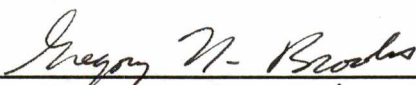


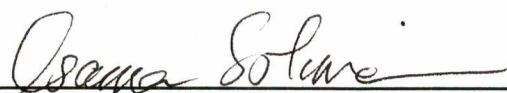
To the Graduate Council:

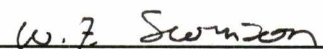
I am submitting herewith a thesis written by Claire Roberta Luttrell entitled "Hydraulically Induced Deflections in Plate Assemblies." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Engineering Science.



Dr. Greg Brooks, Major Professor

We have read this thesis
and recommend its acceptance:





Accepted for the Council:



Associate Vice Chancellor
and Dean of The Graduate School

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Master's degree at The University of Tennessee, Knoxville, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his absence, by the Head of Interlibrary Services when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature Clair R. Huttell

Date 4/27/93

HYDRAULICALLY INDUCED DEFLECTIONS IN PLATE ASSEMBLIES

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Claire Roberta Luttrell

May 1993

ACKNOWLEDGMENTS

The author wishes to thank Dr. W. F. Swinson for his assistance in determining the thesis topic and for his guidance through out the work performed in the course of the thesis. The author wishes to also thank the other committee members, Dr. G. N. Brooks and Dr. O. Soliman, for their comments and assistance. The assistance of Dr. R. C. Gwaltney in developing some of the work discussed in the thesis is also appreciated. Last, but not least, the Author would like to thank her husband, Robert, for his encouragment on her thesis.

ABSTRACT

A major concern in the design of research reactors is the deflection of closely spaced fuel plates due to fluid flowing at high velocities between the plates. The fluid is used for cooling, therefore it is important to insure that adjacent plates do not come into contact and block the flow. Much work has been performed on the deflection of flat plates, but reactors designed recently have been designed using involute shaped fuel plates. This thesis reports on experimental work performed on involute shaped fuel plates, examines various analytical methods that determine the deflection of involute shaped fuel plates and compares the analytical methods to experimental results. The comparisons showed that the standard method used in the past, based on Miller's theory, do not explain what is actually occurring in the reactor fuel plates. A new method examined which is based on converting the parallel plates into pipe systems more closely represents what is actually happening, but for this method it is necessary to assume a channel imperfection and this is hard to accurately predict. The method developed by Dr. Frank Swinson which is termed the dynamic pressure method appears to be the best method in which to base designs. In comparing this method to experimental work it was apparent that it gives an upper limit of plate deflection and is therefore conservative.

TABLE OF CONTENTS

CHAPTER	PAGE
I. INTRODUCTION.....	1
II. BACKGROUND ON FLAT PLATE THEORY.....	3
D. R. Miller's Theory.....	3
E. B. Johansson's Theory.....	4
F. J. Remick's Theory.....	5
R. J. Scavuzzo's Theory.....	5
G. E. Smissaert's Theory.....	6
III. BACKGROUND ON FLAT PLATE EXPERIMENTS.....	8
W. L. Zabriskie's Experiment.....	8
R. D. Groninger and J. J. Kane's Experiment.....	9
F. J. Remick's Experiment.....	10
G. E. Smissaert's Experiment.....	10
IV. INVOLUTE PLATE THEORY.....	12
Miller's Theory Extended to Involute Plates.....	12
W. K. Sartory's Additions to Miller's Theory.....	16
W. F. Swinson's Dynamic Pressure Theory.....	18
V. INVOLUTE PLATE EXPERIMENTAL WORK.....	20
Single Involute Plate Test.....	20
Multiple Involute Plate Test.....	20
The Test Assembly.....	21
Data Collection.....	28
Test Results.....	28
VI. FLOW BETWEEN PARALLEL PLATES.....	44

CHAPTER	PAGE
VII. COMPARISON OF METHODS.....	50
Comparison with Groninger and Kane's Experiment..	51
Comparison with Smissaert's Experiment.....	53
Comparison with ANS Lower Element Experiment.....	56
Comparison with ANS Upper Element Experiment.....	59
VIII. CONCLUSIONS.....	62
LIST OF REFERENCES.....	64
VITA.....	67

LIST OF FIGURES

FIGURE	PAGE
1. Finite Element Model of Involute Plate.....	13
2. Arrangement of Fuel Plates in ANS Core.....	22
3. Aluminum Cylinder for Test Section.....	23
4. Aluminum Cylinder for Flow Straightner.....	26
5. Fuel Plate Test Loop.....	27
6. Upper Fuel Plate Deflection at Entrance.....	30
7. Upper Fuel Plate Deflection at One-Quarter Point.....	31
8. Upper Fuel Plate Deflection at One-Half Point.....	32
9. Upper Fuel Plate Deflection at Three-Quarter Point...	33
10. Upper Fuel Plate Deflection at Exit.....	34
11. Upper Fuel Plate Deflection and Pressure at Entrance.	35
12. Lower Fuel Plate Deflection at Entrance.....	37
13. Lower Fuel Plate Deflection at One-Quarter Point.....	38
14. Lower Fuel Plate Deflection at One-Half Point.....	39
15. Lower Fuel Plate Deflection at Three-Quarter Point...	40
16. Lower Fuel Plate Deflection at Exit.....	41
17. Lower Fuel Plate Deflection and Pressure at Entrance.	42
18. Two Channels for Hydraulic Diameter Calculation.....	45
19. Comparison to Groninger and Kane's Experiment.....	52
20. Comparison to Smissaert's Experiment.....	54
21. Comparison to Lower Plate with Maximum Deflection....	57
22. Comparison to Central Lower ANS Plate.....	58
23. Comparison to Central Upper ANS Plate.....	60

LIST OF ABBREVIATIONS

Advanced Neutron Source.....	ANS
High Flux Isotope Reactor.....	HFIR
Automatic Dynamic Incremental Nonlinear Analysis.....	ADINA

NOMENCLATURE

A	Cross Sectional Area
D_{hn}	Hydraulic Diameter of Channel n
f_n	Friction Factor of Channel n
g	Gravitational Acceleration
h_n	Flow Channel n Gap
k	Roughness of Channel Wall
L_n	Length of Channel n
N_r	Reynolds' Number
P_n	Pressure in Channel n
Q_n	Fluid Discharge in Channel n
s	Span Length of Plate
V_n	Fluid Velocity in Channel n
ν	Kinematic Viscosity
P	Wetted Perimeter
ρ	Fluid Density

I. INTRODUCTION

The Advanced Neutron Source Reactor (ANS) is presently under design at the Oak Ridge National Laboratory. One critical region of design in this highly enriched uranium fission reactor is the closely spaced arrays of fueled plates. These involute shaped fuel plates have fluid flowing between them at high velocities, which causes the plates to deflect. When a reactor is operating it is vital that adjacent fuel plates do not come in contact with each other.

Failures in plates in actual reactors and experiments have been observed when the velocity of the fluid between the plates exceeds some value. The velocity at which this occurs is called the "collapse" or "critical" velocity. There are several definition of the critical velocity. In most of the analytical work performed the critical velocity is defined as the velocity at which the plates undergo a sudden collapse. In the experimental work a sudden collapse of the plates is not seen, but rather a gradual increase in deflection of the plate with an increase in the velocity. For some of the experimental work the critical velocity was defined as the velocity at which deflection was first noticed.

In several of the experiments a high amplitude vibration, large enough to cause adjacent plates to touch, was noticed. The velocity at which this occurred was called the flutter velocity. The velocity that needs to be determined is the

velocity, collapse velocity or flutter velocity, that causes adjacent plates to touch.

Since the 1950's analyses and experiments have been performed on flat fuel plates and curved fuel plates to determine the critical velocity. With the introduction of involute shaped fuel plates in reactors such as the High-Flux Isotope Reactor (HFIR) and the Advanced Neutron Source (ANS) this work had to be extended to involute shaped plates. Several approaches have been taken to try to solve this difficult critical velocity problem.

The goal of this thesis is to determine the best method of solving the problem of hydraulically induced deflection in closely spaced fuel plates. This goal is to be achieved by examining previous methods used to solve this problem, by looking at previously performed experimental work on closely spaced flat fuel plates, by reporting on experimental work performed on involute shaped fuel plates, and by examining alternative methods of solving this problem.

II. BACKGROUND ON FLAT PLATE THEORY

Theoretical work has been performed on flat plates since the 1950's. This work was done to determine the deflection in closely spaced fuel plates due to flow between the plates. Many of the theories that were developed were based on the work done by D. R. Miller (1).

D. R. Miller's Theory

D. R. Miller developed a method of determining the hydraulically induced deflection in parallel flat and curved fuel plate assemblies. He predicted a sudden collapse of the fuel plates, when the flow reached a calculated value of velocity, due to instability in the plates. The velocity at which he predicted a sudden collapse has come to be called Miller's critical velocity.

Miller's critical velocity was determined by coupling a plate deformation equation with Bernoulli's equation for fluid. Some basic assumptions made by Miller were:

1. Plates are homogeneous, isotropic, elastic, initially flat or uniformly curved, uniformly spaced, and contain no unidentified sources of deformation.
2. Incompressible coolant, all channels have the same mass flow, at any cross section the flow within a channel is uniform, and there is no leakage between

the channels.

3. The ratio of width to thickness of the plates are great enough so that shear deformation can be neglected, and that the ratio of length to width is great enough so that the plates can deflect locally without significant redistribution of flow among the coolant channels.

4. Side plates or supports are rigid.

His assumption of constant mass flow through each channel means that if there are two channels and channel A is larger than channel B the fluid velocity in the larger channel A must decrease and the fluid velocity in the smaller channel B must increase. Consequently the static pressure in channel A must increase and the static pressure in channel B must decrease. The decrease in pressure in channel B would allow the plates to move closer together causing an even higher velocity in channel B which in turn would again cause the pressure to decrease. This would continue until the critical velocity was reached at which point the forces on the plates exceed the elastic forces of the plate and the plate would buckle. Miller's model predicts that the collapse of the plate will occur suddenly and away from the inlet.

E. B. Johansson's Theory

Miller's theory was modified by E. B. Johansson (2). Johansson claimed that a local deflection would affect the

friction pressure drop. Johansson's model included the fact that in the reduced channel there would be an increase in the friction pressure drop and in the enlarged channel there would be a reduction in the friction pressure drop. This assumption results in redistribution of flow between channels, therefore there is not constant mass flow in each channel. Johansson's model predicted that the maximum deflection would occur at the inlet. He still assumed small deflection and the remainder of Miller's assumptions.

F. J. Remick's Theory

The work done by F. J. Remick (3) started with Miller's theory and let there be flow redistribution, as Johansson did, due to the change in the friction pressure drop at the local deflection. Remick added a term for the contraction and enlargement losses at the local deflection. He also included the fact that the friction factor is different in the channels that have different flow rates. In Remick's equation for the static pressure difference across the plate if $V_1 = V_2$, the losses due to enlargement and contraction are neglected, and the losses due to friction are neglected, then Miller's equation is obtained.

R. J. Scavuzzo's Theory

R. J. Scavuzzo (4) modified Miller's wide-beam theory to take into account a three-dimensional plate deflection. He

included the effects of fluid friction and flow redistribution. The effects of contraction losses concentrated at the inlet; and, expansion losses concentrated at exit are also included. Scavuzzo coupled the equations for the plate pressure loads, which are non-linear functions of plate deflection, with the classical plate equation. The results of his model show that for a plate assembly with no initial imperfections there would not be any deformation below Miller's velocity. For the case when there are initial imperfections in the plates a deflection below Miller's velocity may occur which is an amplification of the original imperfection.

G. E. Smitsaert's Theory

The analysis of flat fuel plates was also examined by G. E. Smitsaert (5). His hydroelastic stability analysis is based on a set of four coupled differential equations. The linear thin-plate small-deflection Navier equation is used to determine the deformation of the plates due to the load. The non-linear Navier-Stokes equation and the linear equation of continuity are used to describe the flow. The assumptions made for this analysis are:

1. The plates material is homogeneous, isotropic and perfectly elastic.
2. The plate thickness is constant, the edges are clamped and perfectly rigid, and the channel

dimensions for undeformed plates are constant.

3. The fluid is incompressible and flows through narrow channels at a constant flow rate, which is equal in all channels. The flow in the channels is fully developed turbulent flow with no separation.

Smissaert examines a two-dimensional problem where the plates are parallel to each other and infinite in length and width. He also considers the case of plates with finite width and finite length. The third case he examined was the plate leading edge instabilities. For this case he assumed the plates were finite in width and infinite in the direction of flow. Smissaert's theory indicates that there are two velocities which cause the deflection in the plates. One of these velocities he claims is Miller's velocity which is the minimum velocity at which the plates would begin to experience static deflection, where the plates deflect in the shape of an infinite wavelength. The other velocity is what he calls the flutter velocity which is where dynamic instabilities in the form of small-amplitude traveling waves are coupled with the large amplitude flutter at the leading edges of the plates. He determines that the flutter velocity is about twice Miller's velocity.

III. BACKGROUND ON FLAT PLATE EXPERIMENTS

Experimental work was performed by several different people to try and understand this complicated problem. For the experiments arrays of flat parallel plates were assembled and tested. The number of plates in the arrays tested varied from a single plate to 15 parallel plates. Various size plates and channel thicknesses were used in the different experiments. The results of the experiments were compared to various theoretical work.

W. L. Zabriskie's Experiment

One of the first people to examine this problem experimentally was W. L. Zabriskie (6). He attempted to validate Miller's theory, but his experimental work had some complications. Zabriskie's test data was not consistent. He had problems due to using two materials with different thermal expansion coefficients and also with obtaining reliable data from his impact pressure probes. He looked at single and multiple plate assemblies with various length to width ratios. He was able to determine that there was not a sudden collapse as Miller predicted. He found that there was deflection of the flat plates above and below Miller's critical velocity and that it was not always static, but oscillated. Zabriskie also found that the maximum deflection occurred at the inlet, which is not what Miller predicted.

R. D. Groninger and J. J. Kane's Experiment

R. D. Groninger and J. J. Kane (7) also performed experiments on flat plate arrays. They examined three parallel plate assemblies each with 5 plates and 6 channels. The 3 assemblies had varied plate thicknesses and spans. Two of the assemblies contained rectangular fuel bearing compartments separated by Zircaloy ribs and covered with Zircaloy clad. The other assembly was made of solid Zircaloy plates. Hot and cold test were performed with and without combs located at the channel entrance. The case of the solid Zircaloy plate, in the cold loop, without combs, will later be compared to Miller's critical velocity, Swinson's dynamic pressure and Luttrell's hydraulic diameter.

Groninger and Kane showed that the maximum deflection occurs at the inlet, as did Zabriskie, and that adjacent plates move in opposite direction at high flow rates. They found that flow induced deflection occurred at flow rates above and below Miller's critical velocity and that the plates did not undergo a sudden collapse as was predicted by Miller. In the tests without combs they found that at high flow rates, approximately 1.9 times Miller's critical velocity, an extreme vibration or flutter of the fuel plates occurred. This flutter was made up of waves which started at the leading edge of the plates and traveled down the plates. The cases with combs did not show this flutter. They concluded that flow induced deflection is essentially a magnification of built-in

channel imperfections.

F. J. Remick's Experiment

F. J. Remick (3) performed experimental work on flat plates with the original goal of improving on Zabriskie's experiment. His first test was plagued with problems, such as gages coming off, the side walls deflecting and insufficient plate stiffness. The results that he did obtain agreed with Zabriskie in that there was a gradual increase in deflection with increase in flow instead of a sudden collapse. He also found that the largest deflection occurred at the inlet. The second test he performed was used to verify the theory he developed. The plates used in this test were thick plates designed to only deflect due to forces causing magnification of plate imperfection. From this test he obtained static pressure difference profiles which he compared to his theory. The results compared well to his theory, but when compared to Miller's theory they showed that Miller missed the fact that the pressure differential changes signs axially down the plate.

G. E. Smissaert's Experiment

Experimental work on flat fuel plates was also performed by G. E. Smissaert (8). He ran experiments on 3 plate assemblies. One assembly had 5 plates and 6 channels, one had 9 plates and 10 channels, and one had 15 plates and 16

channels. All of his plates had the same thickness, but he varied the channel width. His experimental results again showed the maximum deflection occurred at the inlet. The results he reports are only for the case with 5 plates and a large gap. He found that the deflection was in the form of a wave which travelled down the plate in the direction of flow. Below Miller's critical velocity he found that the fuel plates will deform due to static pressure differences. At about 2 times Miller's critical velocity he found that a high speed vibration or flutter would occur.

The results from all of these experiments showed differences from Miller's theory. In all experiments without combs the maximum deflection was located at the inlet, which was not predicted by Miller. They all showed that there was not a sudden collapse at Miller's critical velocity, but rather the plates deflected at flow rates below the critical velocity and the deflection gradually increased as the flow rate was increased. The work done by Groninger and Kane and the work done by Smissaert reported that an extreme vibration or flutter occurred at about 2 times Miller's critical velocity. In examining the above experimental work it is apparent that the problem may not be one of collapse.

