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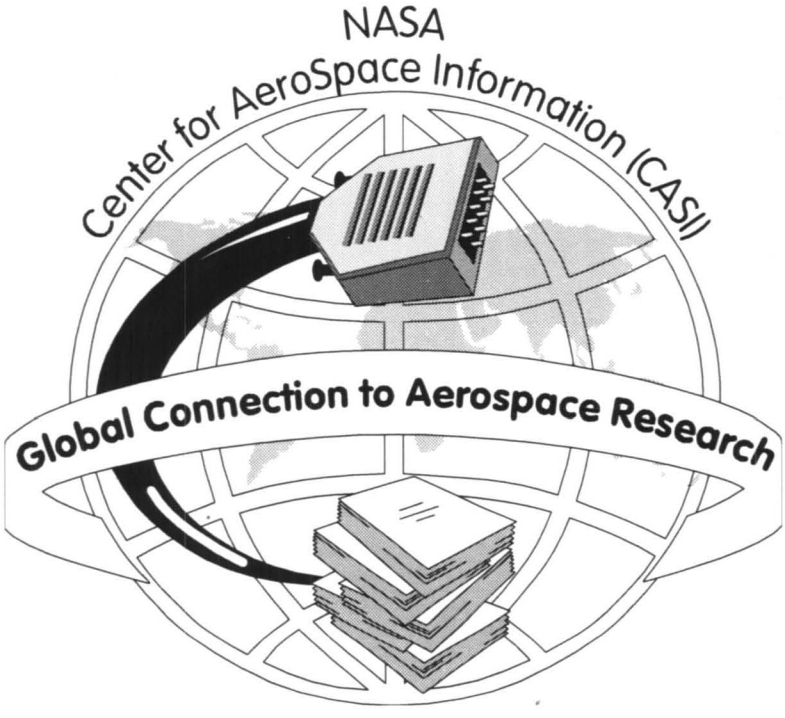

COMPUTATIONAL ANALYSIS OF SCRAMJET DUAL MODE OPERATION

Progress Report for
NASA Grant NAG-1-229
for period
May 1, 1984 - October 31, 1984

January 10, 1985

Prof. Earll M. Murman, Principal Investigator
Mr. Thomas R. A. Bussing, Graduate Research Assistant

DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASS. 02139

The progress for this period of the grant is best described in the attached papers and abstracts which have been prepared.

The first attachment is AIAA paper 85-0331, entitled "A Finite Volume Method for Calculation of Compressible Chemically Reacting Flows." It is to be presented at the AIAA 23rd Aerospace Sciences Meeting in Reno in January 1985. The previously reported algorithm for solving the stiff set of equations for chemically reacting flows is reported in detail. The computations have been done for a two-dimensional geometry and, as we expected, show the excellent computational efficiency obtained in the one-dimensional case. These calculations are for the Euler equations with the Rogers-Chinitz hydrogen-oxygen model.

The second attachment is an abstract submitted to the AIAA CFD Conference to be held in Cincinnati in July 1985. The finite volume method has been extended to viscous flows. Our results verify the accuracy of the non-reacting case by comparison with Carter's calculation. The reacting case for the attached boundary layer appears to be satisfactory, although there is no comparison case for validation. The calculations for recirculating flow are preliminary.

The third attachment is an abstract submitted to the AIAA 21st Joint Propulsion Conference, also in July 1985. It is the start of our study to investigate the effect of parameters such as fuel/air ratio, geometry, etc. on the physics of the flow.

During the reporting period, Mr. Thomas Bussing spent about two months at NASA Langley Research Center during the summer of 1984.

A FINITE VOLUME METHOD FOR THE NAVIER-STOKES EQUATIONS WITH CHEMICAL REACTION

Thomas R. A. Bussing*
Earll M. Murman**

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

ABSTRACT

Over the past two decades Supersonic Combustion Ramjets (Scramjets) have received considerable attention. One critical element in the design of a Scramjet is the detailed understanding of the complex flow field in the engine during various phases of operation. One area of interest is the computation of chemically reacting flows in the vicinity of flame holders. The purpose of this proposed paper is to study the characteristics of a method for solving the Navier-Stokes equations with chemical reaction.

