIVEL 431
SWIVEL 432
SWIVEL 433
SWIVEL 434

```

5

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SUBROUTINE TIMEA(NERR)
  REAL M1,M4P,LAMHDA,MU7
  COMMON/APOINT/VA,V1,V2,V3,EP5,ANG1,ANG2,ANG3
  COMMON/CONST/G,GP,GM,CUN,AI,PI
  COMMON/FREG/LAMHDA,DELTA,THETAF,XIMF,ETA,F,A3F,P3F,U3F
  COMMON/INPUT/M1,XIB,THETA,DELTA
  COMMON/REG/OMEGA1,DELTAH,V4P,M4P,THETAR,OMEGAR,XIR,P6,P6P3,P6P3F
  COMMON/TORIG/THETAT,THETAU,XII,XID,ANG4,ANG5,ANGI,ANGO,ETAT,
    CA4A3
  COMMON/TIME/APOR,CPOR,CHI,OCOR,VC,PSI7,U7,V7,MU7,PSIM,EPOR,VE,
    COPOR,TAU
  COMMON/REG/ THETA,XIM,ETAM,A3,AM3
  FORMAT(//,3X,45HMACH ANGLE SET TO 90-DEGREES--ERROR PROBABLE.)
  T=CON*THETA
  O=CON*DELTA
  AT=CON*ANGT
  AO=CON*ANGO
  OI=CON*OMEGA1
  APOR=SIN (T-O)/SIN (OI)
  CPOR=APOR*SIN (AD-AT)/COS (AO*U-O)
  AA=SIN (T)-APOR*CUS (AT)*CPOR*SIN (U-O)
  BB=CUS (T)-APOR*SIN (AT)-CPOR*CUS (U-O)
  CHI=ATAN (AA/BB)/CON
  C=CON*CHI
  OCOR=SQRT (AA*AA+BB*BB)
  VC=OCOR*VA
  U7=U3F
  AA=VC*SIN (C)-U7*SIN (O)
  BB=VC*CUS (C)-U7*CUS (O)
  PSI7=ATAN (AA/BB)/CON
  V7=SQRT (AA*AA+BB*BB)
  CNST=A3F/V7
  IF (CNST .LE. 1.) GO TO 1
  CNST=1.
  WHITE(6,100)
  MU7=ASIN (CNST)/CON
  PSIM=PSI7+MU7
  PM=CON*PSIM
  EPOR=CPOR*SIN (O*PM-O)/SIN (PM-O)
  AA=COS (T)-APOR*SIN (AT)
  OPOR=AA/CUS (O)
  VE=(OPOR-EPOR)*VA
  TAU=EPOR/(AA*VE)
  IF (TAU .LE. 0.) NERR=1
  RETURN
  END

```

LINE	STATEMENT	SWIVEL
5	SUBROUTINE TIMEB(NERR) HEAL MI,M4P,LAMBDA,MU7 COMMON/APUNT/VA,VI,V2,V3,EPS,ANG1,ANG2,ANG3 COMMON/CONST/G,GP,GM,CON,AI,PI COMMON/FNEG/LAMBDA,DELTA,THETA,FI,ETAF,P3F,U3F COMMON/INPUT/MI,XIB,BETA,DELTA COMMON/AREG/OMEGAT,DELTA,V4P,M4P,THETA,OMEGA,XIR,P6,P6P3,P6P3F COMMON/TOREG/THETA1,THETAU,XIT,XID,ANG4,ANG5,ANGT,ANGO,ETAT, CA4A3 COMMON/TIME/APON,CPOR,CHI,OCOR,VC,PSI7,U7,V7,MU7,PSIM,EPOR,VE, CPOR,TAU COMMON/MEG/ THETA,XIW,ETAW,AJ,AM3 FORMAT(//,39X,45NMACH ANGLE SE(TO 90 DEGREES, ERROR PROBABLE) T=CON*THETA O=CON*DELTA AT=CON*ANGT AD=CON*ANGO O=CON*OMEGAH OJ=CON*OMEGAT IF (DELTA-ANGT) IU,I0,20 10 NERR=I GO TO 30 20 NERR=0 APOR=SIN (T-D)/SIN (OJ) CPOR=APOR*SIN TAO-ATT/SIN TO-D-AD) AA=SIN (T)+APOR*SIN (AT)+CPOR*SIN (U+O) BB=CON (T)+APOR*CON (AT)+CPOR*CON (O+D) CHI=ATAN (AA/BB)/CON C=CON*CHI OCOR=SOBT (AA*AA+BB*BB) VC=OCOR*VA U7=U3F AA=VC*SIN (C)+U7*SIN (O) BB=VC*CON (C)+U7*CON (O) PSI7=ATAN (AA/BB)/CON V7=SOBT (AA*AA+BB*BB) CNST=A3F/V7 IF (CNST .LE. 1.) GO TO 1 CNST=1. 1 WHITE(G,I00) MU7=ASIN (CNST)/CON PSIM=PSI7-MU7 PM=CON*PSIM AA=CON (T)+APOR*CON (AT) TAU=CPOR*SIN (O+D+PM)/(AA*SIN (C-PM)*VC) IF (TAU .LE. 0.) NERR=I 30 CONTINUE RETURN END	482 483 484 485 486 487 488 489 490 491 492 74 3 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530

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SUBROUTINE WEDGE (XII,MI,DELTA,THETA)
C
C THIS CODE COMPUTES THE WEDGE AND SHOCK ANGLE WHEN THE WEDGE
C SURFACE PRESSURE RATIO AND THE AMBIENT MACH NUMBER ARE SPECIFIED
C
5 REAL MS, MI
C
MS=MI*MI
THETA=ASIN (SORT ((6.*XII+1.)/(7.*MS)))
C
10 DELTA=ATAN(1./TAN(THETA)*5.*(MS*SIN(THETA)*SIN(THETA))-1.)/(6.*M
CS= 5.*(MS*SIN (THETA)*SIN (THETA))-1.))
C
15 1 THETA=THETA*57.296
C
DELTA=DELTA*57.296
C
RETURN
END

```

SUBROUTINE PARA (Y1+Y2+Y3+X1+X2+X3+CON1+CON2+CON3)
 CON2=((X2+X2-X3+X3)*(Y1-Y2)-(X1+X1-X2+X2)*(Y2-Y3))/
 C ((X2+X2-X3+X3)*(X1-X2)-(X1+X1-X2+X2)*(X2-X3))
 CON3=((Y1-Y2)-CON2*(X1-X2))/(X1+X1-X2+X2)
 CON1=Y1-CON2+X1-CON3+X1+X1