IV. INVOLUTE PLATE THEORY

Involute shaped fuel plates are being used in research reactors because they allow the plates to be inserted in a core in a circular arrangement with a constant gap size. These plates also provide more structural stability than flat plates. The HFIR is an example of a reactor which uses involute shaped fuel plates. The ANS Reactor is presently being designed using involute shaped fuel plates. A theory to determine the hydraulically induced deflection of the involute plates is still being developed. The velocity of the flow between the proposed fuel plates in the ANS reactor is 67% higher than that used in the HFIR. This requires that the problem be more closely examined than it was for the HFIR design.

Miller's Theory Extended to Involute Plates

In 1988 work was done by R. C. Gwaltney and C. R. Luttrell (9) to determine the involute plate deflection due to coolant flow. This work was based on Miller's theory which was extended to involute shaped plates by coupling elastic finite element models with Bernoulli's equation.

These analyses were done by developing a finite element model of an involute shaped plate and determining the deflection due to a given pressure. Figure 1 shows an example of a finite element model of an involute shaped fuel plate.

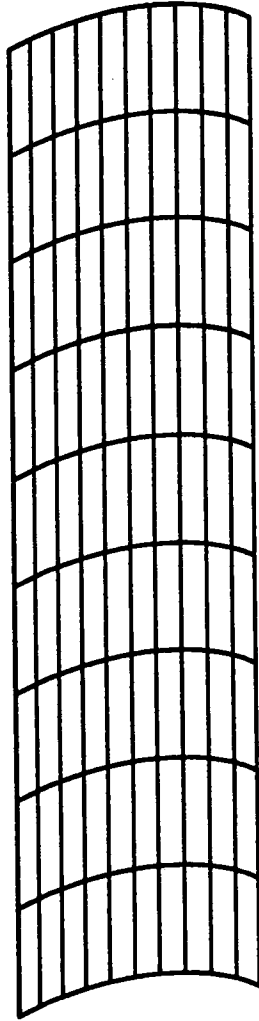


Fig. 1. Finite Element Model of Involute Plate

The finite element code ADINA was used for these analyses. The deflection curve was then integrated and multiplied by two, to account for the plates on each side of the channel, to give the change in cross sectional area for the total channel. This value was then divided by the original channel cross sectional area to give the per-unit change in channel cross section. The per-unit change in the channel cross sectional area along with Bernoulli's theorem was used to calculate the critical velocity. The critical velocity of several flat plates was determined using the method described above by modelling the plates with two-dimensional finite elements and the results were compared with Miller's critical velocity. The comparison of the results showed that this method gives the same critical velocity for flat plates as Miller's method.

The assumptions used for this analysis are basically the same as those used by Miller in his analysis. They are:

1. Plates are homogeneous, isotropic, elastic, initially flat or curved of any shape, uniform in spacing and dimensions, and contain no unidentified sources of deformation.
2. Coolant is incompressible.
3. All channels have the same mass flow with no leakage between channels.
4. Shear deformation is negligible and plates can deflect locally without significant redistribution of flow among the coolant channels.

5. Side plates or supports are rigid.

This method of determining the critical velocity of involute fuel plates was used for several purposes in the early design of the ANS reactor. One way in which this method was utilized was in performing parameter studies on involute fuel plates, of various span lengths, being considered for the ANS reactor. From these analyses dimensions for the upper and lower core for ANS were chosen. Analyses were also performed with this method to determine the effect that various boundary conditions along the length of the fuel plates had on the critical velocity. Cases were considered where the edges were completely fixed and where the boundary conditions on the edges were various combinations of fixed and simply supported. The critical velocity was not affected much by the various edge conditions until a large part of the plates edge was simply supported. The involute plate which was used in this analysis had an inner diameter of 120 mm and an outer diameter of 213.25 mm. The results of varying the edge conditions on this plate can be seen in Table 1. The effects of adding combs at the entrance and exit of the plate assembly was also studied using this method. The result of this analysis showed that the addition of two combs at the top and bottom of the plates would significantly raise the critical velocity. For the case with 100% fixed edges the addition of the combs would raise the critical velocity from 24.55 m/s to 33.55 m/s.

Table 1 - Critical Velocity from Fixity Studies	
Boundary Conditions	Critical Velocity m/s
100% Fixed Edges	46.03
50% Simply Supported	40.56
75% Simply Supported	36.52
100% Simply Supported	3.99

This type of analysis served as a starting place for the design of the ANS fuel plates. This method uses Miller's basic theory and does not take into account the effect of friction and expansion and contraction of the flow. The fact that this method considers the problem one of instability is questioned based on the results of the experimental work.

W. K. Sartory's Additions to Miller's Theory

W. K. Sartory (10) also examined the problem of hydraulically induced deflection in involute shaped fuel plates. He coupled a finite element shell model of the fuel plates with a linearized hydraulic equation including fluid friction effects to determine the critical velocity of the fuel plates. Sartory developed a fully two-dimensional hydraulic model with inlet and outlet fluid and plate boundary conditions. He also included inertial and damping terms in the fluid and plate equations. If the fluid friction factor is set equal to zero for a flat plate in Sartory's work the

results obtained are equivalent to Miller's critical velocity. Sartory found that the addition of the friction factor increased the critical velocity. For the case of a friction number of 6 the critical velocity for a flat plate would be about twice Miller's critical velocity. The effect of including friction on an involute plate also increased the critical velocity of the plate, but not as significantly. For the ANS involute plate he found that the critical velocity for the case with a friction factor of 6 was about 1.4 times the critical velocity for the case with a friction factor of zero.

Sartory (11) developed a second method which examined the effects of channel imperfections on buckling. He developed a two-dimensional hydraulic channel fluid element to be coupled with a standard curved shell element using the commercial finite element code ABAQUS. This model included the effects of friction, contraction and expansion losses, and noninfinitesimal imperfection in channel dimensions. For this case he let flow redistribute between adjacent channels. The results of his analysis show a family of curves of plate deflection vs coolant velocity for various channel imperfections. For the example he discussed, Sartory determined that including an imperfection in the channel dimensions of 30% would reduce the critical velocity by about 18%.

For both of the cases Sartory examined he assumed the problem was one of instability as was done by Miller and all

those who expanded on his theory. As has been previously pointed out this is not necessarily the way the problem should be considered.

W. F. Swinson's Dynamic Pressure Theory

W. F. Swinson (12) contends that Miller's basic assumption of a sudden collapse does not describe the problem. He points out that the test results do not show a sudden collapse, but rather a gradual increase in deflection with an increase in flow velocity. Swinson developed a method to determine the velocity that causes adjacent plates to touch which he terms the dynamic pressure approach.

The dynamic pressure model assumes that there is not constant mass flow between adjacent channels. He assumes that there is parallel flow between the plates. With the assumption of parallel flow he gets the equation for the difference in pressure between two adjacent channels. This equation is:

$$P_B - P_A = \frac{\rho (V_A^2 - V_B^2)}{2g} \quad (1)$$

This equation shows that the pressure is higher in the smaller channel, the channel with the lower velocity. This larger pressure is trying to increase the size of the channel, which tends to equalize the channel dimensions. He concludes that

this model predicts stable flow. For the limiting case when V_B is equal to zero the equation becomes:

$$P_B - P_A = \frac{\rho V_A^2}{2g} \quad (2)$$

In comparing the results from his method to experimental results Swinson claims the dynamic pressure is an upper limit.

Groninger and Kane's experiments and Smitsaert's experiments showed that at about 2.0 times Miller's critical velocity the plates began to oscillate. Using the dynamic pressure approach Swinson found that the critical velocity, the velocity where the plates touch, is about 1.5 times Miller's critical velocity. The experimental data reported falls below the values calculated by Swinson. He claims that since the deflections can be bounded the problem does not appear to be one of instability for the range of velocities examined. Swinson also claims that his method is conservative and is an upper limit that could be used for design purposes.

V. INVOLUTE PLATE EXPERIMENTAL WORK

Single Involute Plate Test

An experiment was performed by W. F. Swinson on a single HFIR involute plate to determine the hydraulically induced deflection. The HFIR plates have an inner radius of 149.2 mm and an outer radius of 211.9 mm. The length of the HFIR plates are 609.6 mm. The results of this test showed that there was a gradual increase in plate deflection with an increase in flow velocity. Comparing this case to Sartory's theory it was noted that there was not a collapse at Sartory's predicted collapse velocity.

Multiple Involute Plate Test

Experimental work was reported by W. F. Swinson, R. L. Battiste, C. R. Luttrell and G. T. Yahr (13-14) which determined the deflection of involute plates as a result of fluid flowing past the plates at high velocities. Experiments were performed on epoxy plates shaped like the proposed involute plates in the ANS research reactor. The ANS research reactor consists of an upper and a lower core, each with unique involute plates. Test were run on both configurations of involute fuel plates.

The actual plates to be used in the reactor are aluminum clad with a core of a uranium silicide/aluminum mixture. The arrangement of the fuel plates in the ANS core can be seen in

Fig. 2. The upper and lower fuel plates are 1.27 mm thick and the flow channels are 1.27 mm thick. The epoxy material was chosen instead of aluminum, because this allowed the use of lower fluid velocities. The results obtained from the epoxy plates were converted through the use of model theory to represent the aluminum plates.

The Test Assembly

Two sets of experimental data were collected for both the upper and lower ANS cores. To collect this data four test sections had to be assembled. Two of the test sections had the dimensions of the upper ANS core and the other two had the dimensions of the lower ANS core. Aluminum cylinders to be used for a flow straightening section and aluminum cylinders to be used to hold the test sections were machined. The test sections which were inserted into the aluminum cylinders consisted of seven plates and six flow channels. The three central plates each had five strain gages and the four central channels each had five pressure taps. Figure 3 shows the test section located in the aluminum cylinder.

The epoxy plates were formed by pouring a predetermined amount of epoxy on a level surface between four rectangular boundaries. Before the epoxy was completely set it was rolled to a thickness of 1.27 mm and placed on an involute mandrel to finish setting. The variation in plate thickness was measured to be ± 0.05 mm. The edges of the plates were trimmed with a

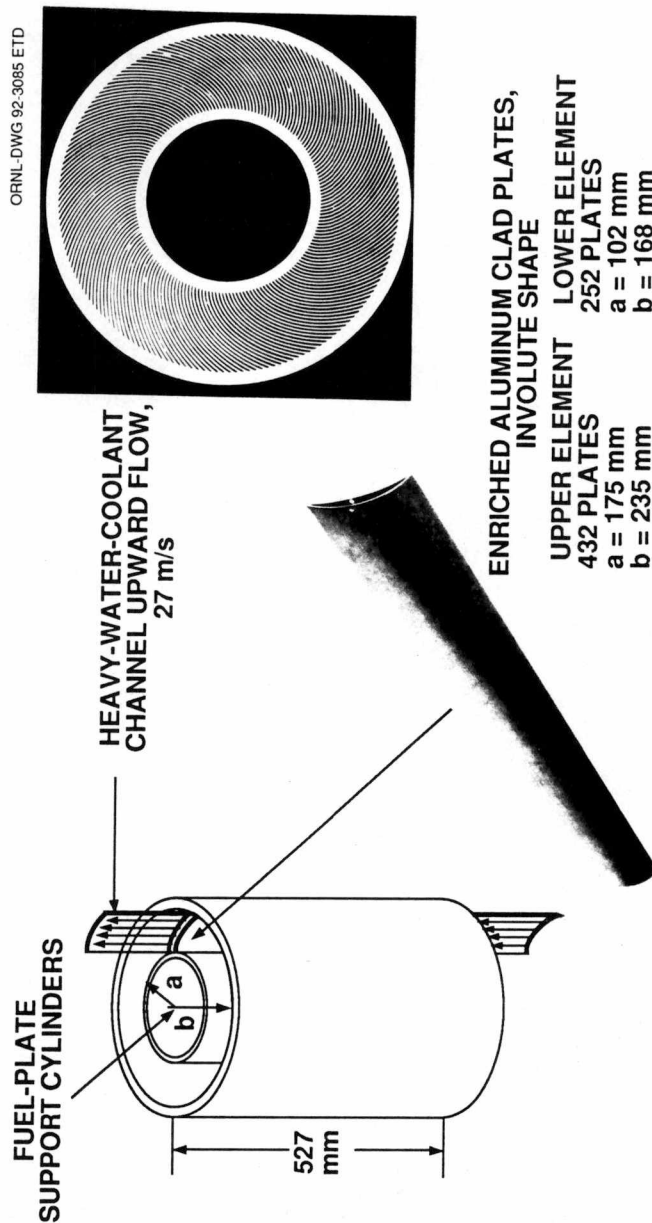


Fig. 2. Arrangement of Fuel Plates in ANS Core

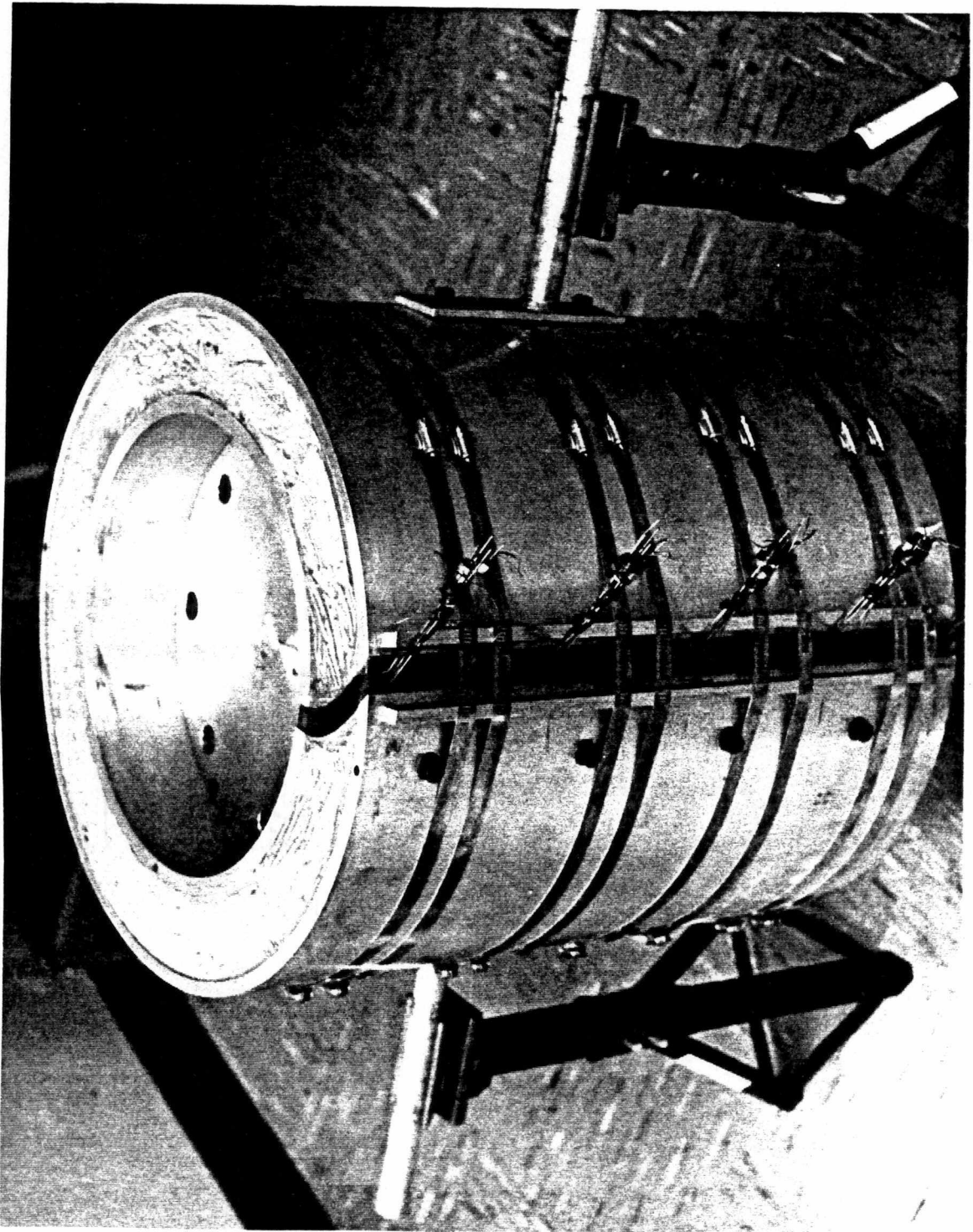


Fig. 3. Aluminum Cylinder for Test Section

router to obtain the final dimensions of the ANS fuel plates. Two rectangular epoxy strips, 1.22 mm thick x 12.7 mm wide x 527 mm long, were epoxied to each of the plates.