 RETURN
 END

5

60	C	100	FORMAT(//,20X,41HSMALL ANGLE OF ATTACK ASSUMPTION VIOLATED.)	NUCONE 98
	C			NUCONE 99
	C		THETA=THETA0-ALFA*UMHA	NUCONE 100
	C		IF (THETAF .LT. DELTA) THETA=DELTA	NUCONE 101
	C		IF (ALFA .GE. DELTA) WRITE(6,100)	NUCONE 102
	C			NUCONE 103
	C			NUCONE 104
	C		CONE=SURFACE-DENSITY	NUCONE 105
	C			NUCONE 106
	C		STAL=SIN (THETAF*CON)	NUCONE 107
	C		HSP=H2*M2*STAL*STAL	NUCONE 108
	C		P3SP2=1.+2.*G*(ABS(HSP-1.))/GP	NUCONE 109
	C		R3SH2=GP*HSP/(GM*HSP*2.)	NUCONE 110
	C		RC=(H3SH2*G/ETAF)*(P3F/(P3SP2*ABS))*.417/G	NUCONE 111
	C		ETAF=(G/ETAB)/RC	NUCONE 112
	C			NUCONE 113
	C		SURFACE SOUND SPEED	NUCONE 114
	C			NUCONE 115
	C		A3F=SURT(G*P3F/RC)	NUCONE 116
	C			NUCONE 117
	C		CURVE FIT TO SURFACE MACH NO. AT ANGLE OF ATTACK	NUCONE 118
	C			NUCONE 119
	C		ZERO ANGLE OF ATTACK TERM	NUCONE 120
	C			NUCONE 121
	C		AMIM2=CS*CS*(1.025-0.16*HSF)	NUCONE 122
	C		IF (AMIM2 .GT. 1.) AMIM2=1.	NUCONE 123
	C			NUCONE 124
	C		ANGLE OF ATTACK TERM	NUCONE 125
	C			NUCONE 126
	C		AM2H2=2.8*SN*SN*(HSF*(-1.107))	NUCONE 127
	C		IF (AM2H2 .GT. 1.) AM2H2=1.	NUCONE 128
	C			NUCONE 129
	C		WINDWARD HAY SURFACE VELOCITY	NUCONE 130
	C			NUCONE 131
	C		CNST=SUNT(2./GP*(GM/GP)*M2)	NUCONE 132
	C		U3F=M2*A2*CNST*(AMIM2-AL*AM2M2)	NUCONE 133
	C			NUCONE 134
	C		DELTAFCONE	NUCONE 135
	C			NUCONE 136
	C		RETURN	NUCONE 137
	C		END	

CHECK CASES FOR PRIMUS

1. Wedge

Flight Mach Number = 10.,
Blast Pressure Ratio = 1.513,

Wedge Angle=11.536°
Intercept Angle=70°

INPUT CARD

10. 1.513 70. 11.536

2. Cone (flow deflection at shock specified)

Flight Mach Number = 5.,
Blast Pressure Ratio = 1.64,

Cone Semi-Angle=11.2°
Intercept Angle=70°

INPUT CARD

5. 1.64 70. 6.86 2.605 11.2

OBLIQUE BLAST WAVE REFLECTION FROM WEDGE OR CONE IN SUPERSONIC FLOW

INPUT CONDITIONS-

MSUB1	XISUB8	BETA(DEG)	DELTA(DEG)
10.00000	1.51300	70.00000	11.53600

CONSTANTS-

GAMMA	ASUB1	PSUB1
1.40000	1.00000	1.00000

CONDITIONS ACROSS BLAST WAVE-

MSUB8	VSUB8N	ETASUB8	ASUB2	USUB8	USUB2	MSUB2
1.11988	1.11988	.74549	1.06204	4.62008	10.10852	9.51807

NEW STEADY STATE CONDITIONS, (F), ATTACHED FINAL BOW SHOCK-

LAMBDA(DEG)	DELTA(DEG)	THETA(DEG)	XISUBWF	ETASUBWF	ASUB3F	PSUB3F	USUB3F
1.62679	13.16279	18.05207	9.98260	.26246	1.71906	15.10367	9.64603

CONDITIONS ACROSS BOW WAVE, ATTACHED BOW SHOCK-

THETA(DEG)	XISUBW	ETASUBW	ASUB3	MSUB3
16.07256	8.77565	.27539	1.55458	6.20061

STEADY CONDITIONS FOR POINT A-

VSUBA	VSUB1	VSUB2	VSUB3	EPSA(DEG)	SIGMA1(DEG)	SIGMA2(DEG)	SIGMA3(DEG)
67.45333	57.91043	57.90491	57.84924	2.74020	71.18723	70.88512	73.17228

CONDITIONS IN REGIONS 4 AND 5-

THETA(DEG)	THETA(DEG)	XISUBT	XISUBD	SIGMA4(DEG)	SIGMA5(DEG)	PHIT(DEG)	PHID(DEG)	ETASUBT	A4/A3
1.75300	2.74748	1.34515	7.80210	72.83893	72.83893	71.41929	73.63260	.80975	1.04366

CONDITIONS OF REGULAR REFLECTION-

OMEGA1(DEG)	DELTA1(DEG)	VSUB4P	VSUB4P	THETA1P(DEG)	OMEGA1P(DEG)	XISUBR	PSUB6	P6/P3	P6/P3F
7.04471	1.33037	14.39180	8.87038	7.33142	6.00105	1.32816	15.67939	1.78658	1.03805

NOMINAL TIME OF PEAK OVERPRESSURE-

AP/R	CP/R	OC/R	EP/R	OP/R
.84492	.13253	.22544	.15849	.35682

CHI(DEG)	PSIT(DEG)	MUT7(DEG)	PSIM1(DEG)
15.05949	21.12487	17.84243	38.96730

VSUBC	USUB7	VSUB7	VSUBE	IAU
15.20690	9.64603	5.61051	13.37757	.03389

OBLIQUE BLAST WAVE REFLECTION FROM WEDGE ON CONE IN SUPERSONIC FLOW

INPUT CONDITIONS-

MSUB1 XISUBH BETA(DEG) DELTA(DEG)
5.00000 1.64000 70.00000 6.86000

CONSTANTS-

GAMMA ASUB1 PSUB1
1.40000 1.00000 1.00000

CONDITIONS ACROSS BLAST WAVE-

MSUBH VSUBHN ETASUBH ASUB2 USUB2 MSUB2
1.24442 1.24442 .70480 1.07511 2.95452 5.13725 4.77834

NEW STEADY STATE CONDITIONS, (P), ATTACHED FINAL BOW SHOCK-

LAMBDA(DEG) DEL(AFI(1/2) DEG) THETA(1/2) DEG XISUBH ETASUBH ASUB3F PSUB3F USUB3F
3.85293 10.71293 20.55649 3.11760 .46269 1.29125 5.11287 4.88202

CONDITIONS ACROSS BOW WAVE, ATTACHED BOW SHOCK-

THETA(DEG) XISUBH ETASUBH ASUB3 MSUB3
16.58992 2.21104 .57556 1.12809 4.30977

STEADY CONDITIONS FOR POINT A-

VSUBA VSUB1 VSUB2 VSUB3 EPSA(DEG) SIGMA1(DEG) SIGMA2(DEG) SIGMA3(DEG)
49.67075 44.90159 44.89291 44.88641 1.82197 71.58812 71.11944 72.36120

CONDITIONS IN REGIONS 4 AND 5-

THETA1(DEG) THETA2(DEG) XISUBT XISUBD SIGMA4(DEG) SIGMA5(DEG) PHIT1(DEG) PHIT2(DEG) A4/A3
1.74970 1.91164 1.55536 2.09693 71.89115 71.89115 70.61150 73.03108 .73125 1.06647

THIS CASE IS BEING COMPUTED FOR A CONE

SINGLE STEP SHOCK COMPRESSION TO CONE SURFACE PRESSURE

PCONE/PSHOCK MSUB1W SHOCK ANGLE DEFL. ANGLE ENTROPY JUMP BLAST ANGLE
1.1782 4.3098 14.425 1.5364 .57720E-03 70.611

OBLIQUE BLAST WAVE REFLECTION FROM WEDGE ON CONE IN SUPERSONIC FLOW

INPUT CONDITIONS-

MSUB1 X1SUBH BETA(DEG) DELTA(DEG)
4.30977 1.55536 70.61150 1.53638

CONSTANTS-

GAMMA ASUB1 PSUB1
1.40000 1.00000 1.00000

CONDITIONS ACROSS BLAST WAVE-

MSUBH VSUBH ETASUBH ASUB2 USUB8 MSUB2
1.21492 1.21492 .73125 1.06647 2.64564 4.42889 4.15286

NEW STEADY STATE CONDITIONS. (F). ATTACHED FINAL BOW SHOCK-

LAMBOA(0EG) DELTAF(0EG) THETAF(0EG) X1SUBHF ETASUBHF ASUB3F PSUB3F USUB3F
3.98770 5.52408 17.88335 1.73067 .67908 1.15615 2.69181 4.31490

CONDITIONS ACROSS BOW WAVE. ATTACHED BOW SHOCK-

THETA(0EG) X1SUBW ETASUBW ASUB3 MSUB3
14.42542 1.17818 .88959 1.02377 4.18238

STEADY CONDITIONS FOR POINT A-

VSUBA VSUB1 VSUB2 VSUB3 EPSA(0EG) SIGMA1(0EG) SIGMA2(0EG) SIGMA3(0EG)
30.58057 26.42849 26.41549 26.42394 2.32826 73.24631 72.53883 73.50313

CONDITIONS IN REGIONS 4 AND 5-

THETA(0EG) THETA(0EG) X1SUBT X1SUBD SIGMA4(0EG) SIGMA5(0EG) PHIT(0EG) PHID(0EG) ETASUBT A4/A3
2.68572 2.47341 1.53980 1.16639 72.77583 72.77583 70.81742 75.01225 .73640 1.06485

THIS CASE IS BEING COMPUTED FOR A CONE

NEW STEADY STATE CONDITIONS. (F). ATTACHED FINAL BOW SHOCK-

LAMBOA(0EG) DELTAF(0EG) THETAF(0EG) X1SUBWF ETASUBWF ASUB3F PSUB3F USUB3F
3.85293 11.20000 15.90160 3.52093 .40957 1.29105 5.77432 5.48085

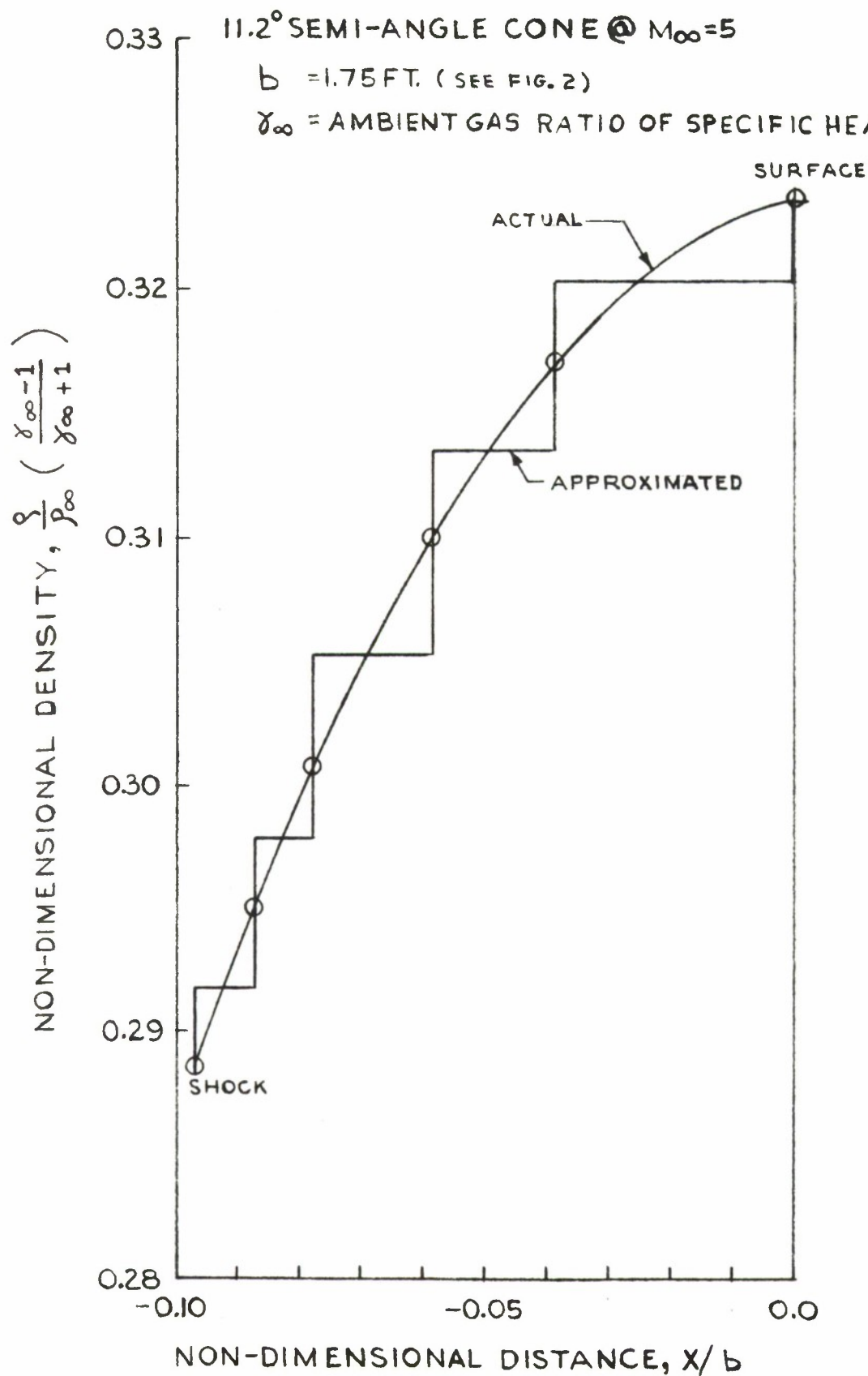
CONDITIONS OF REGULAR REFLECTION-

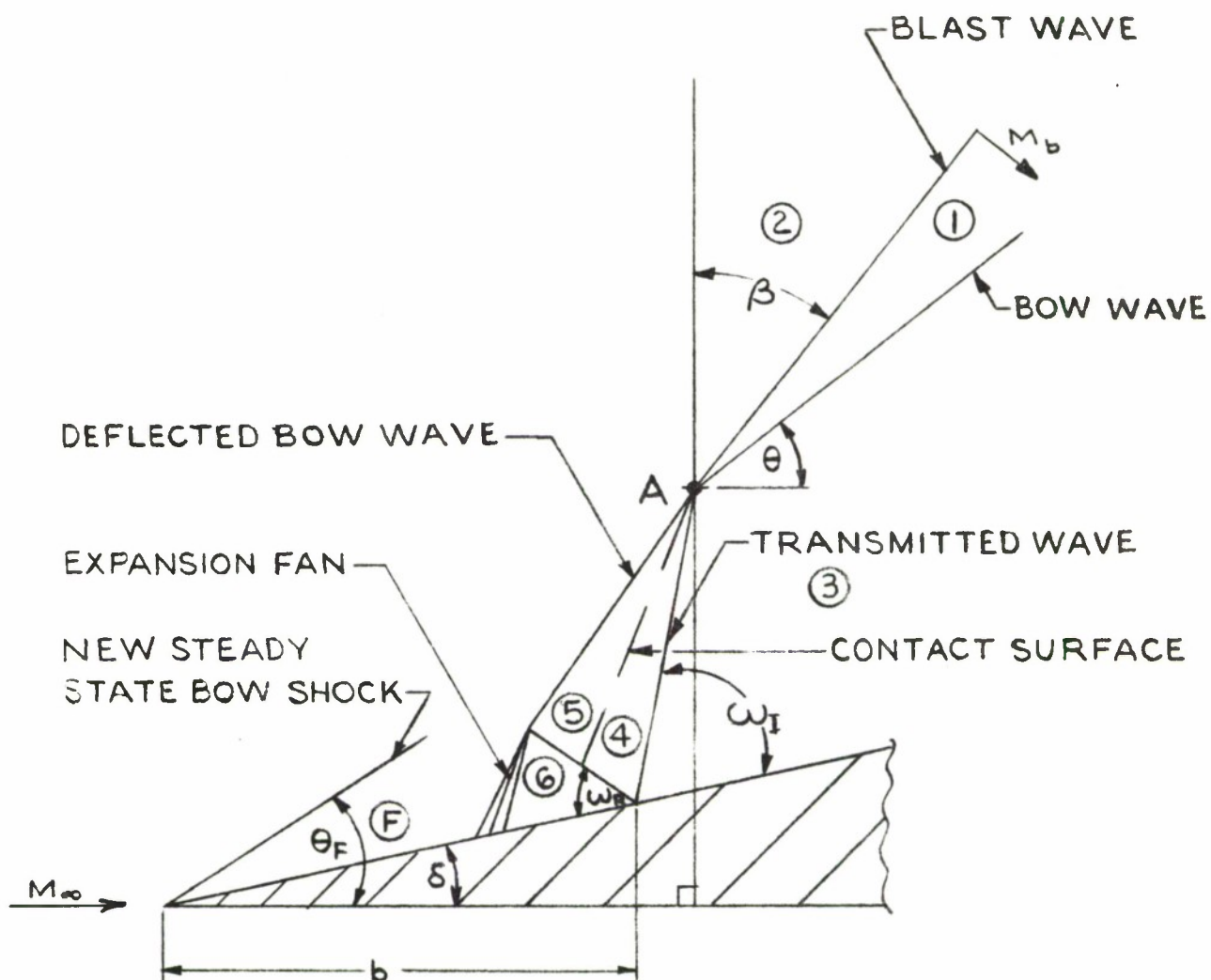
OMEGA(0EG) OELTAR(0EG) VSUB4P MSUB4P THETARP(0EG) OMEGAR(0EG) X1SUBRH PSUB6 P6/P3 P6/P3F
7.98258 2.08681 8.87637 8.14231 8.43865 6.35184 1.49904 2.71949 2.30822 1.04132

CONE RESULTS ARE

MSUBF THETAC ALPHAFAC CONANGL PC/P1 P6/PC PSUB6 PSCALE TMSCALE TAU
4.245256 15.901597 3.852930 11.200000 2.604499 2.308223 6.012918 2.211044 1.128087 .047.

DENSITY VARIATION ACROSS SHOCK LAYER





BASIC GEOMETRY AND NOMENCLATURE OF 2-D ANALYSIS

PEAK REFLECTION PRESSURE/PRE-INTERACTION SURFACE PRESSURE, p_{REFL}/p_{CONE}

MCDONNELL-DOUGLAS PREDICTION OF MACH REFLECTION
BOUNDS FOR DNA SLED TEST.

CONE CONDITIONS

$$M_{\infty}=5, \theta_c=11.2^\circ$$

$$p_{BLAST}/p_{\infty}=1.63$$

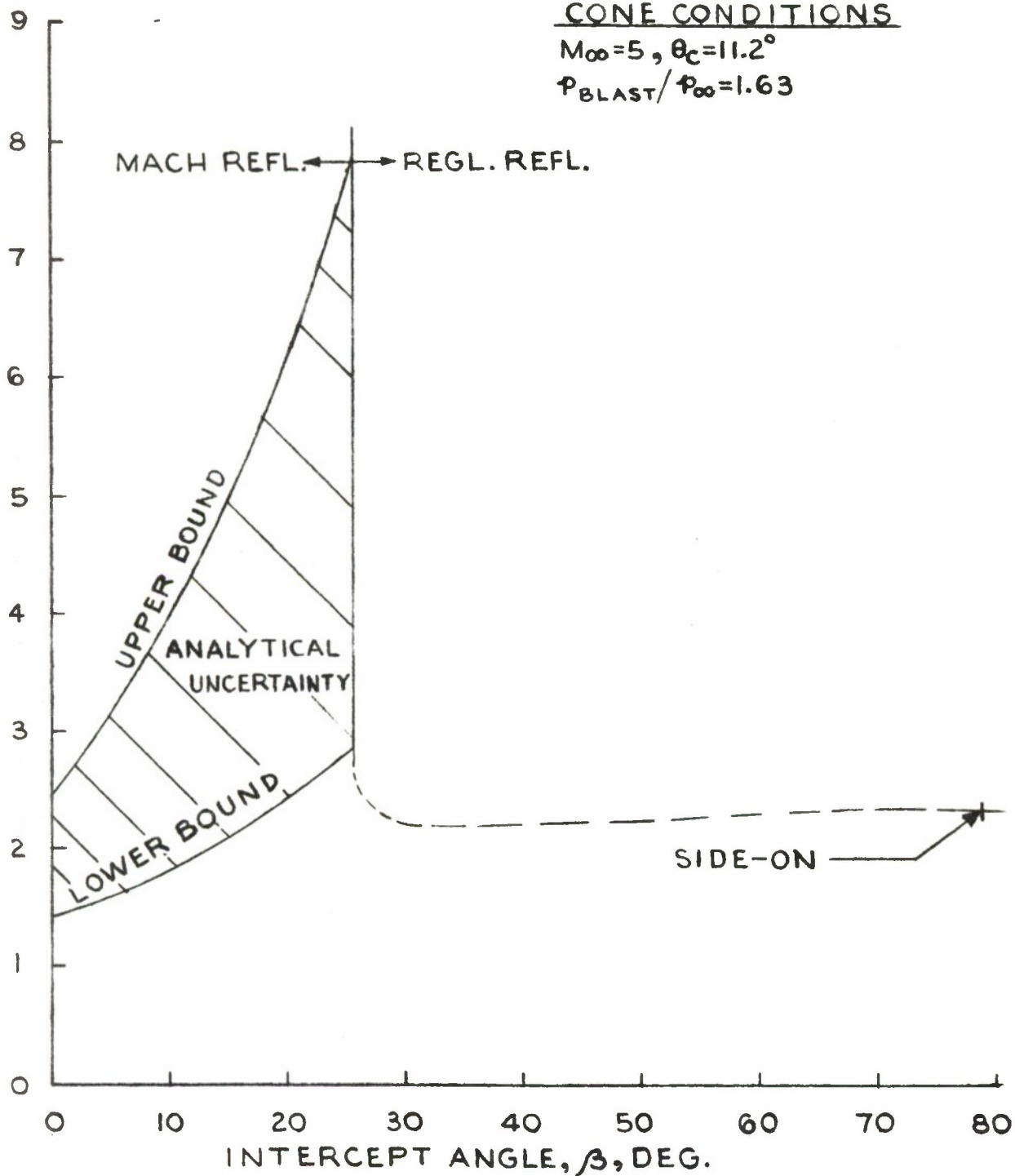


FIG.3.