Five strain gages were affixed to three of the plates for each test section. The strain gages were located at the two ends of the plates, the one-quarter point, the one-half point and the three-quarter point. The leads of the strain gages were placed in groves cut through the spacers of the plates and the groves were filled with epoxy. Five pressure tubes were epoxied in place in groves cut in the spacers of four of the plates. The pressure tubes were located in the plates adjacent to the strain gage locations. The strain gages were calibrated so the maximum plate deflection due to a pressure difference across the plate could be determined from the strain gage reading.

Each test section was assembled by gluing, using epoxy, seven plates and their spacers together. The spacers, along with the epoxy used to glue the assembly, formed the 1.27 mm spacing for the channel. Out of seven plates and six channels, due to the boundary conditions, the three central plates and the four central channels were considered to give accurate information. In the test section the plates with strain gages were located as the three central plates and the plates with the pressure tubes in the spacers were located such that the four middle channels contained the pressure tubes.

For the final assembly the test sections were inserted into the aluminum cylinder machined for the test section and two epoxy plates were inserted into the cylinder machined for the flow straightener section. Both the aluminum cylinder for the test section and the one for the flow straightener were back filled with an aluminum filled epoxy. Figure 3 and Fig. 4 show the aluminum cylinder holding a test section and the aluminum cylinder used as the flow straightener, respectively. The back fill created the fixed boundary plates for the test section. After the test section was inserted into the aluminum cylinder the channel thickness was measured as 1.27 ± 0.08 mm.

After the individual cylinders were assembled, the flow straightener cylinder, the test section cylinder and an exit chamber were bolted together. This assembly was then placed in the test loop as shown in Fig. 5. The fifteen strain gages were connected to the conditioning circuit and each of the twenty pressure tubes were connected to separate pressure transducers.

The flow in the test loop was generated by a centrifugal pump capable of producing flow of 22 l/s at 2.413 MPa. The test loop contained two paths. One path consisted of flow coming from the pump, flowing through the test section and returning to a storage tank. The other path consisted of flow coming from the pump, flowing through a by-pass line and returning to a storage tank. The flow through each path was

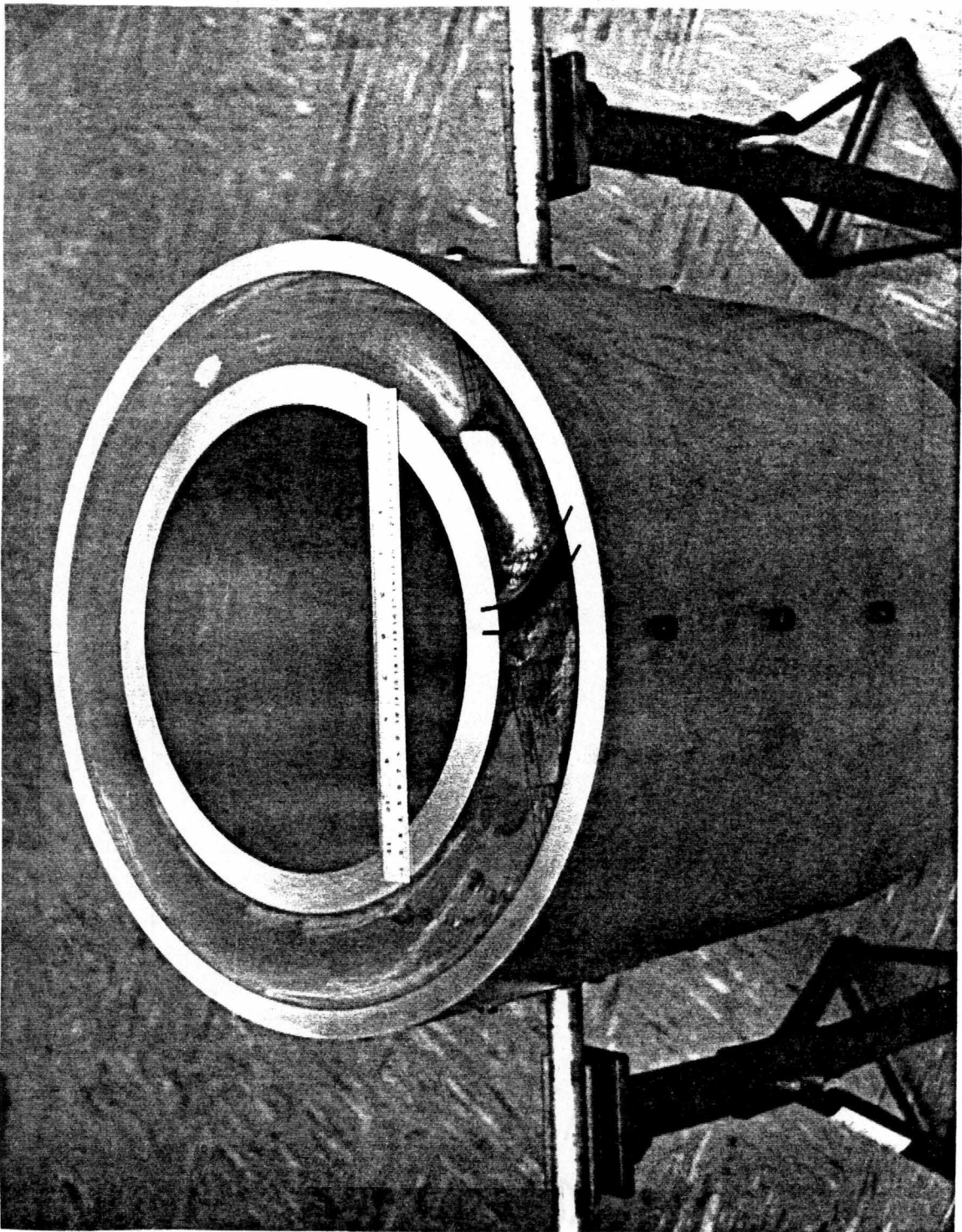


Fig. 4. Aluminum Cylinder for Flow Straightener

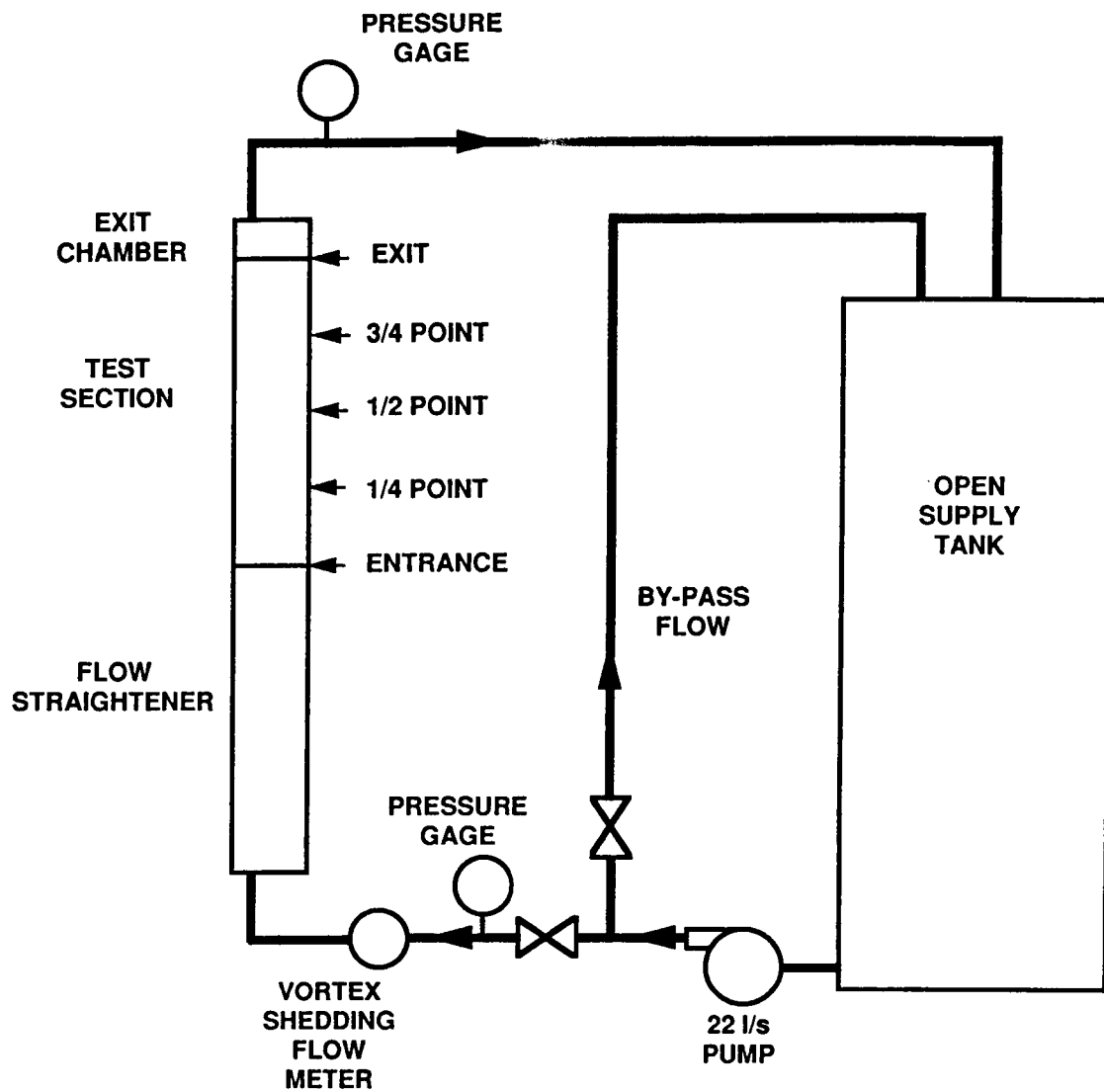


Fig. 5. Fuel Plate Test Loop

controlled by a gear regulated, full flow ball valve.

Data Collection

The data collection from the experiment was computer controlled. The data obtained included the flow volume determined by a vortex shedding meter, the strain determined by the fifteen strain gages, the up and down stream pressure, pressure in the channels determined by the twenty pressure transducers and the water temperature determined by a thermocouple. For each run three sets of zero data, no flow, were first taken, next the flow was adjusted to the desired velocity and three sets of loaded data were taken, then the flow was shut off and three more sets of zero data were taken. By following these steps each run could be immediately examined. A large variation in the zero data before the load and after the load signalled that there was a problem in the test and that the data was probably not reliable.

Test Results

From each test section the deflection of the plates due to various flow velocities was determined. Having two test sections for each the upper and lower fuel plates allowed the results for two test sections to be compared so the effect of tolerances on the channel and plate dimensions could be examined. It was found that the test results from the two test sections of the upper core gave similar results, as did

the two test sections of the lower core.

The results from the tests on the fuel plates for the upper element show that the maximum deflection, of any of the gaged plates, occurred on the central plate at the entrance. The maximum deflection was 0.373 mm at a velocity of 56.12 m/s. Figures 6 through 10 show the deflection of the three central plates at the locations of the five strain gages on each plate. The velocity illustrated in these figures is the prototype velocity scaled from model theory. The deflections are plotted such that a zero deflection for the three plates would give an offset of 1.27 mm, which is the channel thickness.

For the range of velocity used in this experiment the deflections do not suddenly increase as predicted by Miller. The plates do not start deflecting in one direction and increase until collapse. It can be seen that they can actually deflect in one direction and then reverse the direction of deflection. Based on the assumption of parallel flow between plates this makes sense. When the channel dimension is decreased the pressure increases which then increase the channel dimension. As was pointed out by Swinson this leads to a stable flow as opposed to the prediction of unstable flow which Miller's theory is based on. Figure 11 shows the relationship between plate deflection and scaled plate pressure for the central plate at the entrance. The scaled pressure is based on the relationship between the

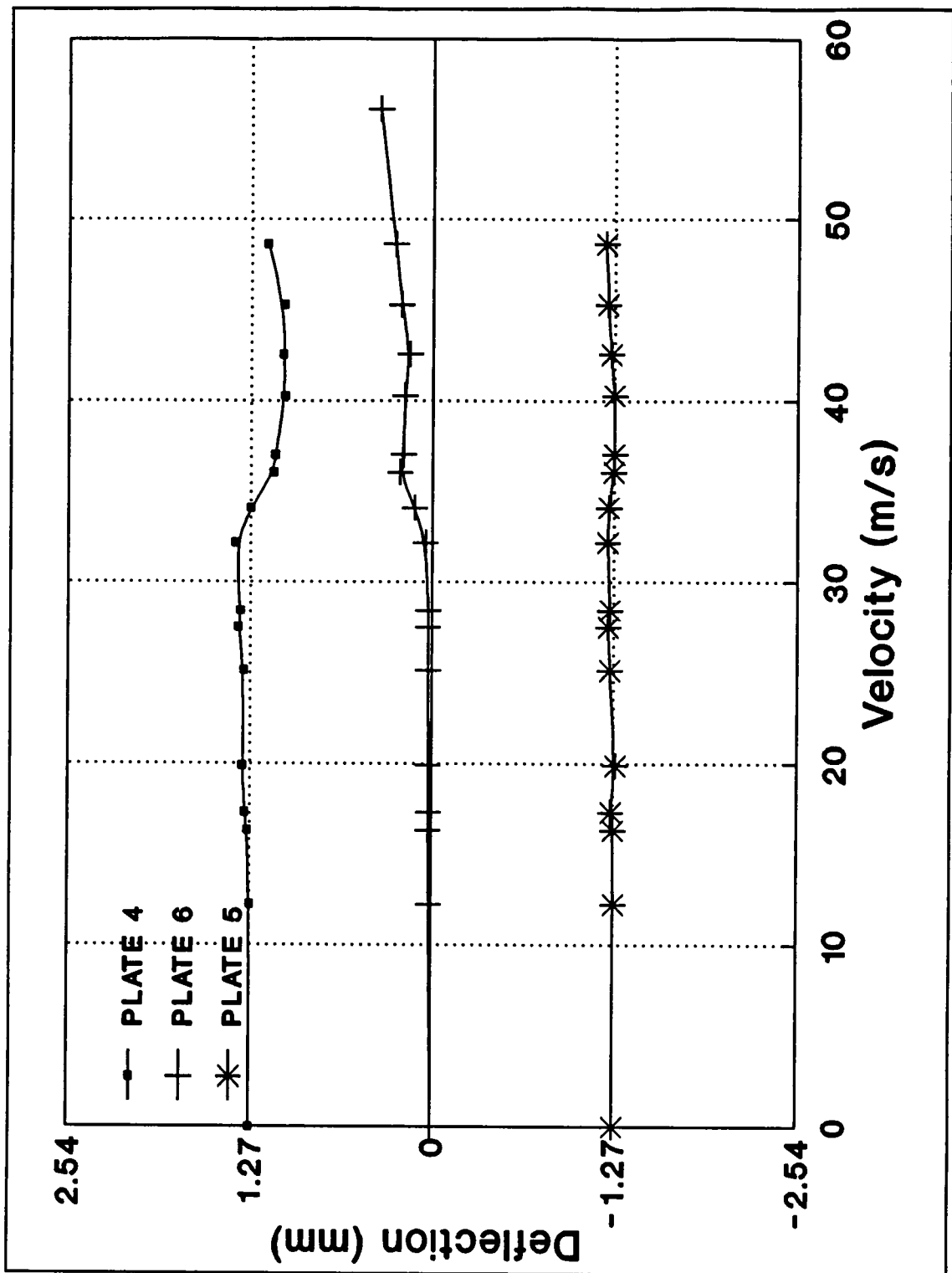


Fig. 6. Upper Fuel Plate Deflection at Entrance

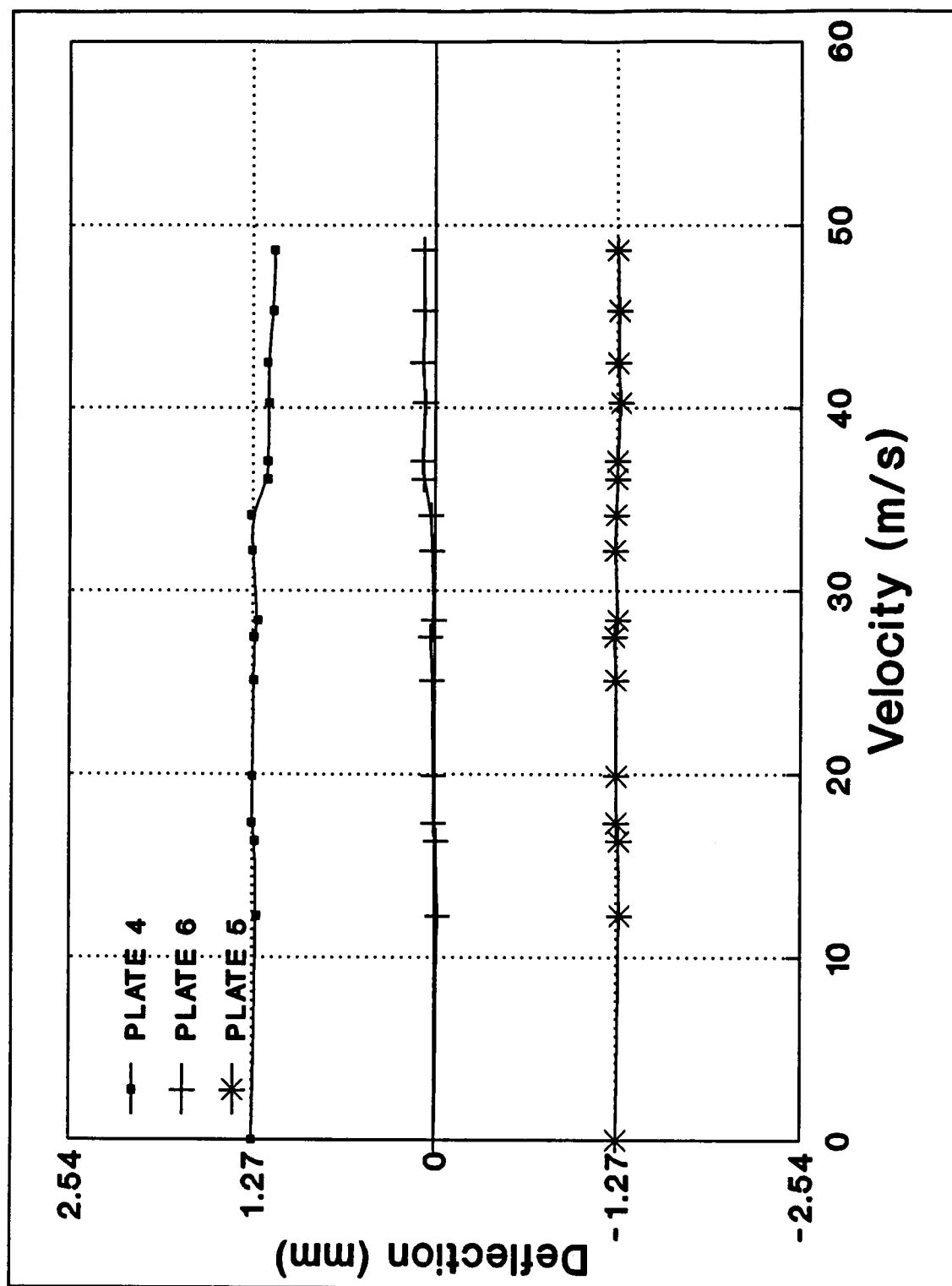


Fig. 7. Upper Fuel Plate Deflection at One-Quarter Point

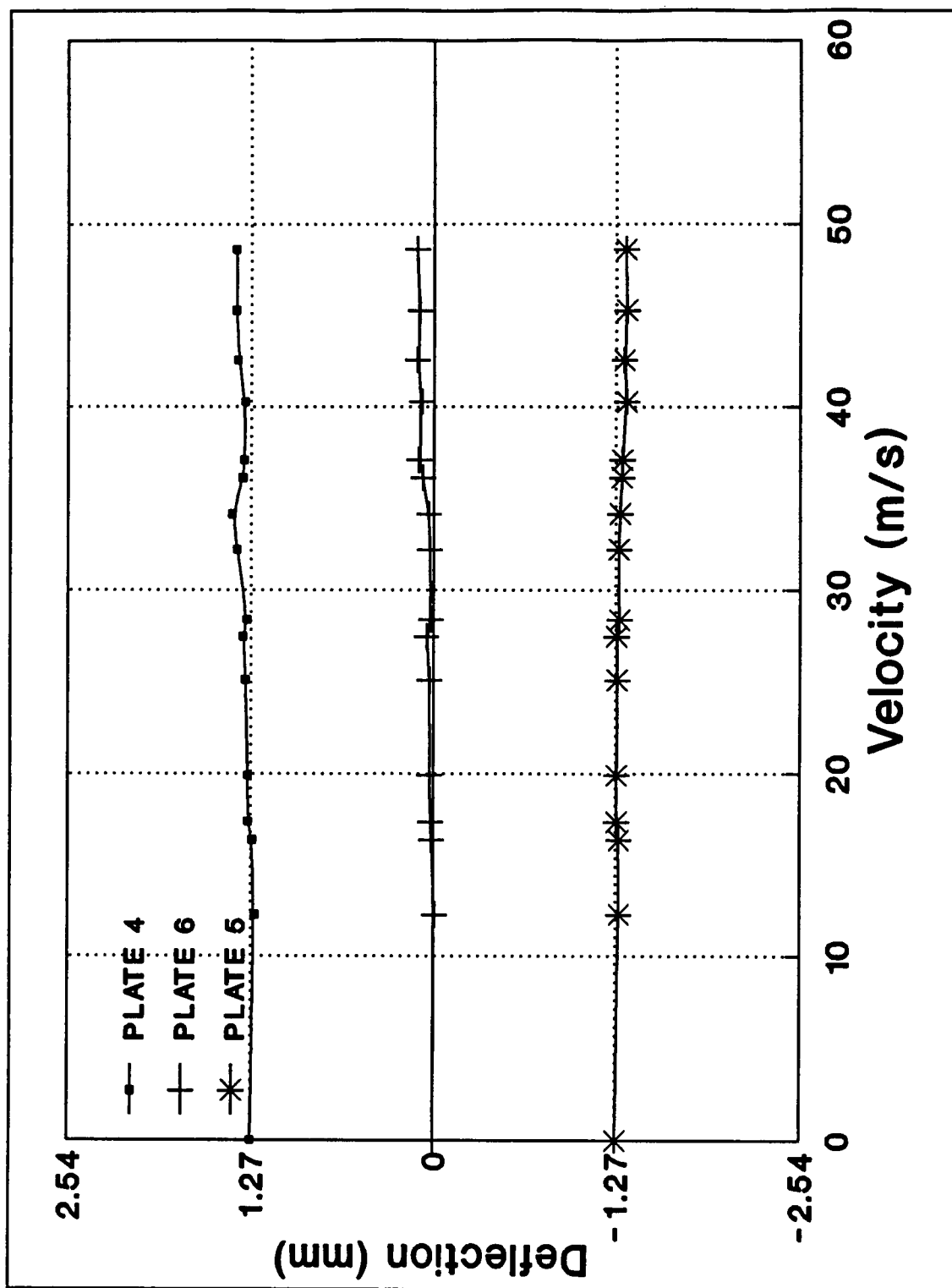


Fig. 8. Upper Fuel Plate Deflection at One-Half Point

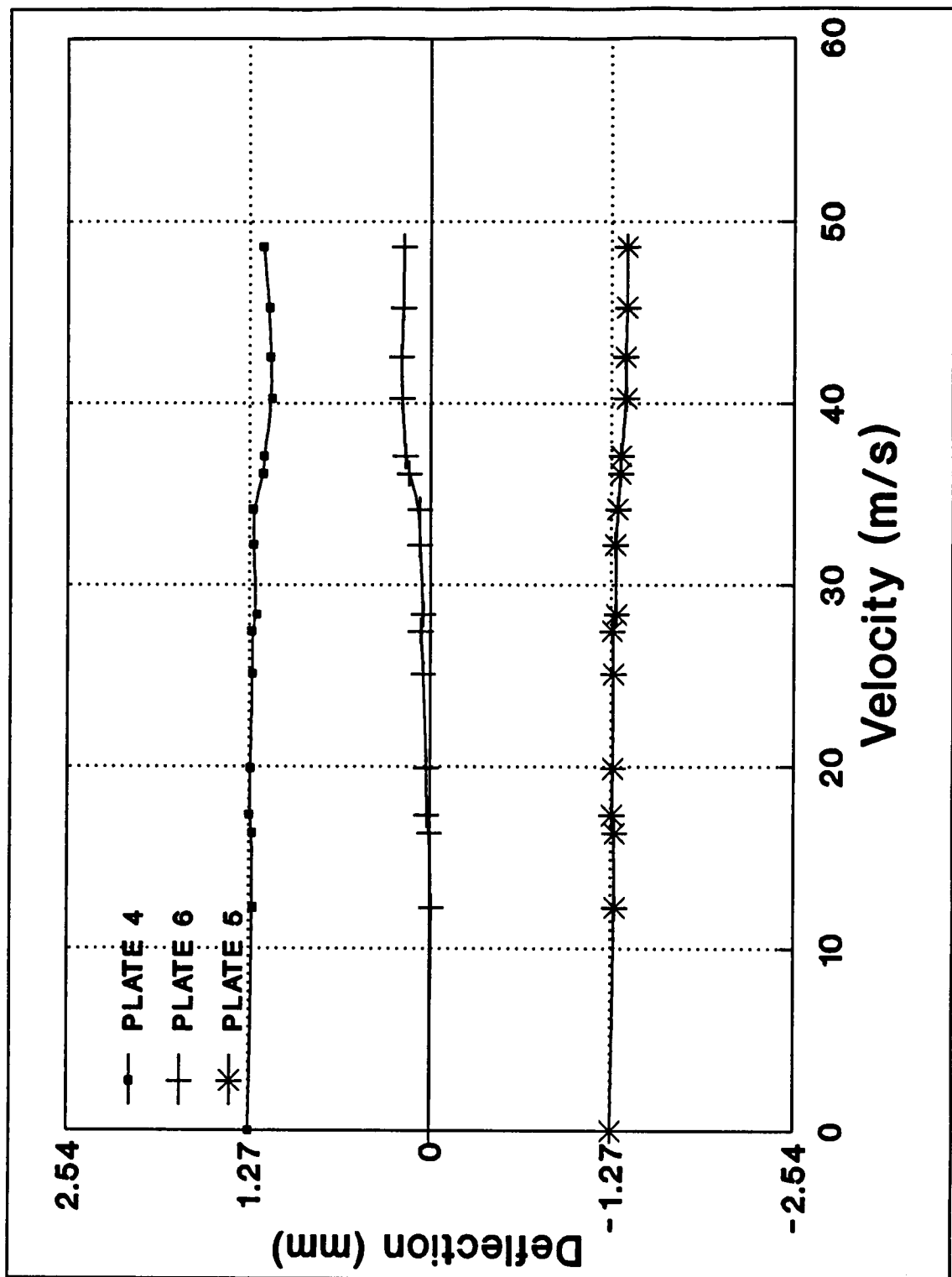


Fig. 9. Upper Fuel Plate Deflection at Three-Quarter Point

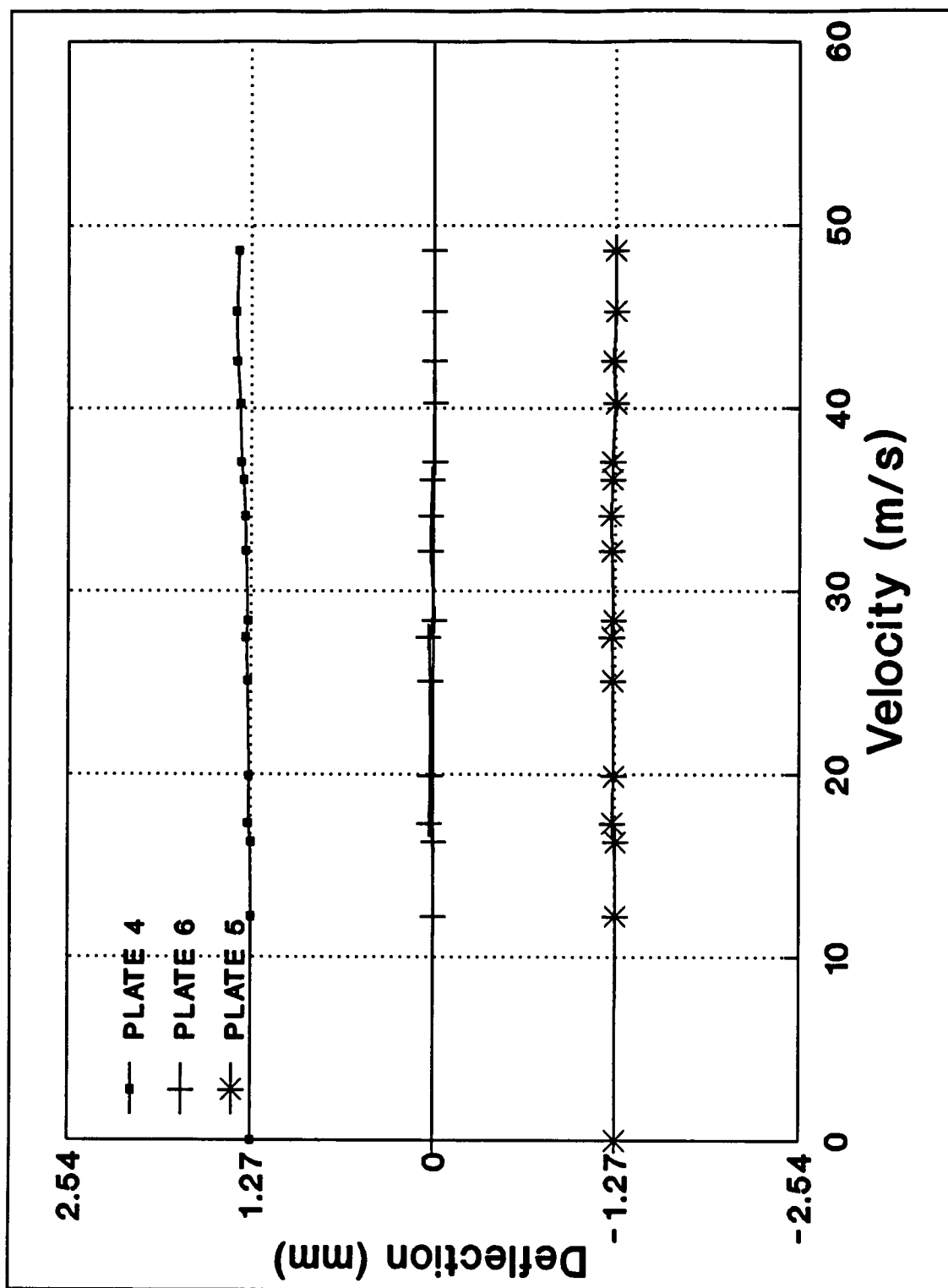


Fig. 10. Upper Fuel Plate Deflection at Exit

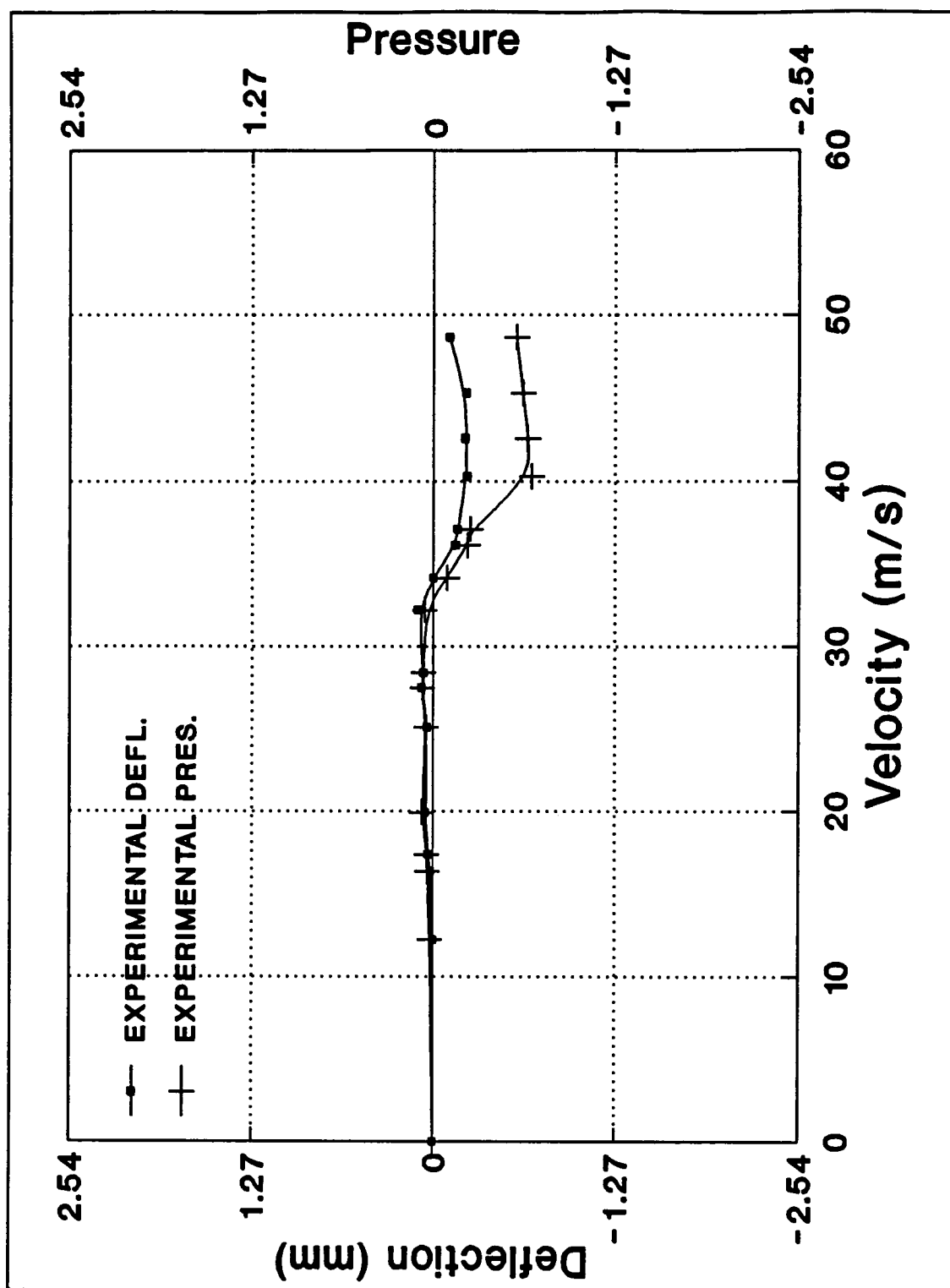


Fig. 11. Upper Fuel Plate Deflection and Pressure at Entrance

pressure and deflection of the plate found when the strain gages were calibrated. From this figure it can be seen that there is a close relationship between deflection and pressure.