COMPARISON OF CONE AND WEDGE SOLUTIONS

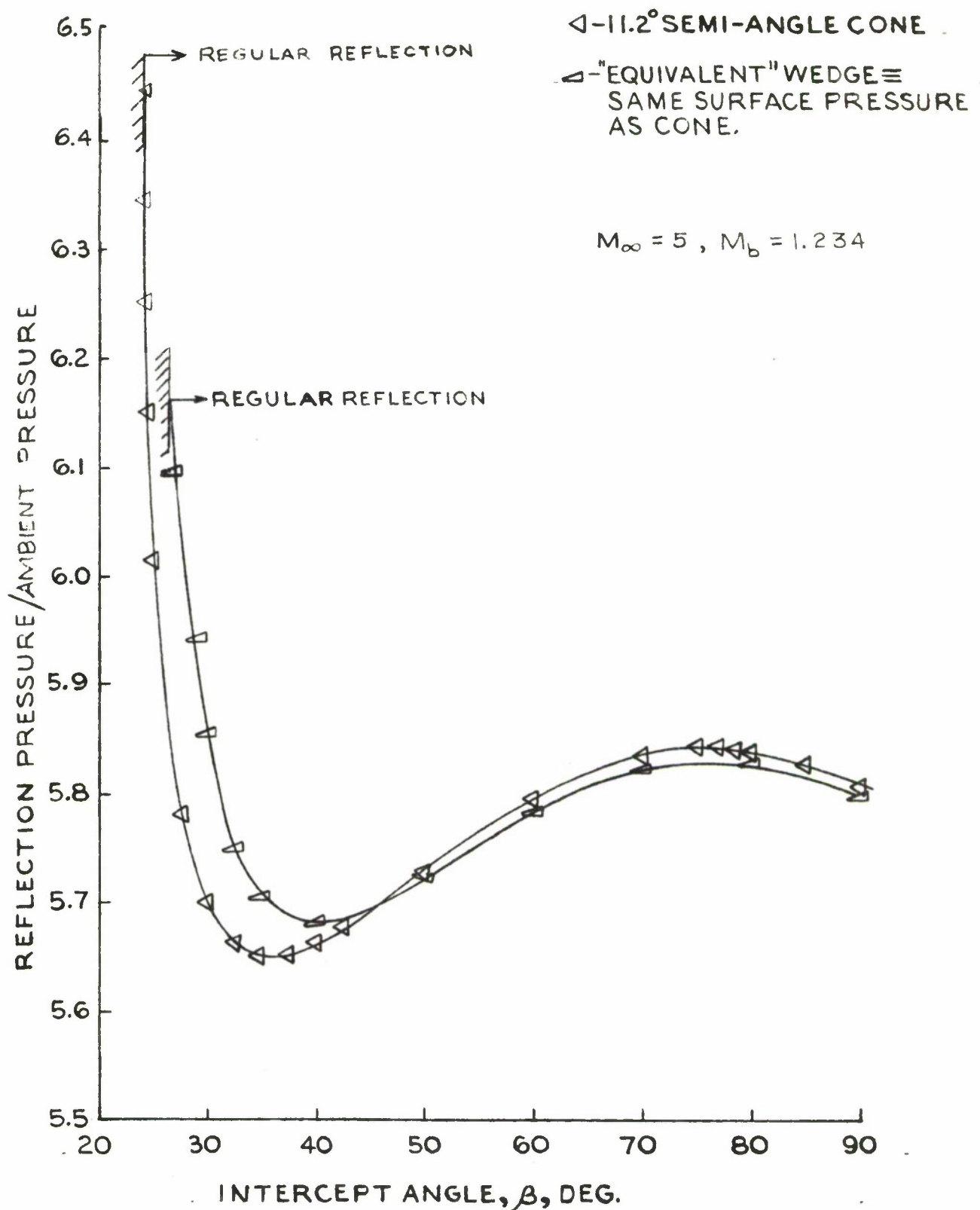
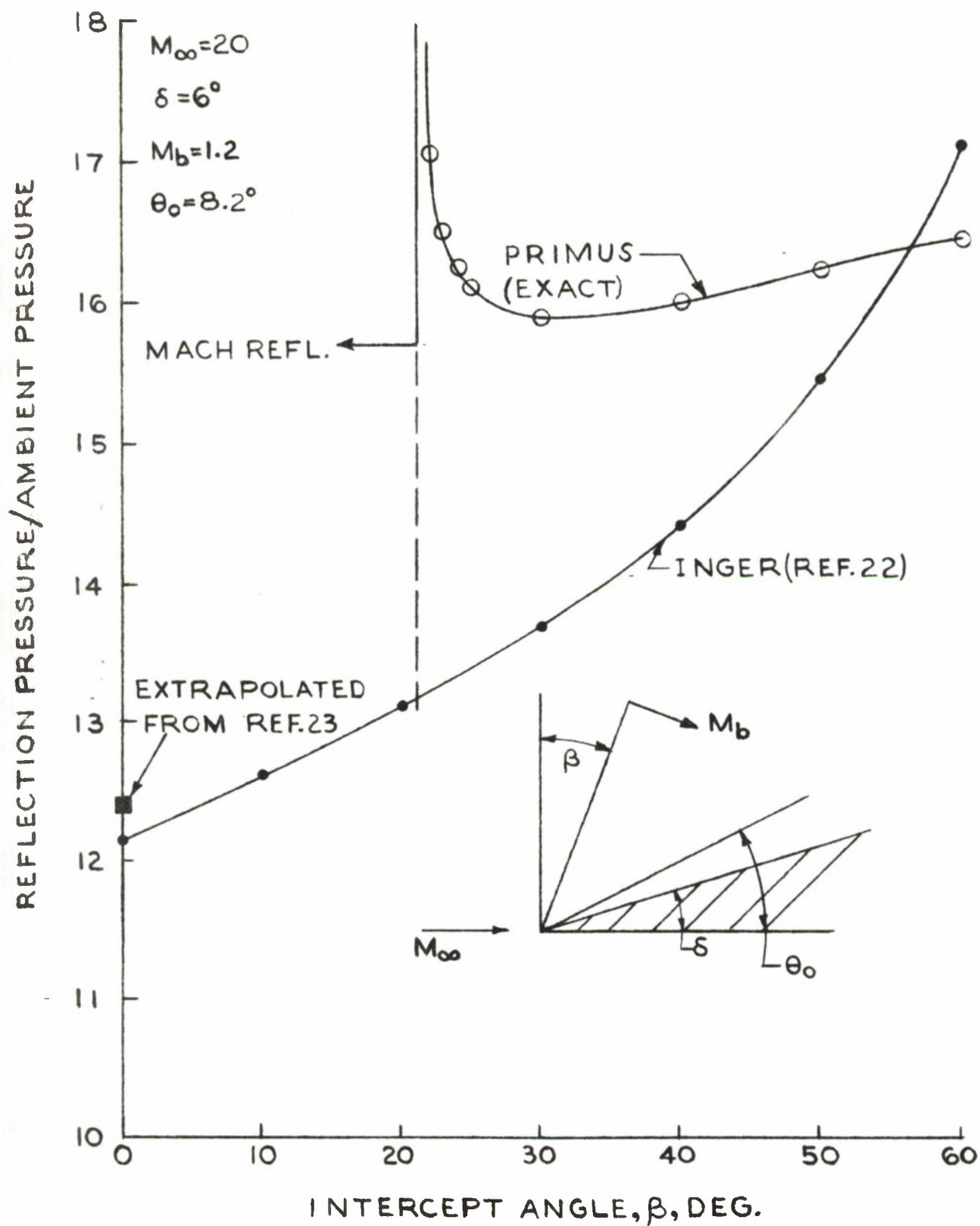


FIG.4.

COMPARISON OF WEDGE SHOCK-SHOCK METHODS



DNA SLED TEST 4B-B3-COMPARISON OF SEVERAL
THEORIES AND EXPERIMENT.

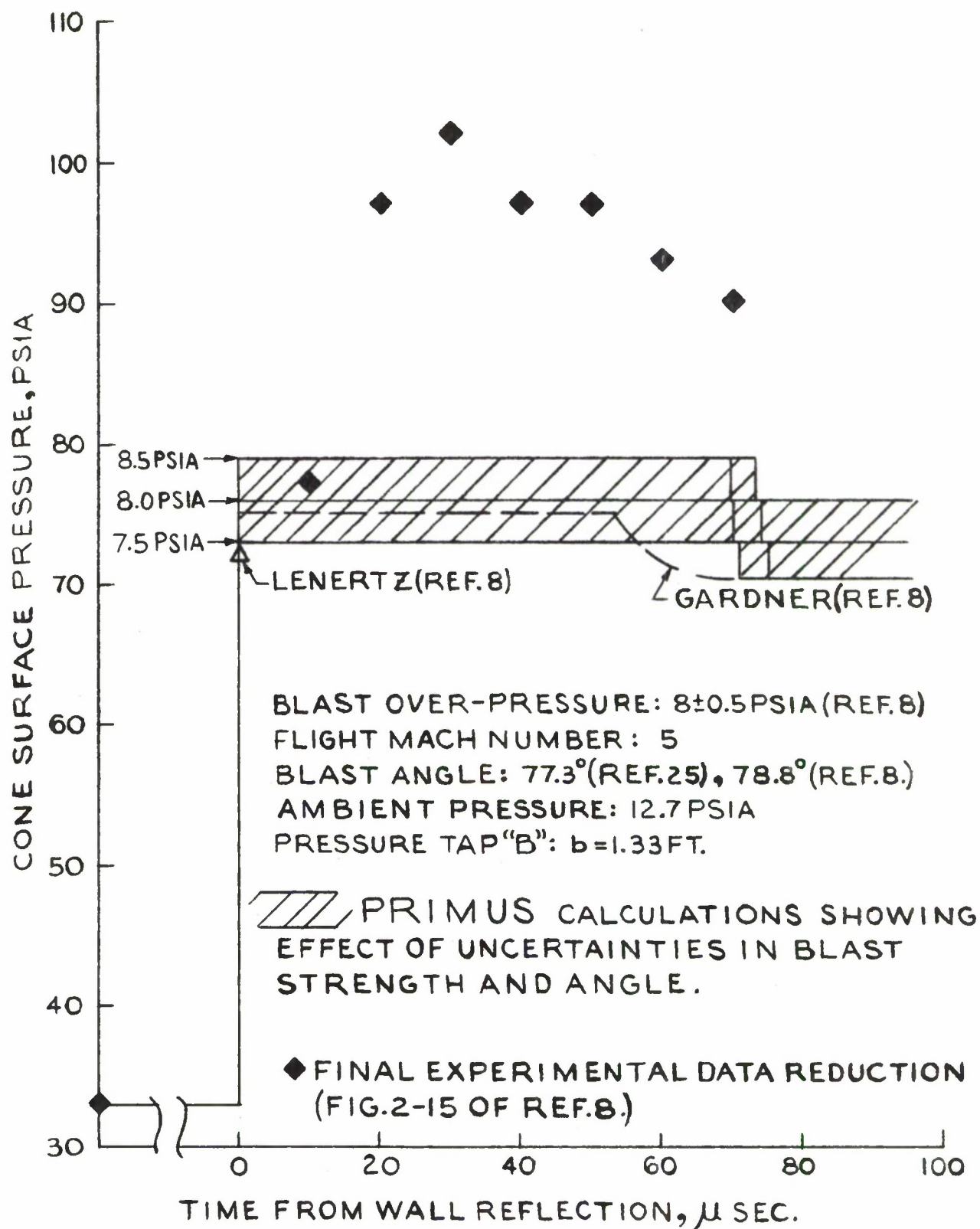


FIG. 6

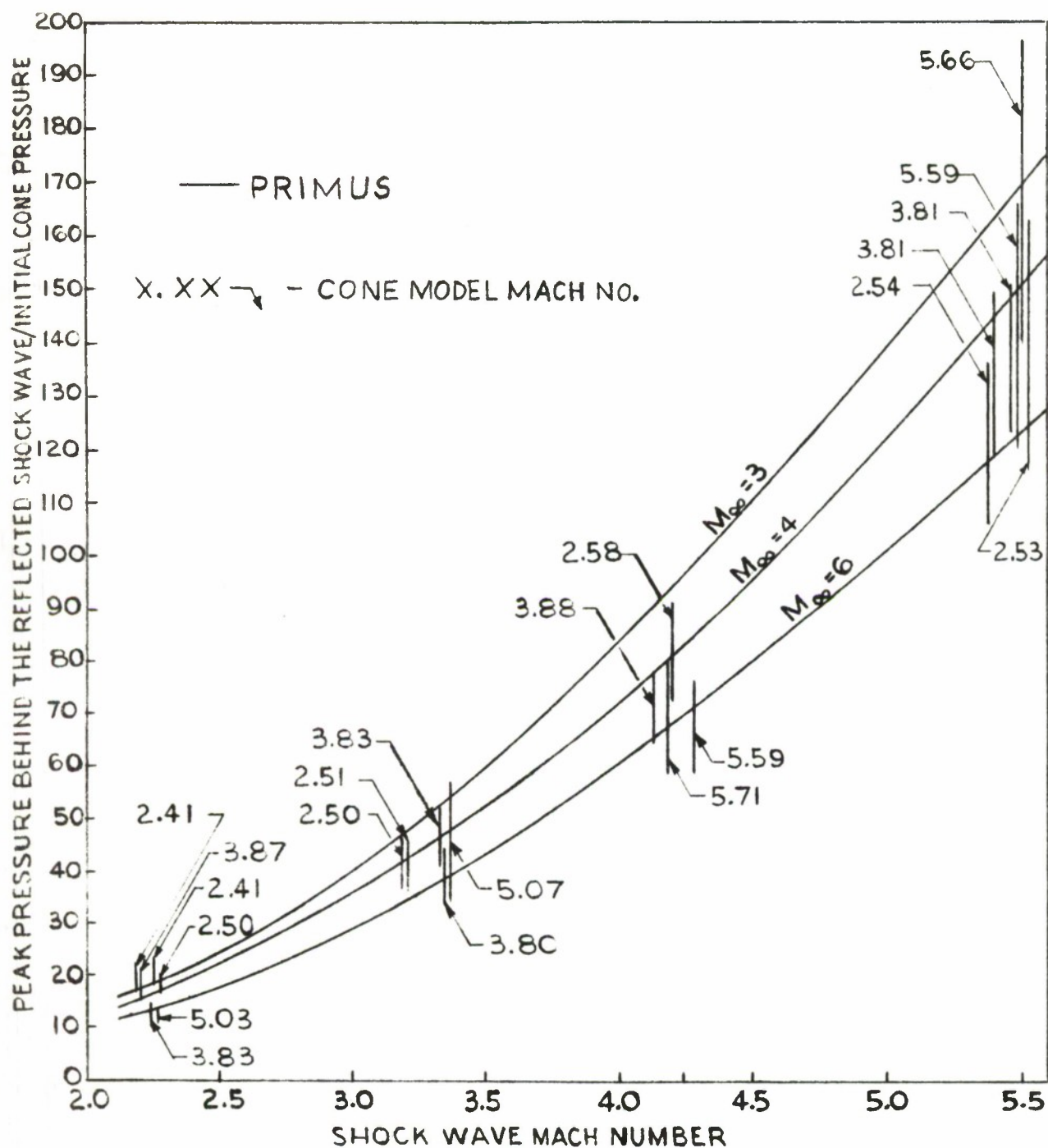


FIG. 7 RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. THE SHOCK WAVE MACH NUMBER - PRIMUS AND EXPERIMENT, 9° CONE MODELS

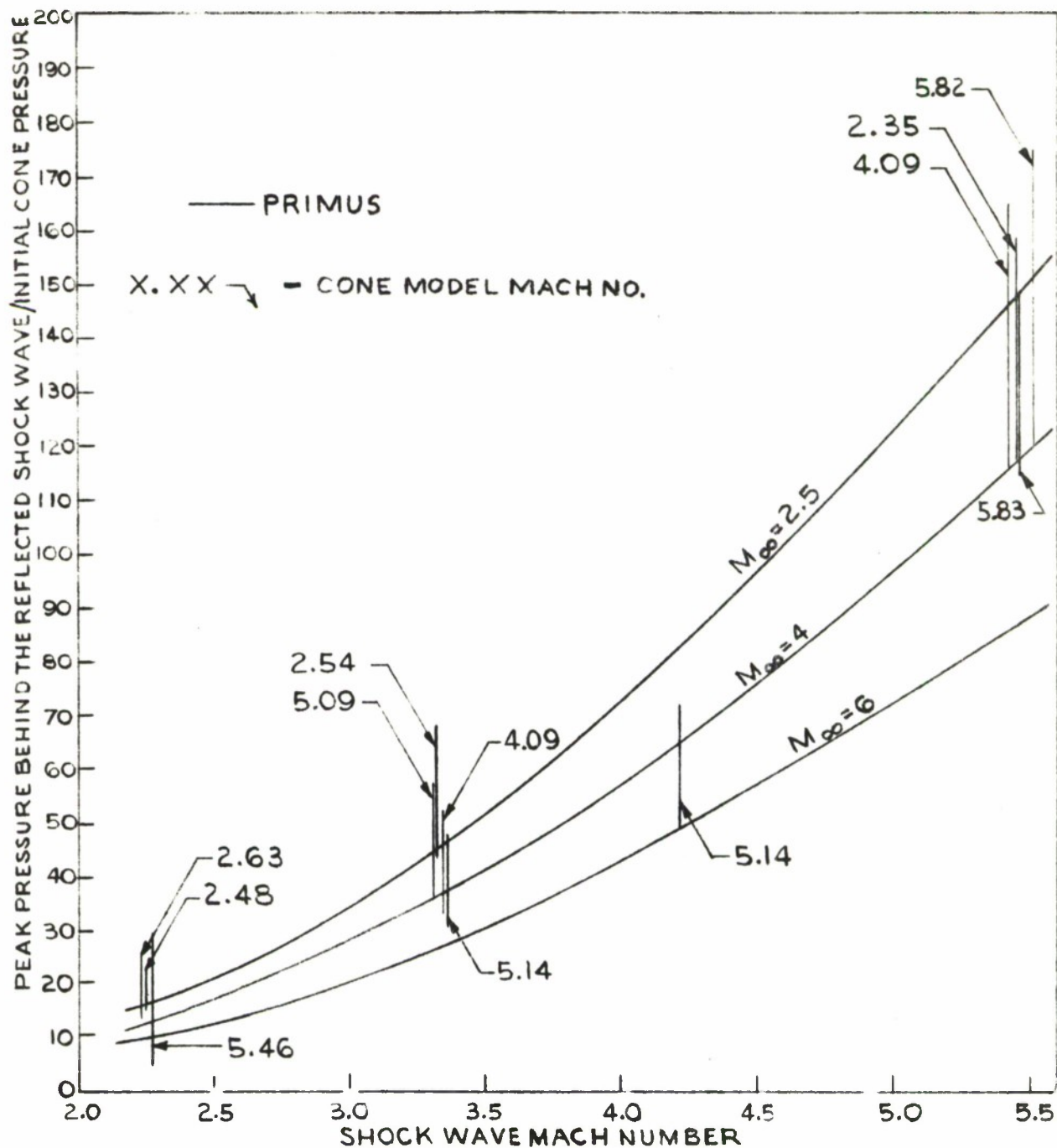


FIG. 8 RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. THE SHOCK WAVE MACH NUMBER - PRIMUS AND EXPERIMENT, 15° CONES

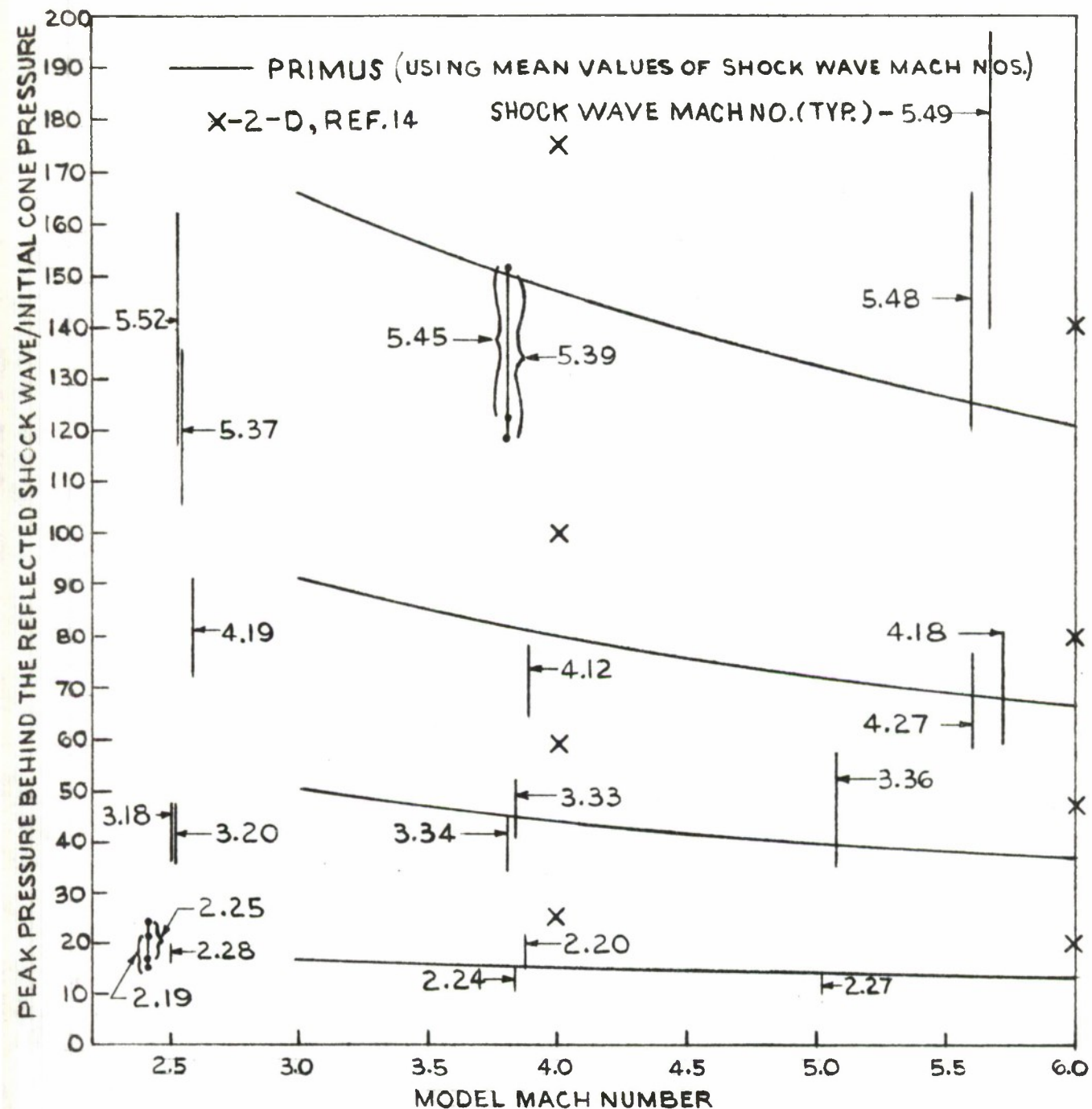


FIG. 9 RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. MODEL MACH NUMBER - PRIMUS, NOL, & EXPERIMENT, 9° CONE MODELS

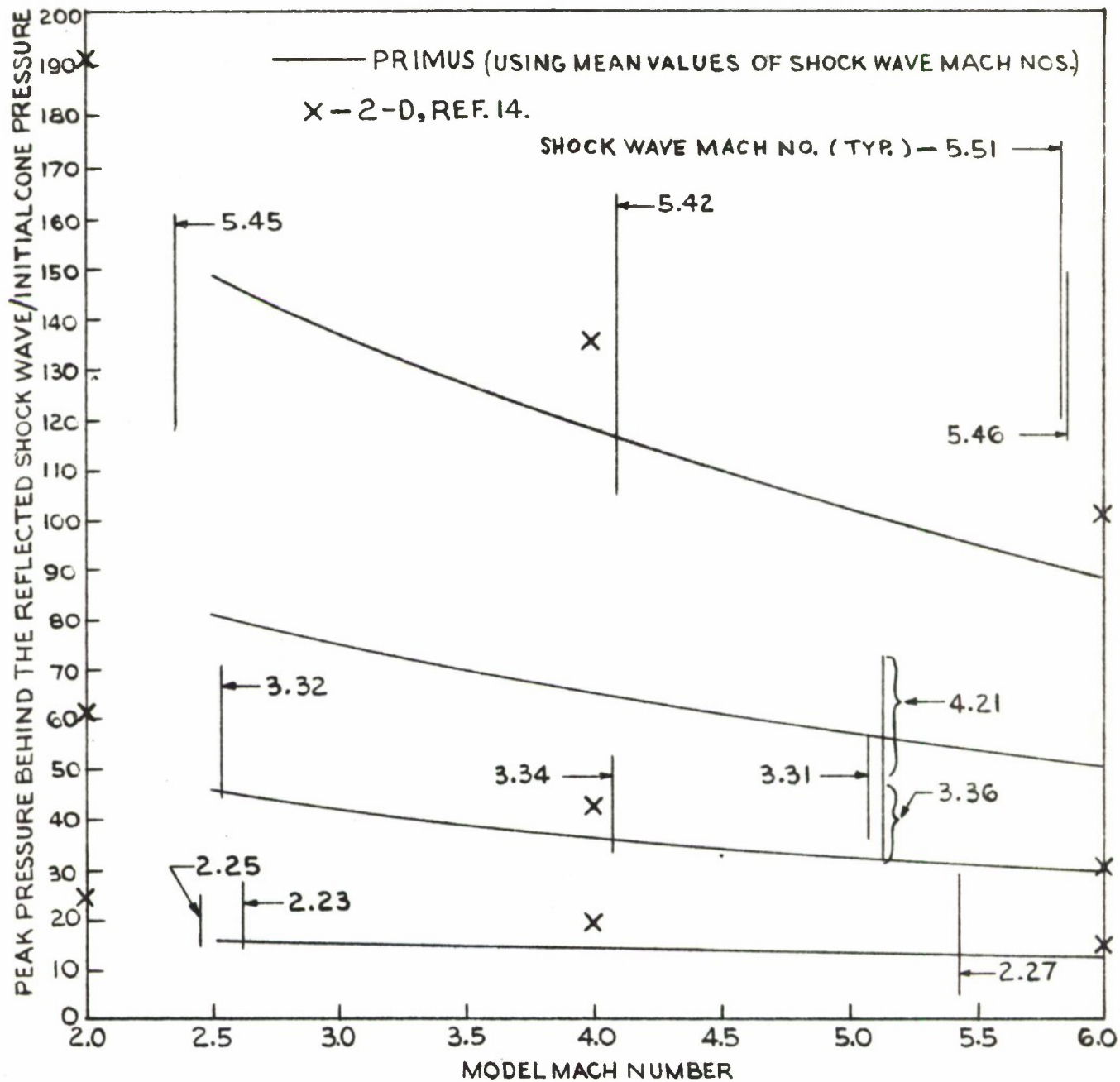


FIG.10. RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. MODEL MACH NUMBER— PRIMUS, NOL, & EXPERIMENT, 15° CONE MODELS

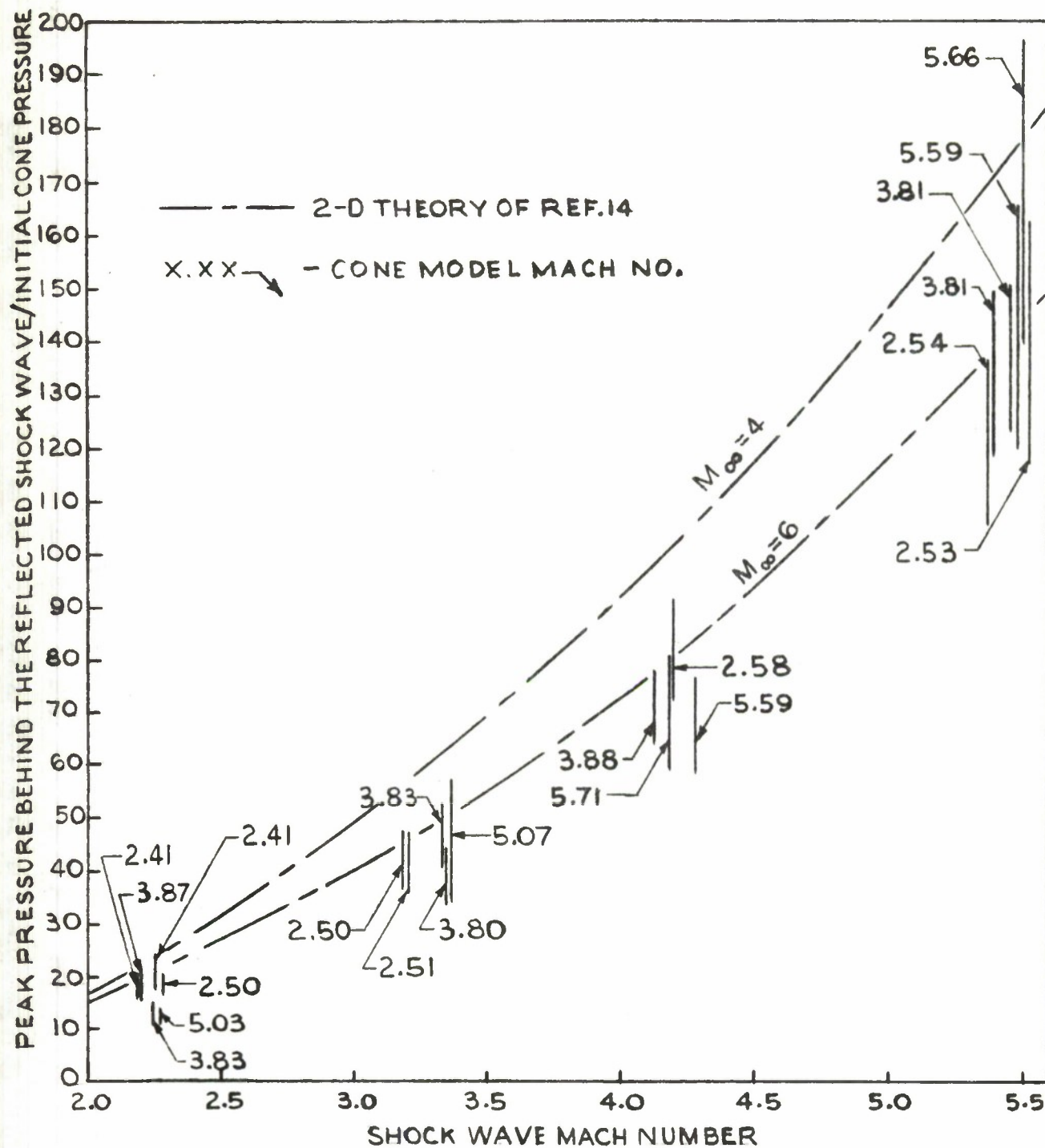