The results from the test on the lower element fuel plates are similar to those for the upper element. For the upper fuel plate test the maximum deflection was again found at the entrance. This time the plate with the maximum deflection was not the central plate, but one of the plates adjacent to the central plate. The maximum deflection in the central plate was found $3/4$ of the way down the plate. The maximum deflection in the plates at the entrance was 0.917 mm at a velocity of 53.7 m/s. The maximum deflection of the central plate $3/4$ of the way down the plate was 0.833 mm at a velocity of 53.7 m/s. The deflections of the three central plates for the lower element can be seen in Fig. 12 through 16. These figures show the deflection of the plates at the five locations of the strain gages. In these figures a zero deflection for each plate would show up as a 1.27 mm offset. This 1.27 mm accounts for the thickness of the channel.

The tests on the lower fuel plates were run up to a velocity of 53.7 m/s. As can be seen in Figs. 12 through 16 as the velocity increased the magnitude of the deflection tended to increase. These test showed that the maximum deflection for each plate does not necessarily occur at the entrance. Figure 17 shows that as in the upper fuel plates the deflection and pressure are closely related. This figure

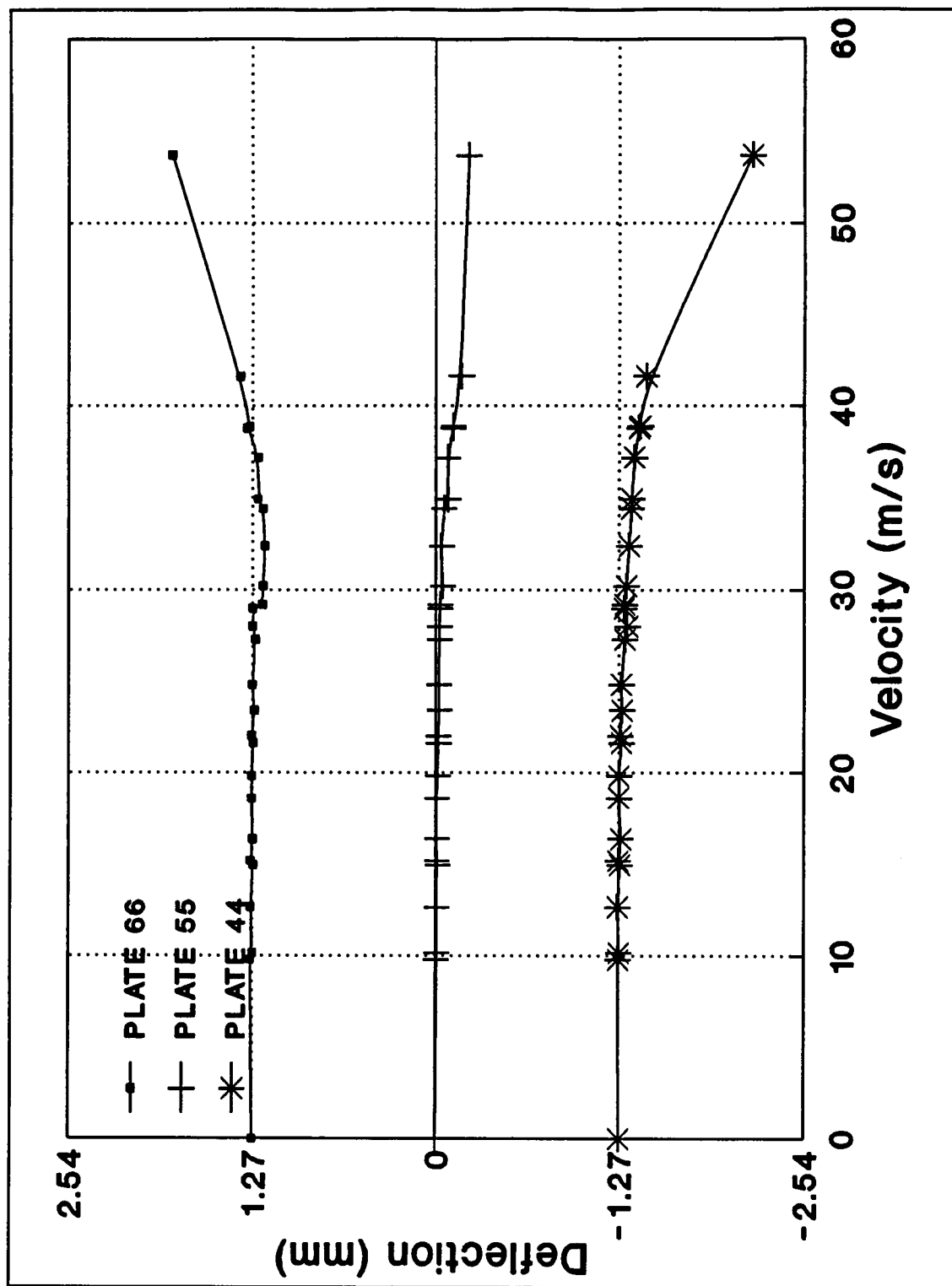


Fig. 12. Lower Fuel Plate Deflection at Entrance

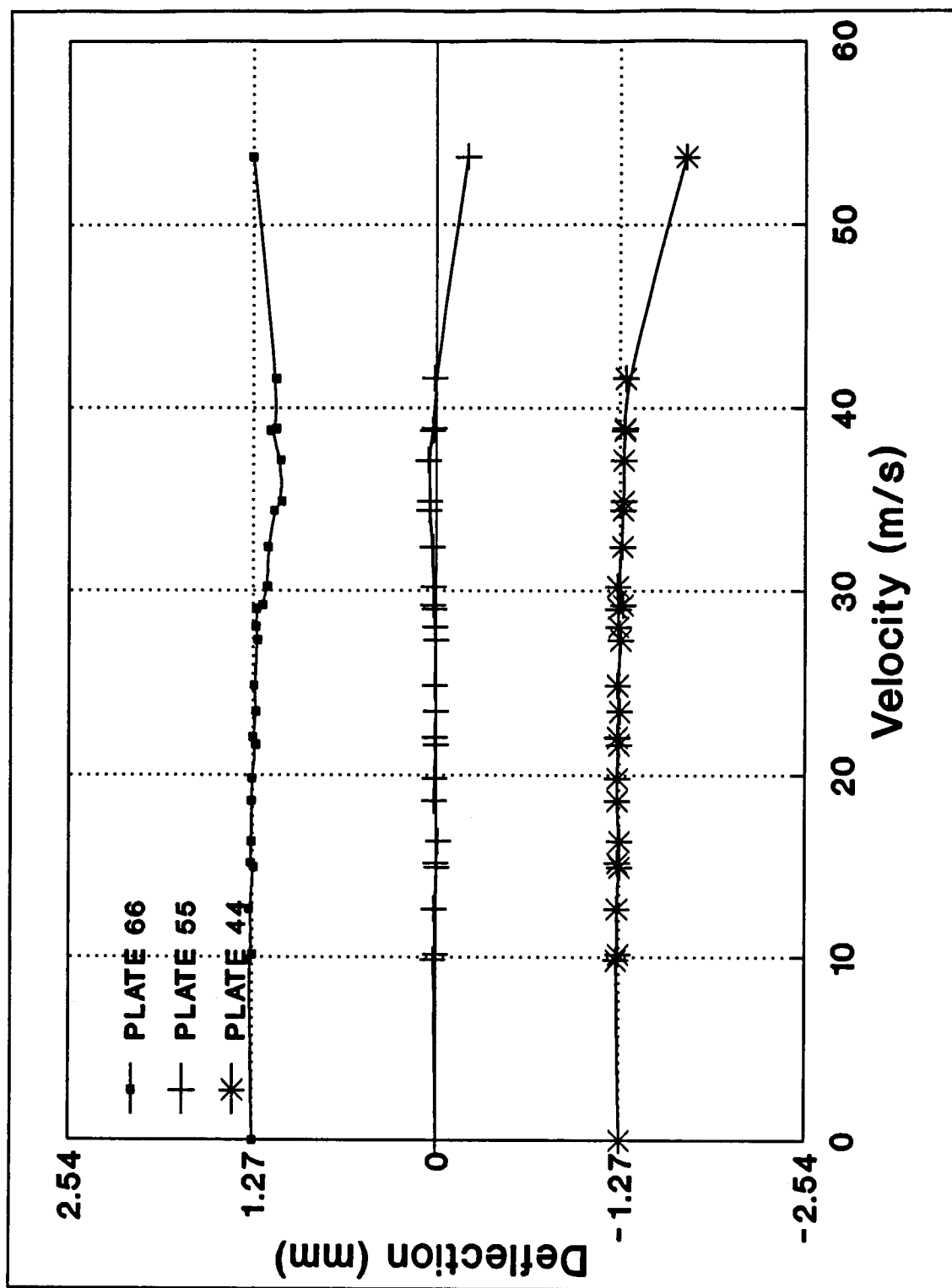


Fig. 13. Lower Fuel Plate Deflection at One-Quarter Point

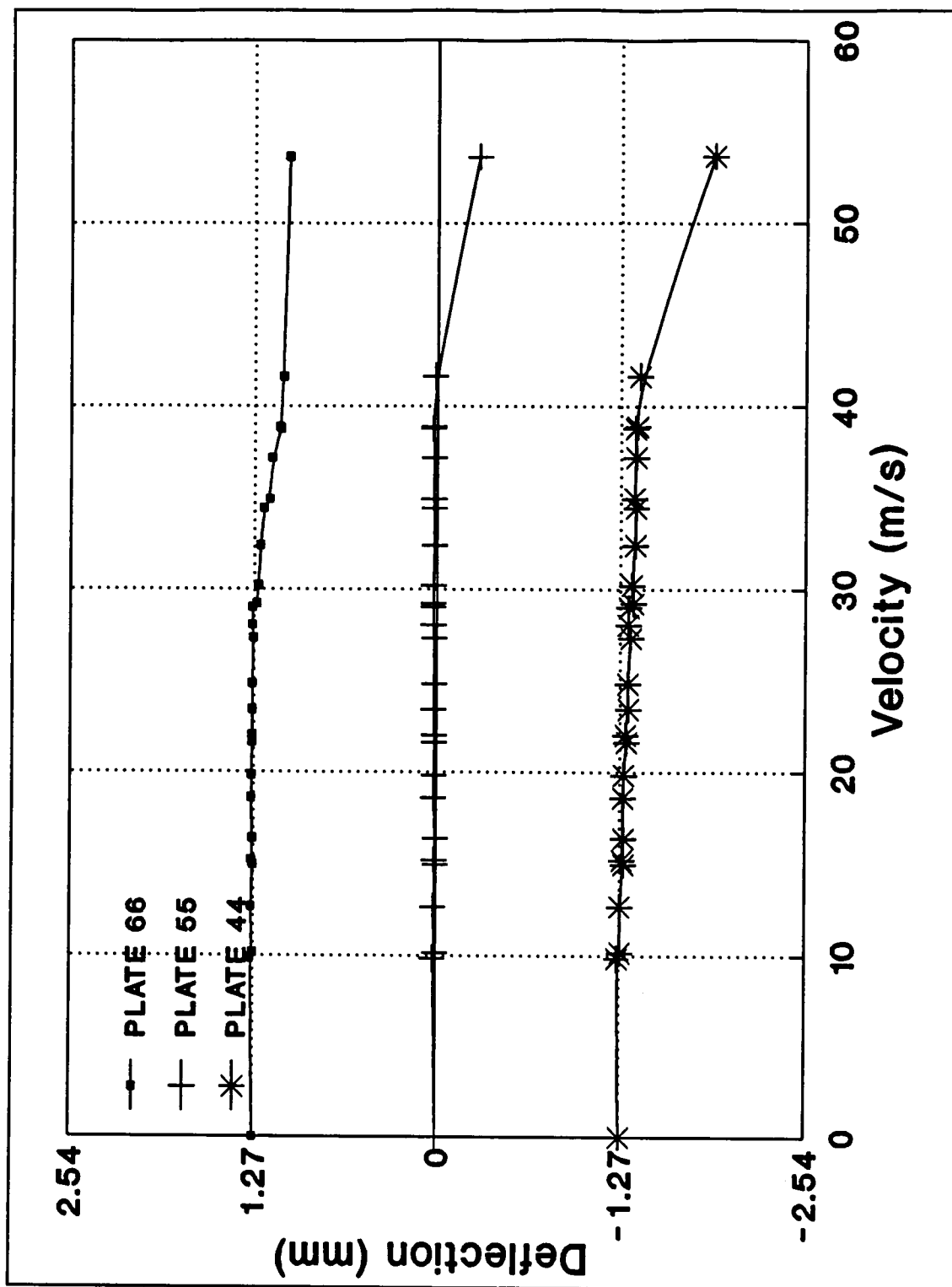


Fig. 14. Lower Fuel Plate Deflection at One-Half Point

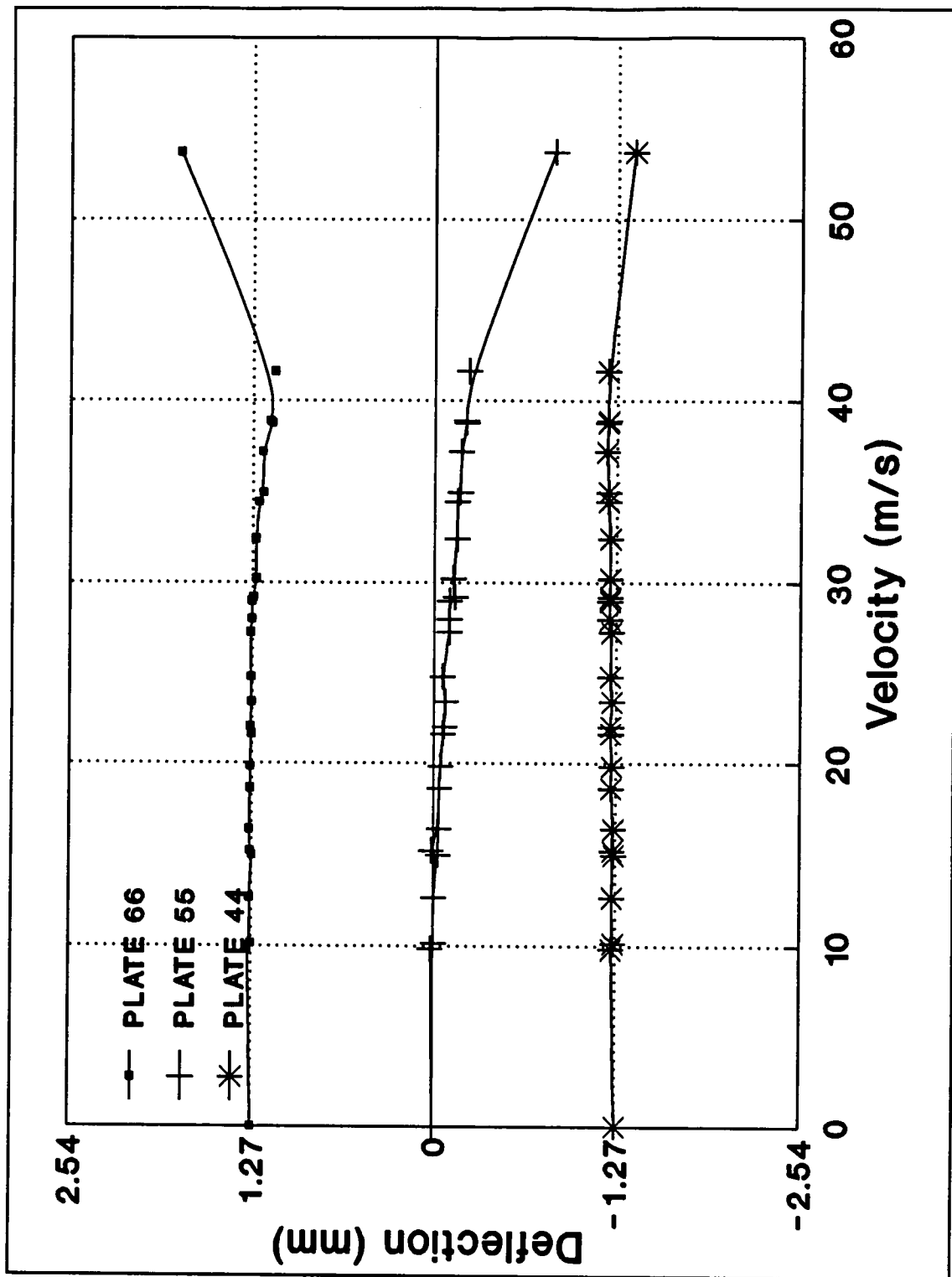


Fig. 15. Lower Fuel Plate Deflection at Three-Quarter Point

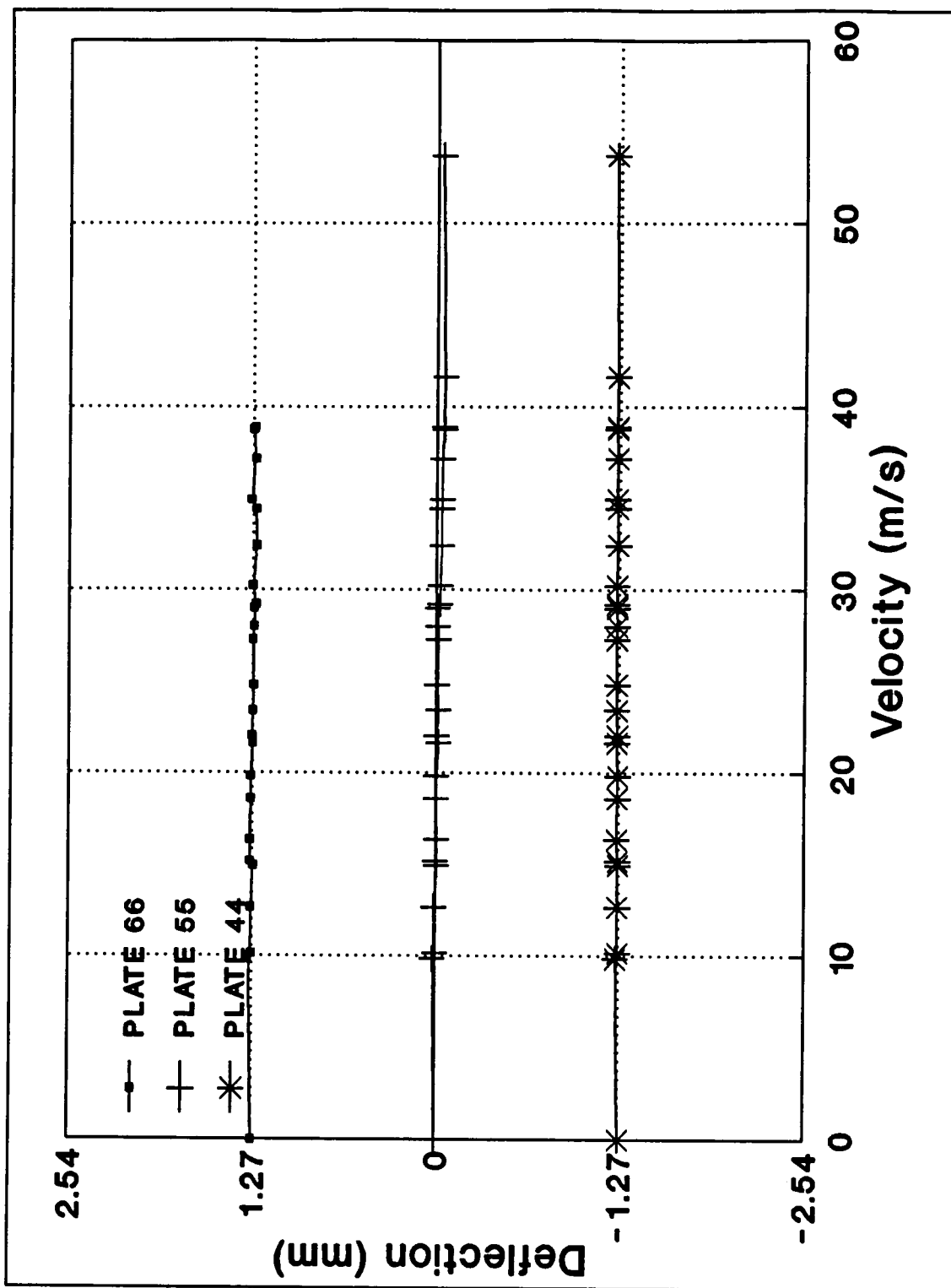


Fig. 16. Lower Fuel Plate Deflection at Exit

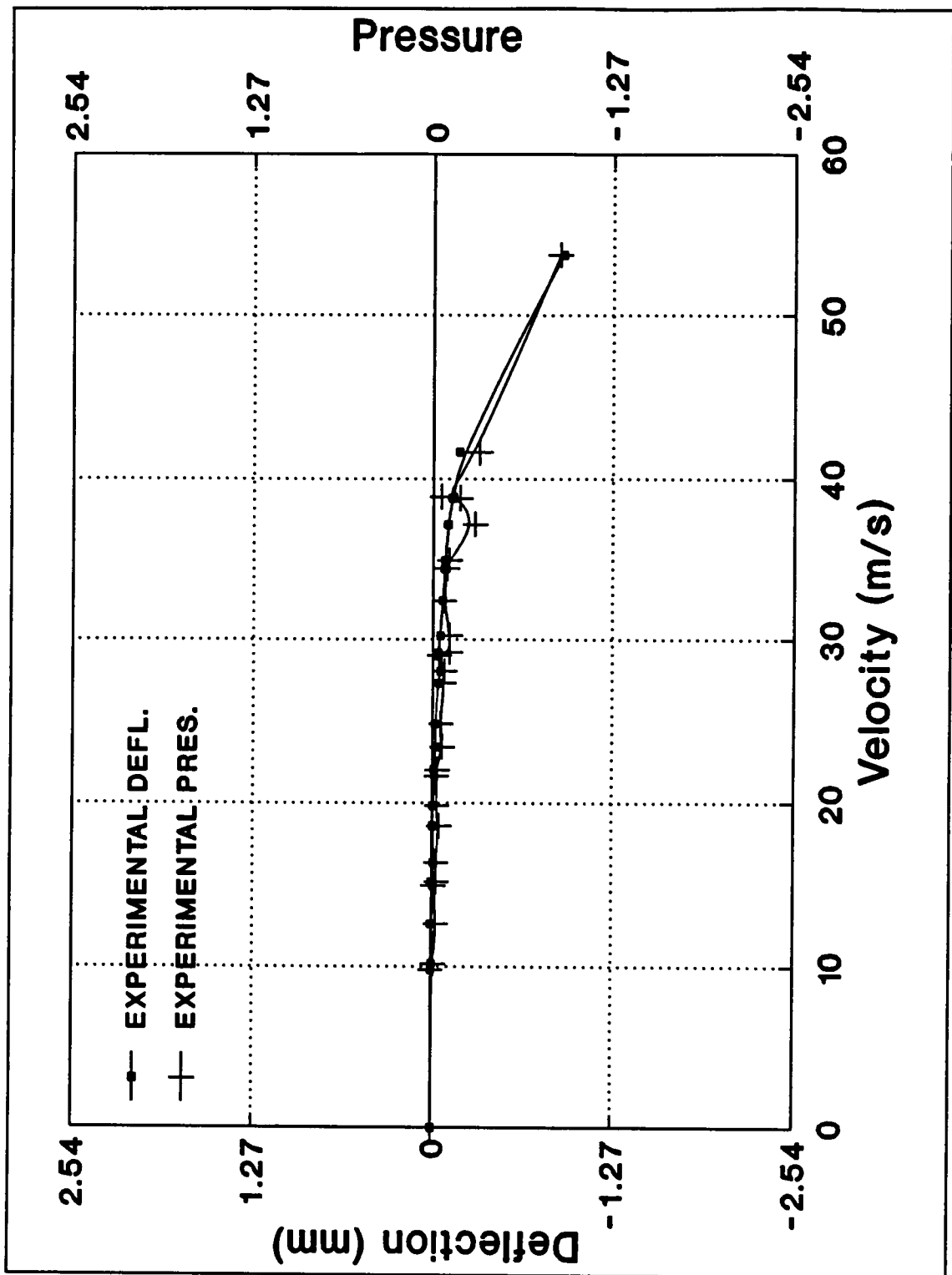


Fig. 17. Lower Fuel Plate Deflection and Pressure at Entrance

shows the relationship for the plate adjacent to the central plate at the entrance.

The test on the upper and lower elements show that there is not a sudden increase in deflection leading to collapse. Figures 12 through 16 for the lower element and Figs. 6 through 10 for the upper element show that the deflections in the plates at a given location can actually change direction as the velocity is increased. This phenomena can be explained by the parallel flow theory which assumes that the head lost in each channel is equal. From this assumption it can be found that when a channel thickness is decreased the flow velocity is less in the smaller channel which leads to higher pressure in the smaller channel. The higher pressure in the smaller channel tends to increase the channel thickness. The experimental work does not support the theories based on Miller's work which assume unstable conditions. The deflections in the plates appear to be stable.

VI. FLOW BETWEEN PARALLEL PLATES

One method of analyzing flow between parallel plates is by following the method of fully developed flow in circular channels. For turbulent flow in a noncircular channel an approximation can be made by converting the noncircular channel to a "circular" channel by using an equation for a hydraulic diameter.

The hydraulic diameter is found by taking the dimensions of the noncircular channel and determining an equivalent diameter. The equation for the hydraulic diameter is

$$D_h = \frac{4A}{P} = \frac{4 \times \text{area}}{\text{wetted perimeter}} \quad (3)$$

The hydraulic diameter allows the plates to be analyzed as if they were pipes by converting the area of flow into a diameter. The case with several plates in parallel can be examined as if it was a pipe system with branches in parallel.

Flat plates and involute plates can be analyzed using this method to determine the change in pressure between adjacent plates. The first thing that needs to be determined for this type of calculation is an imperfection in the channel dimensions. Next the hydraulic diameter for each channel is determined based on the assumed imperfection. For the case of three plates with two channels, shown in Fig. 18, two different hydraulic diameters were calculated. For the two

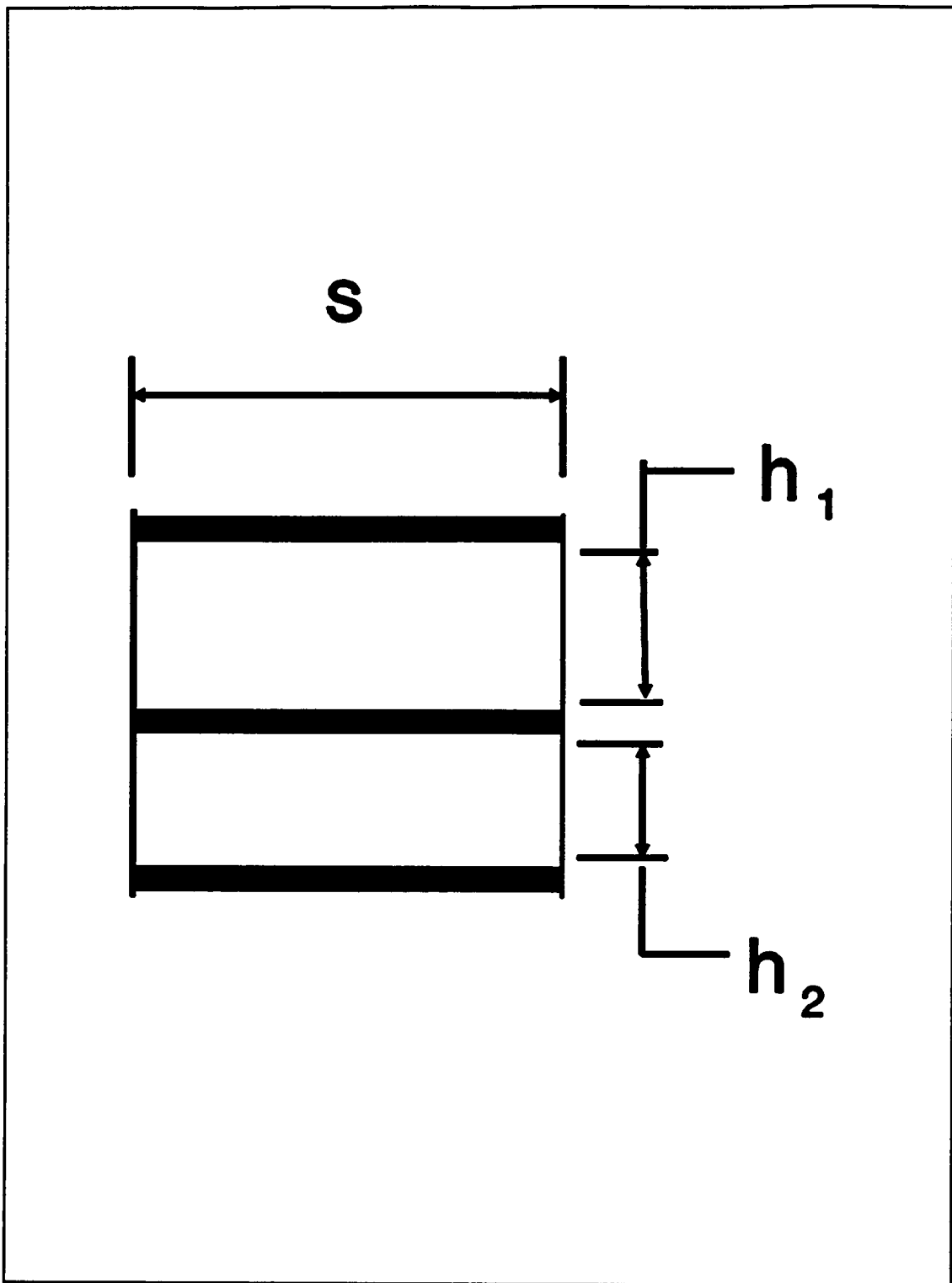


Fig. 18. Two Channels for Hydraulic Diameter Calculation

channels the hydraulic diameters are

$$D_{h1} = \frac{4sh_1}{2s+2h_1} \quad (4)$$

$$D_{h2} = \frac{4sh_2}{2s+2h_2} \quad (5)$$

where s is the span length of the plates and h_1 and h_2 are the two channel gaps. The discharge in each channel can be determined by solving the equation of the ratio of discharge in each channel and the equation of total discharge simultaneously. The ratio of discharge in each channel is found from the equation

$$\frac{Q_1}{Q_2} = \left(\frac{D_{h1}}{D_{h2}} \right)^{\frac{5}{2}} \times \sqrt{\frac{f_2}{f_1}} \times \sqrt{\frac{L_2}{L_1}} \quad (6)$$

Equation 6 is based on the fact that the total head in each channel is equal. The equation of total discharge is

$$Q = Q_1 + Q_2 \quad (7)$$

Initially the friction factors, f_1 and f_2 , are unknown so it is assumed that they are equal. Equation 6 becomes

$$\frac{Q_1}{Q_2} = \left(\frac{D_{h1}}{D_{h2}} \right)^{\frac{5}{2}} \quad (8)$$

when the above assumption is combined with the fact that the length of the channels are equal. Using Equations 7 and 8 an initial value for the discharge in each channel is calculated. From these values a Reynolds number

$$N_r = \frac{D_h V}{\nu} = \frac{Q}{\frac{\pi}{4} \nu D_h} \quad (9)$$

can be determined. Using Reynolds number and the value of the reciprocal of the relative roughness, D_h/k , a value for the friction factor can be determined. Once an initial estimate of the friction factor has been determined Equations 6 and 7 can be solved simultaneously to determine new values for the discharge from each channel. The above steps are repeated using the new values of Q until the value for Q in two consecutive iterations are approximately the same. The velocity in each channel is determined by

$$V = \frac{Q}{\frac{\pi}{4} D_h^2} \quad (10)$$

From the velocities in adjacent channels the pressure difference between the channels can be determined using

$$P_2 - P_1 = \frac{\rho (V_1^2 - V_2^2)}{2g} \quad (11)$$

Equation 11 is derived from Bernoulli's equation assuming that the total head in each channel is equal.