FIG.11 RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. THE SHOCK WAVE MACH NUMBER - THEORY AND EXPERIMENT, 9° CONE MODELS

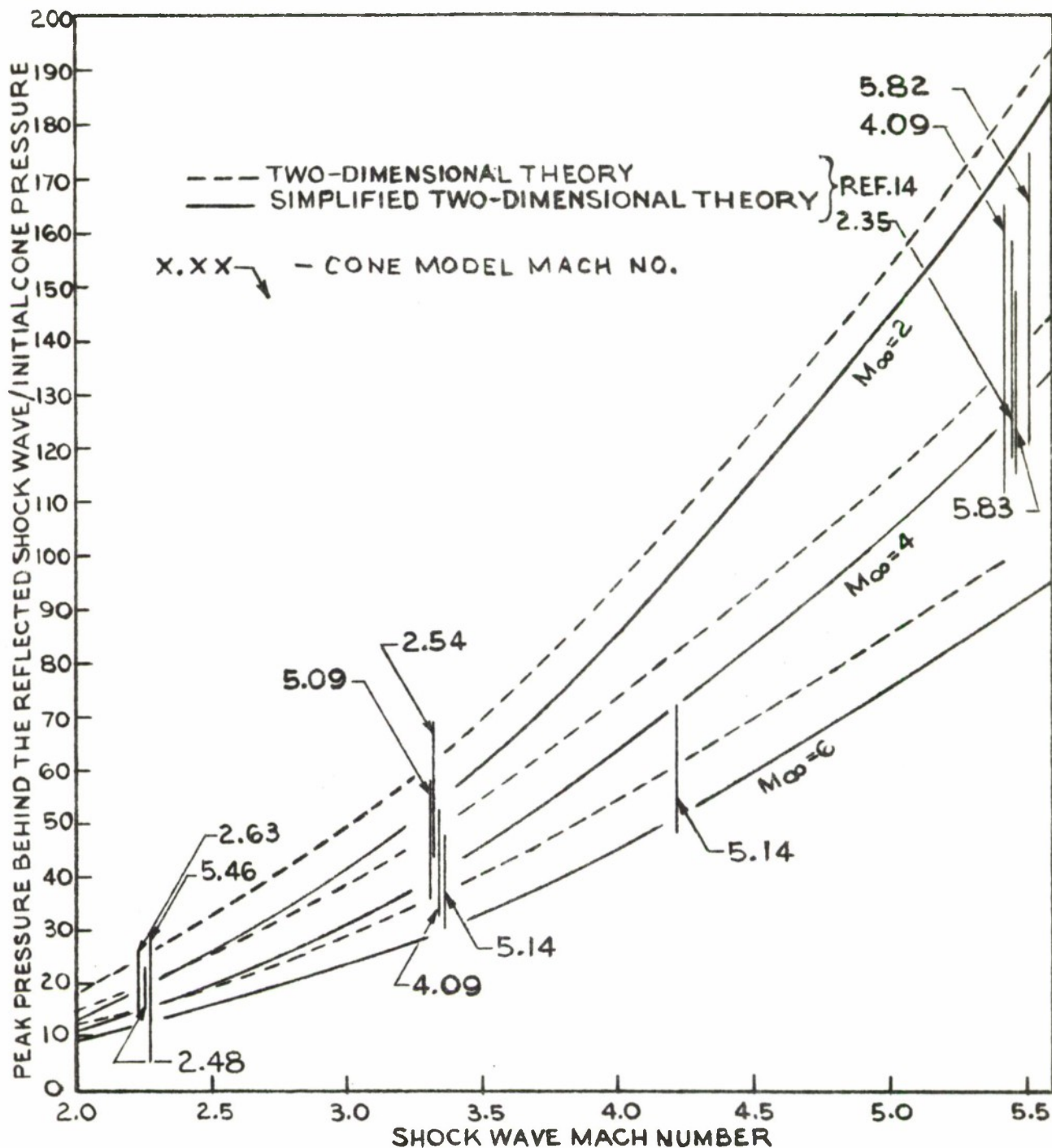
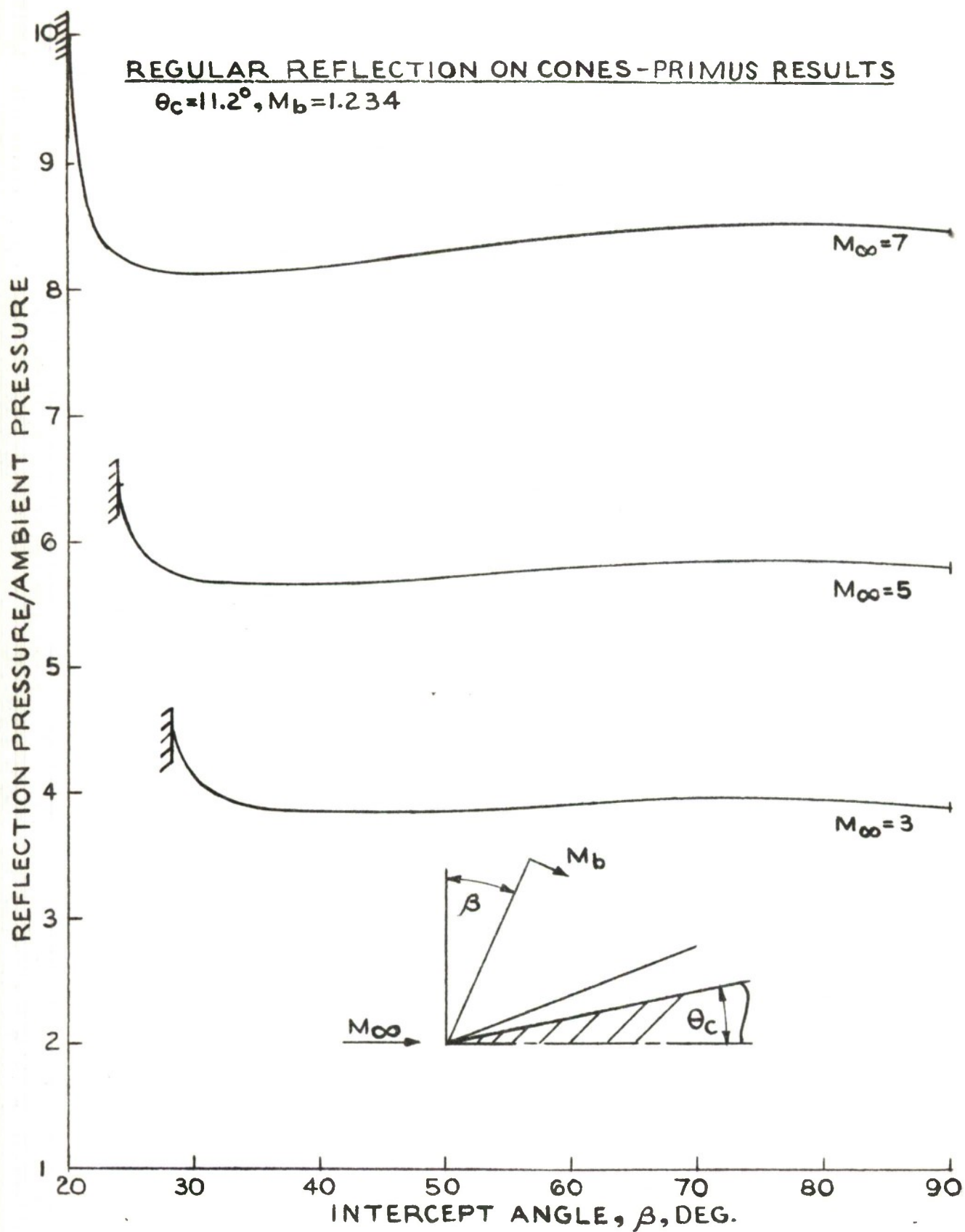


FIG.12 RATIO OF THE PEAK PRESSURE BEHIND THE REFLECTED SHOCK WAVE TO THE INITIAL CONE PRESSURE VS. THE SHOCK WAVE MACH NUMBER — THEORY AND EXPERIMENT, 15° CONE MODELS

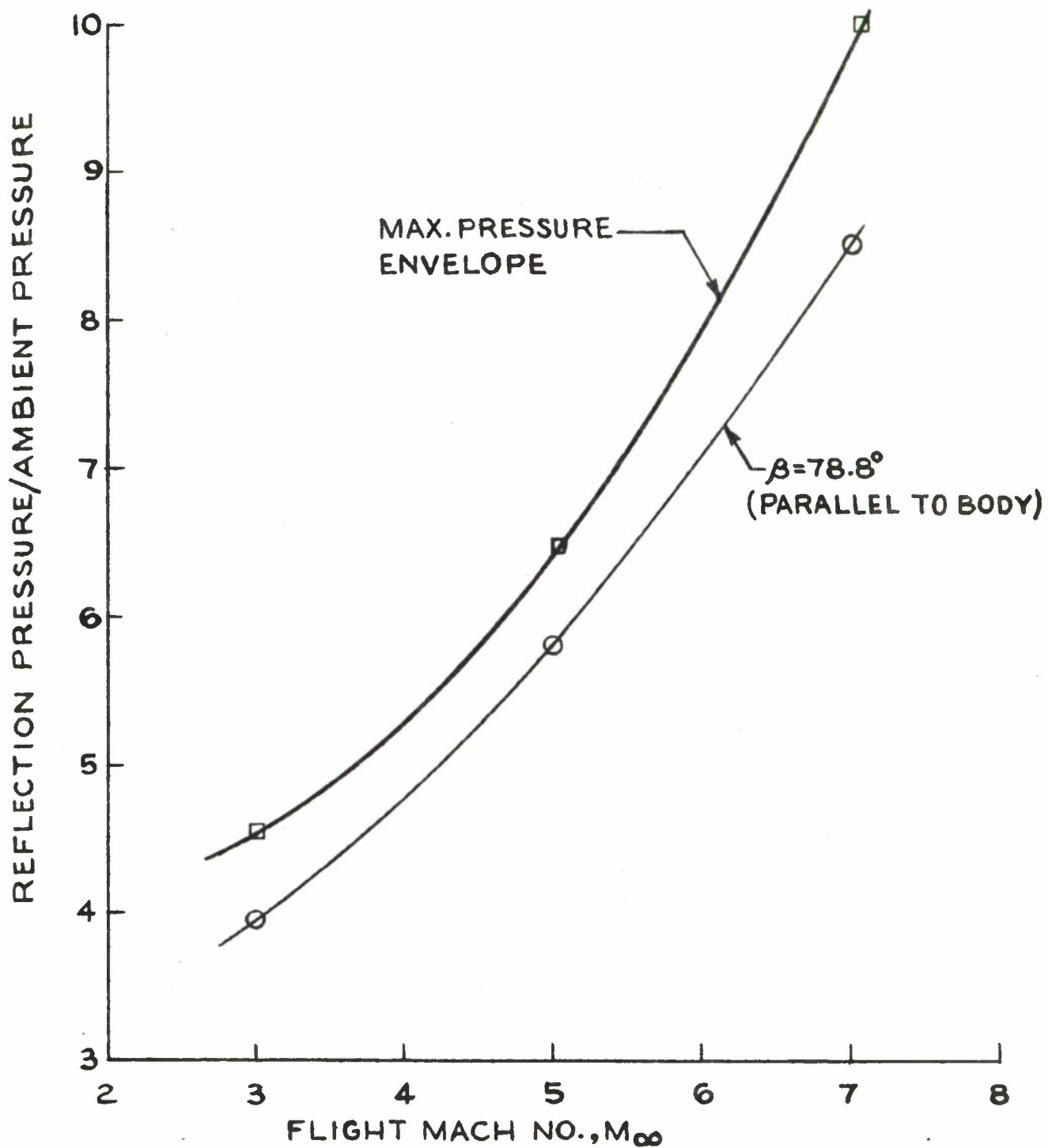
REGULAR REFLECTION ON CONES - PRIMUS RESULTS

$\theta_c = 11.2^\circ, M_b = 1.234$



COMPARISON OF MAXIMUM AND SIDE-ON PRESSURES
FOR REGULAR REFLECTION

$\theta_c = 11.2^\circ$
 $M_b = 1.234$



COMPARISON OF TWO WEAK BLAST CASES FOR
VALIDITY OF HYPERSONIC SIMILITUDE

$$M_b = 1.234$$

$$K_N = M_\infty \sin \theta_c = 0.9712$$

$$\text{---} M_\infty = 5, \theta_c = 11.2^\circ$$