For cases with multiple plates and multiple channels Equation 6 must be repeated for each additional channel and Equation 7 must be modified to include the discharge from the additional channels. For example if there were four channels the following equations would be necessary instead of Equation 6

$$\frac{Q_2}{Q_1} = \left(\frac{D_{h2}}{D_{h1}} \right)^{\frac{5}{2}} \times \sqrt{\frac{f_1}{f_2}} \times \sqrt{\frac{L_1}{L_2}} \quad (12)$$

$$\frac{Q_3}{Q_1} = \left(\frac{D_{h3}}{D_{h1}} \right)^{\frac{5}{2}} \times \sqrt{\frac{f_1}{f_3}} \times \sqrt{\frac{L_1}{L_3}} \quad (13)$$

$$\frac{Q_4}{Q_1} = \left(\frac{D_{h4}}{D_{h1}} \right)^{\frac{5}{2}} \times \sqrt{\frac{f_1}{f_4}} \times \sqrt{\frac{L_1}{L_4}} \quad (14)$$

and Equation 15

$$Q=Q_1+Q_2+Q_3+Q_4 \quad (15)$$

would be used instead of Equation 7. The deflection of the plates due to this pressure difference can be found either by a finite element analysis or by a scale determined experimentally.

The results of the calculations done using the hydraulic diameter method vary depending on the imperfection that is assumed. The limiting values for pressure difference between the channels is Swinson's dynamic pressure. For his dynamic pressure calculation it is assumed that the flow in one channel approaches zero. For this case Equation 11 becomes

$$P_2-P_1=\frac{\rho V_1^2}{2g} \quad (16)$$

which is the same as Equation 2.

VII. COMPARISON OF METHODS

Various methods have been discussed for analyzing hydraulically induced deflections in closely spaced fuel plates. Of the methods discussed the ones applicable to involute shaped fuel plates are the Gwaltney and Luttrell method of extending Miller's theory to involute shaped plates, Sartory's methods which included friction effects and contraction and expansion losses, Swinson's dynamic pressure method and the method of converting the parallel plates to pipe systems by use of a hydraulic diameter.

One way of evaluating the above methods is by comparing them to experimental work performed on closely spaced plates. The only experimental work that has been performed on involute shaped plates is that which was described in this thesis earlier. Therefore the only comparison that can be made between the theory and actual data for involute shaped plates is with this experiment. Several people have performed experiments on flat plates. The theories developed for involute shaped plates should compare to flat plate data as well as the data on involute shaped plates. In looking over the experimental work which has been done on flat plates it appears that the experiments by Groninger and Kane, and the experiments by Smissaert are the most reliable. Comparisons will be made with these two flat plate experiments and with the experiment performed on the involute shaped plates.

Comparison with Groninger and Kane's Experiment

Groninger and Kane reported on data from 3 assemblies each containing 5 plates and 6 channels. Comparisons will be made here with their data for the solid Zircaloy plate in a cold loop. Miller's critical velocity for this plate is 6.3 m/s. Gwaltney and Luttrell's method should give the same results as Miller's method. Figure 19 shows a comparison of Groninger and Kane's experimental plate which deflected the maximum amount at the entrance with various methods described previously.

In comparing the experimental results to Miller's critical velocity it can be seen that there is not a sudden collapse at 6.3 m/s. The results from Sartory's method depend on the friction number which is chosen. For a friction number of 0 his results are the same as Millers. He shows that as the friction number is increased to about 6 the critical velocity is about 2 times Miller's critical velocity. For this range of friction factors the critical velocity would change from 6.3 m/s to about 12.6 m/s. In this range there is no sudden collapse. Instead of a sudden collapse the plate deflection continues to steadily increase as the velocity is increased, although at about 1.9 times Miller's critical velocity Groninger and Kane report a high amplitude flutter. The velocity at which this occurs would seem to agree with Sartory's case with a friction factor of 6, but he is predicting a collapse and this is not what is occurring.

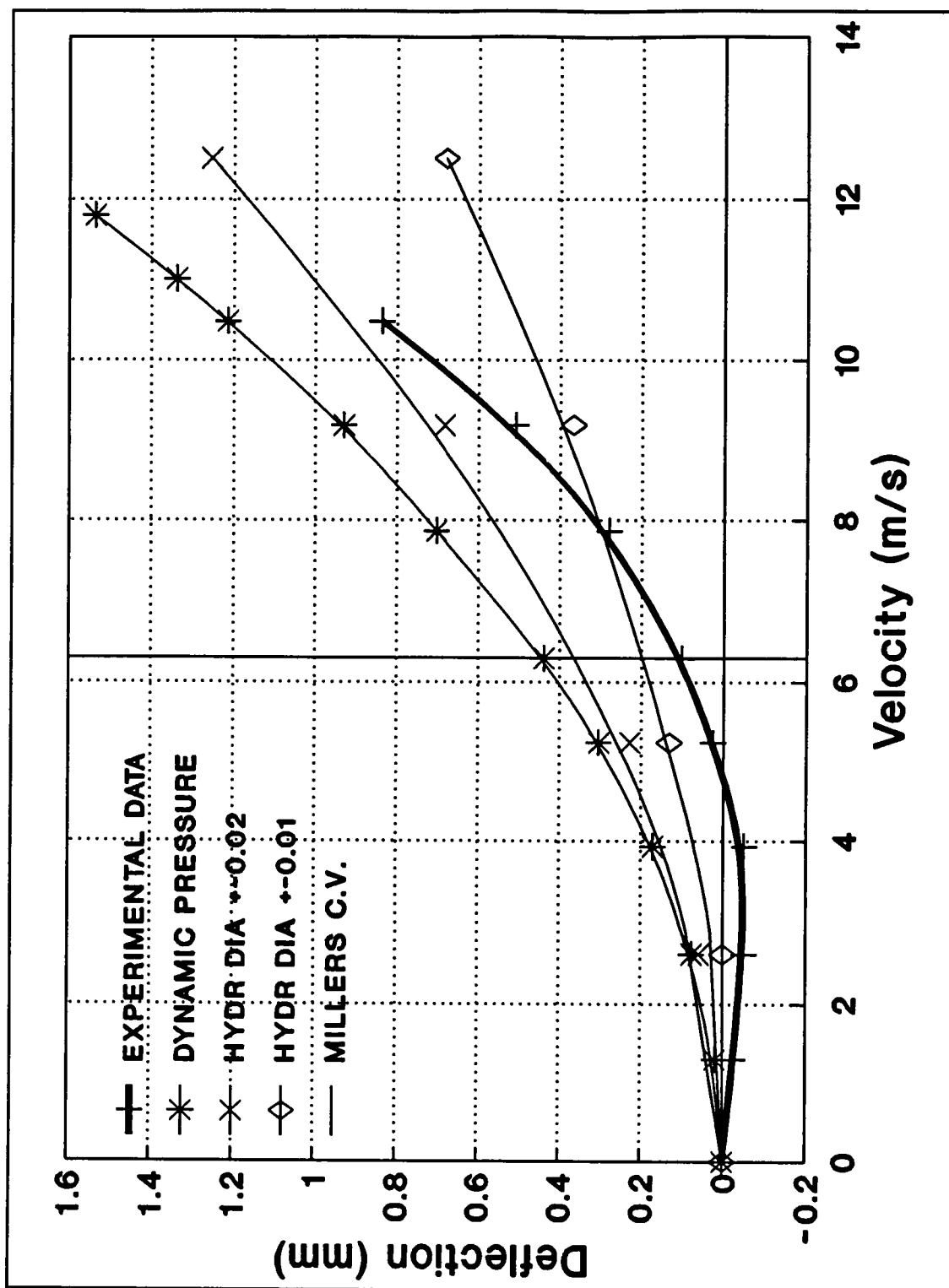


Fig. 19. Comparison to Groninger and Kane's Experiment

Figure 19 also shows the results of the experiment compared with the dynamic pressure method and the hydraulic diameter method. The results from the experiment all fall below the values calculated using the dynamic pressure method. There are two results from the hydraulic diameter method shown in this figure. As was discussed earlier for the hydraulic diameter method the first thing that needs to be done is to assume a channel imperfection. The two hydraulic diameter cases in Fig. 19 are for a channel with a 1.778 ± 0.254 mm gap and for a channel with a 1.778 ± 0.508 mm gap. In examining these results the case with the larger imperfection does contain all of the experimental data points, but the case with the smaller imperfection is only larger than the experimental deflection up to a velocity of about 8 m/s.

Groninger and Kane's experiment does not validate the idea of a sudden collapse. The dynamic pressure method does appear to be a limiting case. Using the hydraulic diameter a closer value of the deflection can be found assuming that the correct imperfection is chosen.

Comparison with Smitsaert's Experiment

Smitsaert also performed experiments on 3 flat plate assemblies. His assemblies had various numbers of plates and channels with the channel dimension varied in each assembly. He reported data on the case with 5 plates and 6 channels with a large channel gap. Figure 20 shows the results from this

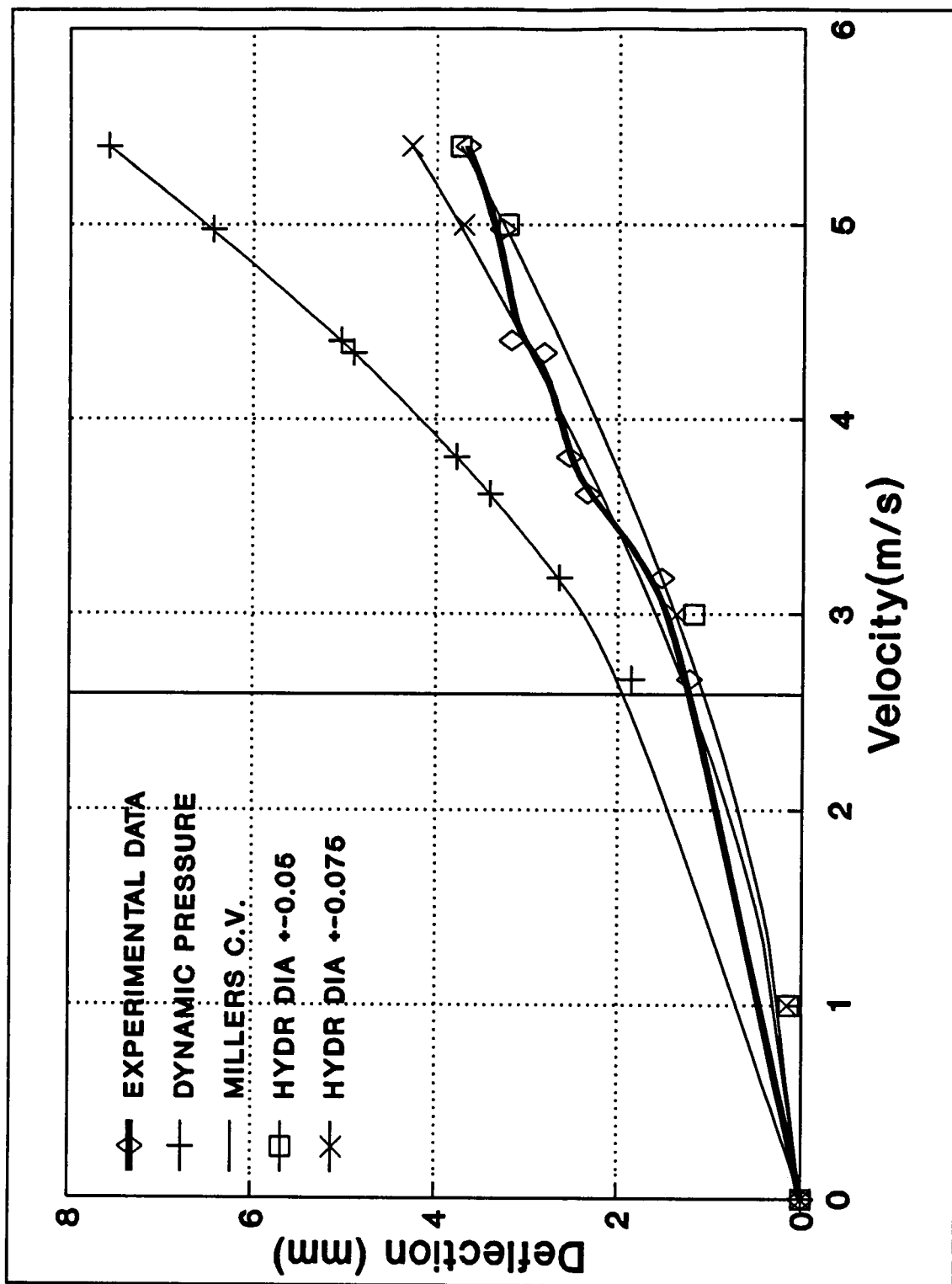


Fig. 20. Comparison to Smitsaert's Experiment

assembly at the entrance.

Miller's critical velocity for this plate is 2.6 m/s. As in Groninger and Kane's experiment there is not a sudden collapse at this velocity. Sartory's results, which depend on the choice of friction number, range from 2.6 m/s to about 5.2 m/s. At a velocity of about 2 times Miller's velocity Smitsaert reported that the plates began to flutter. This velocity does agree with Sartory's velocity with a friction factor of about 6, but this occurrence of flutter is not a collapse as predicted by the Sartory's model.

The dynamic pressure method and the hydraulic diameter method are compared with Smitsaert's experiment in Fig. 20. As was seen in comparisons with Groninger and Kane's data the dynamic pressure method bounds the data from Smitsaert's experiment. For this experiment the hydraulic diameter method was compared to the data assuming an imperfection of ± 1.27 mm and an imperfection of ± 1.905 mm. The deflections from the case with the larger imperfection follow along closely with the experimental data. The case with the smaller imperfection is slightly below the experimental data.

Smitsaert's experimental plate does not undergo a sudden collapse. The results of his plate deflection in general gradually increase as the velocity is increased. As in Groninger and Kane's experiment the dynamic pressure method is an upper limit.

Comparison with ANS Lower Element Experiment

The maximum deflection found from the experiment run on the ANS Lower Element assembly was on the plate adjacent to the central plate at the entrance. The deflection of this plate vs fluid velocity is shown in Fig. 21. This figure shows the experimental results compared to several methods used to evaluate the deflection in involute plates due to fluid flowing between the plates.

In comparing these experimental results to the methods based on sudden collapse the deflection does appear to increase more quickly in the region of the predicted collapse. The method developed by Gwaltney and Luttrell predict collapse at 44.7 m/s. Sartory's original method predict collapse at 49.4 m/s. Figure 22 shows the deflection of the central plate at the entrance. For this plate the maximum deflection is not at the entrance, but 3/4 of the way down the plate. Figure 22 does not show the increase in deflection in the range of the predicted critical velocities.