$$\text{---} M_\infty = 10, \theta_c = 5.57^\circ$$

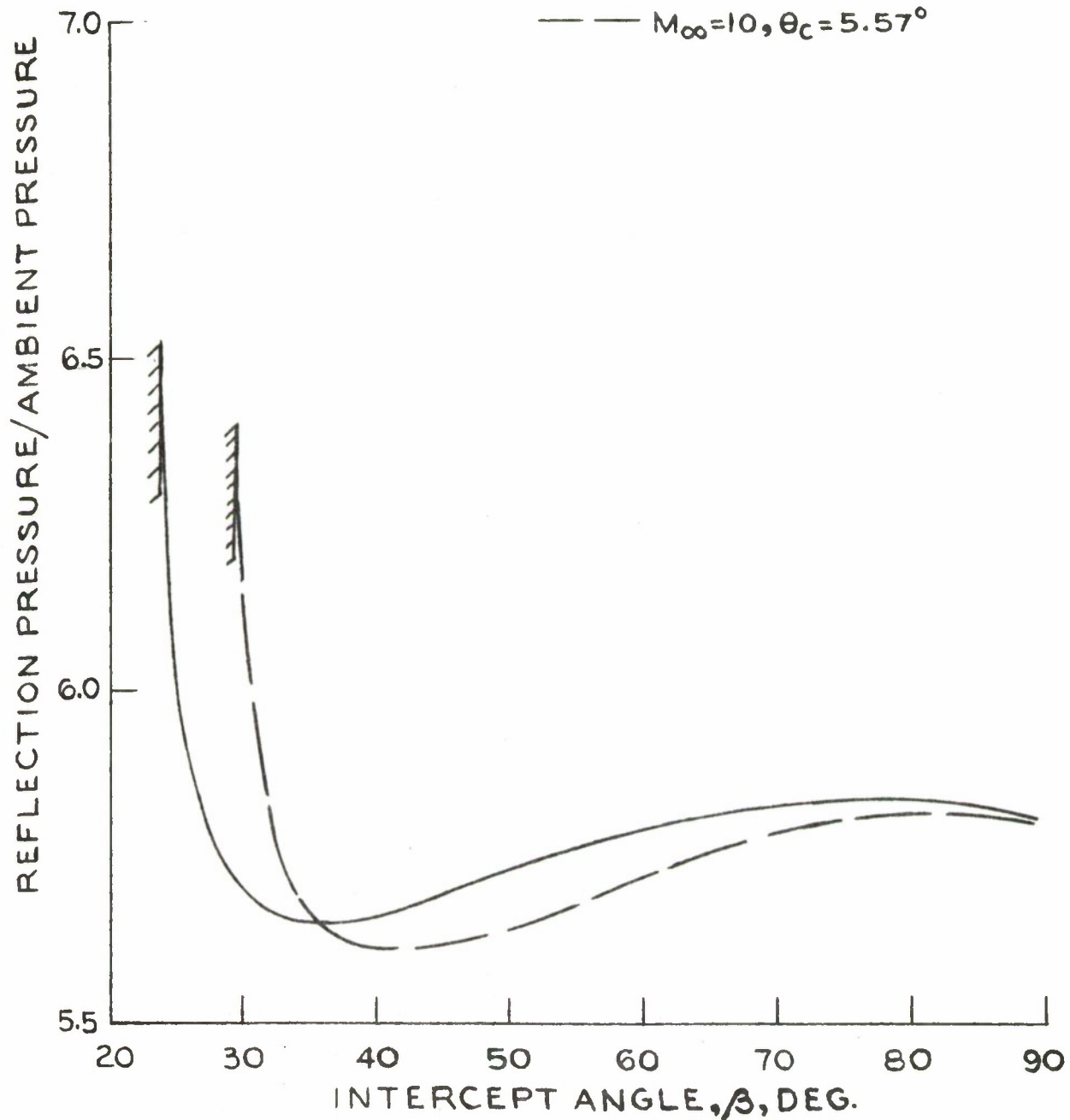


FIG.15.

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13. ABSTRACT The shock-shock interaction problem for weak incident waves impinging on a supersonic cone has been examined. The purpose of this study was to establish methods for predicting surface pressures since existing methods have been found inadequate for practical problems with weak blast waves. It is shown in this study that one-dimensional theory, which works well for strong blast waves, fails when the components normal to the surface of the flight velocity and of the blast particle velocity become comparable. As a consequence, an axisymmetric two-dimensional solution method was developed using a "primary wave" approximation. This approach has been automated in the PRIMUS computer code. The predictions from the code have been checked against experiment and other theory. The comparisons are presented and the agreement is quite good. The code was also used to predict the cone pressures for DNA Sled Test experiments. The results are presented and compared with the experimental results and other theoretical predictions. This study established that for weak blast waves the maximum pressure for regular reflection occurs at the Mach reflection limit, not at side-on intercept. The question of whether reflection pressures are even higher on the Mach reflection side of the boundary was examined, but existing			

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14. KEY WORDS	LINK A		LINK B		LINK C	
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