Figures 21 and 22 show that the dynamic pressure method does still create an upper bound for the deflection of these plates in the range of velocities studied. The hydraulic diameter method was compared to the lower element plates with an imperfection of ± 0.127 mm and an imperfection of ± 0.254 mm. For the plate adjacent to the central plate shown in Fig. 21 the deflection calculated using the hydraulic diameter method is larger than the actual deflection until about 42 m/s. For

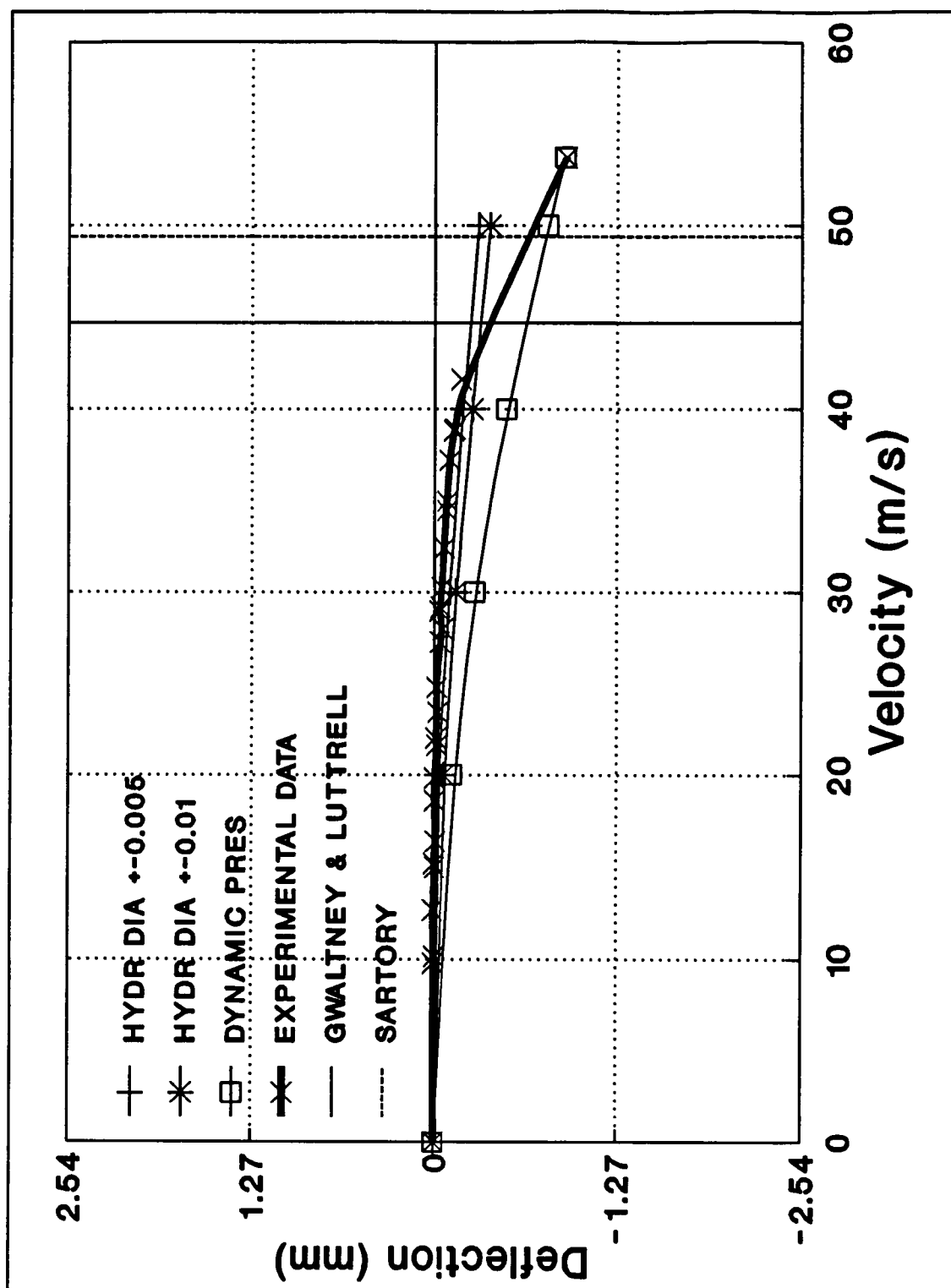


Fig. 21. Comparison to Lower Plate with Maximum Deflection

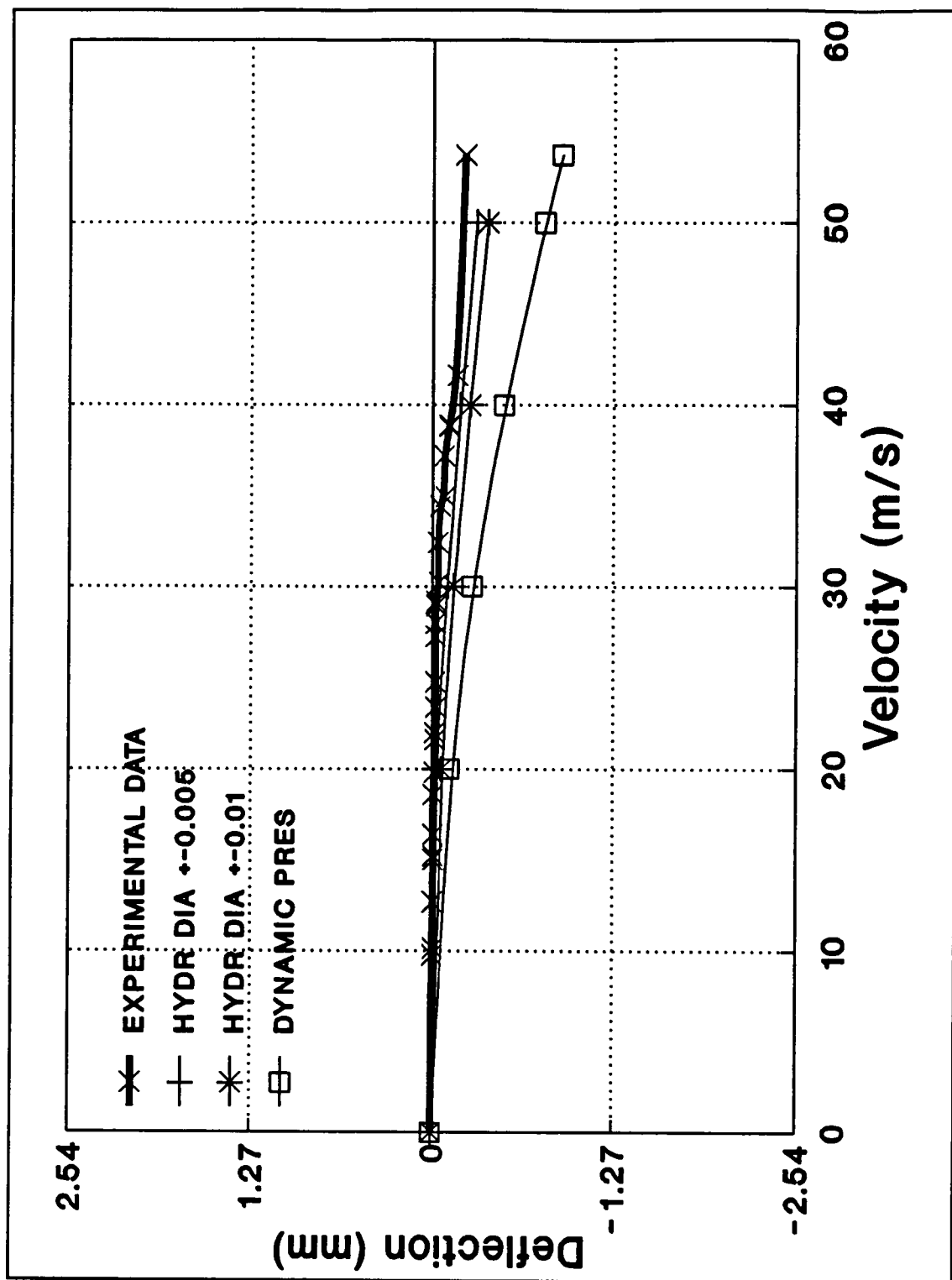


Fig. 22. Comparison to Central Lower ANS Plate

the central plate the hydraulic diameter calculations bounds the experimentally determined deflections.

Comparison with ANS Upper Element Experiment

In the experiment performed on the involute plates shaped like the plates being considered for the ANS Upper element the maximum deflection was on the central plate at the entrance. Figure 23 shows the deflection of the central plate at the entrance compared to various calculated deflections.

The method developed by Gwaltney and Luttrell which extends Miller's theory to an involute shaped plate predicts a collapse at 49.4 m/s. Examining Fig. 23 it can be seen that the plate does not undergo a sudden collapse at 49.4 m/s.

Sartory studied the ANS upper element using the second method he developed. For this method he had to assume an imperfection. Sartory examined the cases with a 0% imperfection, a 1% imperfection, a 10% imperfection and a 30% imperfection. From these analyses he found the range of collapse velocities was between 45 m/s for a 0% imperfection to about 37 m/s for a 30% imperfection. Figure 23 shows that there is no sudden collapse as predicted by Sartory up to a velocity of 56.12 m/s.

Swinson's dynamic pressure method is an upper bound for deflection of the ANS upper fuel plate. At a velocity of 36.12 m/s the experimental deflection approaches the dynamic pressure deflection, but it then decreases slightly.

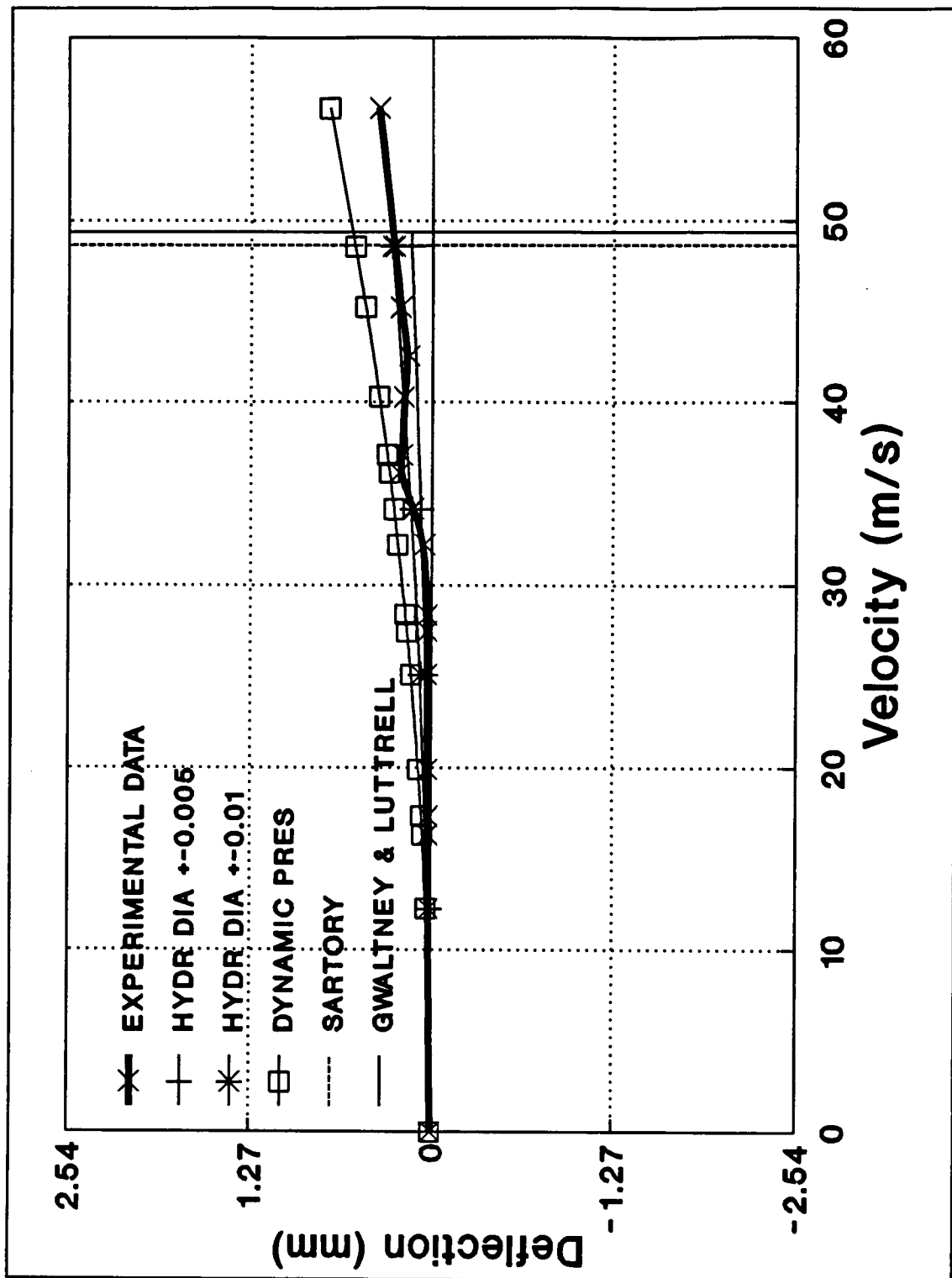


Fig. 23. Comparison to Central Upper ANS Plate

To perform the calculation of the deflection in the ANS upper element using the hydraulic diameter method two different imperfections in the channel gap were assumed. One case assumed the channel gap was 1.27 ± 0.127 mm and the other case assumed the channel gap was 1.27 ± 0.254 mm. The deflection for both of these cases is more than the experimental deflection up to a velocity of about 32 m/s. Above this velocity the deflection from the case with the larger imperfection is very similar to the experimental values. The case with the smaller imperfection shows values of deflection slightly below the experimentally determined deflections.

Comparisons to this experimental work show that the assumption of instability leading to sudden collapse do not occur in the range of velocity used in the experiment. The dynamic pressure calculations are an upper limit on the plate deflection.

VIII. CONCLUSIONS

In examining the various methods of analyzing the problem of hydraulically induced deflection in plates it does not appear that any of the methods fully explain what is actual occurring. The comparison of the methods with experimental data show that none describe exactly what is happening.

The methods based on Miller's original analyses predict that the plates undergo a sudden collapse at some velocity. In examining the experimental data there is no evidence that a sudden collapse occurs. Both the Gwaltney and Luttrell extension of Miller's theory to involute plates and Sartory's methods are based on this philosophy. Since these methods do not explain what is actually occurring they are not reliable for the basis of a design.

Swinson's method of dynamic pressure appears to be an upper limit for plate deflection. The conclusions of Swinson's analysis could be used for the design of fuel plates. The values of deflection calculated from this method are conservative. From the dynamic pressure calculations the velocity that causes the plates to deflect to half the channel width can be determined. This velocity would be the velocity to be used for design purposes.

The values of deflection determined using the hydraulic diameter method are accurate for lower velocities, but at higher velocities the calculated deflections are not as

accurate. One difficulty of using this method is determining an imperfection in the channel dimensions. The results of the calculation depend on the assumption of imperfection chosen. In comparing the results to experimental data for most cases with an assumption of 30% imperfection the calculated values of deflection are higher than the experimental data for the range of velocities used. For the smaller values of imperfection the calculated deflections are still larger at low fluid velocities. This method appears to be accurate at low velocities.

None of the methods developed for analyzing the flow induced deflection problem consider the unique flow paths between the plates as a result of turbulent conditions. The affects of turbulence on closely spaced arrays of fuel plates has not been thoroughly studied. For high values of velocity turbulence is likely to have a significant affect on the plate behavior. The effects of turbulence on the plates could be the reason the hydraulic diameter method is more accurate at low velocities than high velocities. The influence that the turbulent flow conditions have on this problem is one that should be considered. This is an area in which further work on this problem could be continued.

LIST OF REFERENCES

LIST OF REFERENCES

1. D. R. Miller, "Critical Flow Velocities for Collapse of Reactor Parallel-Plate Fuel Assemblies," *J. eng. Power, Trans ASME*, 83-95, April 1960.
2. E. B. Johansson, "Hydraulic Instability of Reactor Parallel-Plate Fuel Assemblies," Paper No. 57, *Nuclear Engineering and Science Conference*, Engineers Joint Council, April 4-7, 1960.
3. F. J. Remick, *Hydraulically Induced Deflection of Flat Parallel Fuel Plates*, Ph.D. Dissertation, Pennsylvania State University, 1963.
4. R. J. Scavuzzo, "Hydraulic Instability of Flat Parallel Plate Assemblies," *Nuclear Science Engineering*, 21, 463 (1965).
5. G. E. Smissaert, "Static and Dynamic Hydroelastic Instabilities in MTR-Type Fuel Elements. Part II. Theoretical Investigation and Discussion," *Nuclear Engineering and Design*, 9, 105-122 (1969).
6. W. L. Zabriskie, *An Experimental Evaluation of the Critical Flow Velocity Formulas for Parallel Plate Assemblies*, Report No. 58GL297, General Engineering Laboratory, KAPL, October 1958.
7. R. D. Groninger and J. J. Kane, "Flow Induced Deflections of Parallel Flat Plates," *Nuclear Science and Engineering*, 16, 218-226 (1963).
8. G. E. Smissaert, "Static and Dynamic Hydroelastic Instabilities in MTR-Type Fuel Elements. Part I. Introduction and Experimental Investigation," *Nuclear Engineering and Design*, (1968).
9. R. C. Gwaltney and C. R. Luttrell, "Critical Flow Velocity for Involute Parallel Fuel Plate Assemblies," *Trans. of American Nuclear Society*, 57, 298 (1988).
10. W. K. Sartory, *Analysis of Hydraulic Instability of ANS Involute Fuel Plates*, ORNL/TM-11580, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, November 1991.

11. W. K. Sartory, *Nonlinear Analysis of Hydraulic Buckling Instability of ANS Involute Fuel Plates*, ORNL/TM-12319, Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, March 1993.
12. W. F. Swinson and G. T. Yahr, "Dynamic Pressure Approach to Analysis of Reactor Fuel Plate Stability," *Trans. of American Nuclear Society*, 61, 390, June 1990.
13. W. F. Swinson, R. L. Battiste, C. R. Luttrell, and G. T. Yahr, "Fuel Plate Stability Experiments and Analysis for the Advanced Neutron Source," *PVP-Vol. 244, Symposium on Flow-Induced Vibration and Noise*, Volume 5, 133-143, ASME 1992.
14. W. F. Swinson, R. L. Battiste, C. R. Luttrell, and G. T. Yahr, *Structural Response of Reactor Fuel Plates To Coolant Flow*, ORNL/TM-12353. Martin Marietta Energy Systems, Inc., Oak Ridge National Laboratory, April 1993.

VITA

Claire Roberta Luttrell was born in Galveston, Texas on January 11, 1963. She graduated from Oak Ridge High School in Oak Ridge, Tennessee in June, 1981. In June of 1986 she obtained her undergraduate degree from the University of Tennessee, Knoxville in Mechanical Engineering. She reentered the University of Tennessee, Knoxville in August, 1987 and received a Master of Science degree in Engineering Science in May, 1993.

She has been employed at Oak Ridge National Laboratory since July, 1986 as an Engineer working in a structural mechanics group.