The flow field in a Scramjet is governed by the Navier-Stokes equations coupled to the finite rate chemistry equations. These equations represent different processes which can have their own characteristic time scales. In the problems of interest the time scales can be orders of magnitude different (stiff) leading to severe time step restrictions on the computational procedure. If only the steady state solution is desired several steps can be taken to accelerate the iterative solution. The details of these steps for the Euler equations with Finite Rate Chemistry are given in reference [1]. The numerical procedure is based on a point implicit version of the Jameson, Schmidt and Turkel [2] finite volume/multistage scheme.

Briefly the idea behind the point implicit method involves modifying the original stiff set of equations to another set where the time stiffness associated with the chemical time scales has been removed. This can be accomplished by multiplying the unsteady terms by a scaling matrix. For example, instead of solving the stiff equation system given by

$$\frac{\partial \vec{U}}{\partial t} = -\frac{\partial \vec{F}}{\partial x} - \frac{\partial \vec{G}}{\partial y} + \vec{H} \qquad (1)$$

we could solve

$$\bar{\bar{S}}\frac{\partial \vec{U}}{\partial t} = -\frac{\partial \vec{F}}{\partial x} - \frac{\partial \vec{G}}{\partial y} + \vec{H} \qquad (2)$$

where $\bar{\bar{S}}$ is picked to be the desired scaling matrix. A convenient choice for S is the matrix obtained by numerically treating the chemical source terms implicitly. Hence, the name point implicit. The technique translates to solving the equations in pseudo time, marching each physical process at its own respective characteristic time scale. Note equations (1) and (2) have the same steady state solutions.

The method is being applied to reacting boundary layer and rearward facing step flows. The full Navier-Stokes equations with H_2-Air finite

*Research Assistant, Dept. of Aero and Astro; Associate Member AIAA
**Professor, Dept. of Aero and Astro; Associate Fellow AIAA

rate chemistry are used. The chemistry model was developed by Rogers and Chinitz [3] and consists of the following two steps:

$$H_2 + O_2 \underset{k_{b_1}}{\overset{k_{f_1}}{\rightleftharpoons}} 2\ OH \qquad\qquad H_2 + 2\ OH \underset{k_{b_2}}{\overset{k_{f_1}}{\rightleftharpoons}} 2\ H_2O$$

Tentatively we expect to apply the method to chemically reacting flows over flat plates and rearward facing steps. A few preliminary examples of these types of flows will now be given. The first example compares the predicted non-reacting solution to a numerical data set generated by Carter [4]. The results are for supersonic flow over a flat plate. As the figure illustrates, our computed velocity profile agrees well with Carter's data. If chemical reaction is allowed to occur, then an H_2 species contour like that shown in Figure 2 is produced. Note as expected the reaction is largest next to the surface where the static temperature is highest. Finally a chemically reacting flow over a rearward facing step is shown in Figure 3 ($M_{in} = 3$, $T_{in} = 900K$, $T_{ig} = 1000K$, $\phi = 0.1$). Each of these examples would be considered in greater detail in the proposed paper. With the method proposed in this abstract, convergence to steady state was achieved in approximately 500 iterations compared to approximately 5×10^3 for a purely explicit scheme.

TABLE OF SYMBOLS

HR	$\int (\sum_i Y_i\ HF_i)dA/(Cv_{in}\ T_{in} + .5\ U^2)$
ϕ	Stochiometric mixture ratio
Y_i	ρ of species i/mixture density
HF	Heat of formation

REFERENCES

[1] Bussing, T.R.A., Murman, E.M., "A Finite Volume Method for the Calculation of Compressible Chemically Reacting Flows," AIAA Paper 85-0331, Aerospace Meeting, Reno, January 1985.

[2] Jameson, A., Schmidt, W., Turkel, E., "Numerical Solution of the Euler Equations by Finite Volume Methods Using Runge-Kutta Time-Stepping Schemes," AIAA Paper 81-1259.

[3] Rogers, C., Chinitz, W., "On the Use of a Global Hydrogen-Air Combustion Model in the Computation of Turbulent Reacting Flow," AIAA Paper 83-0112.

[4] Carter, J.E., "Numerical Solution of the Navier-Stokes Equations for Supersonic Laminar Flow over a Two-Dimensional Compression Corner," NASA TR R-385, 1972.

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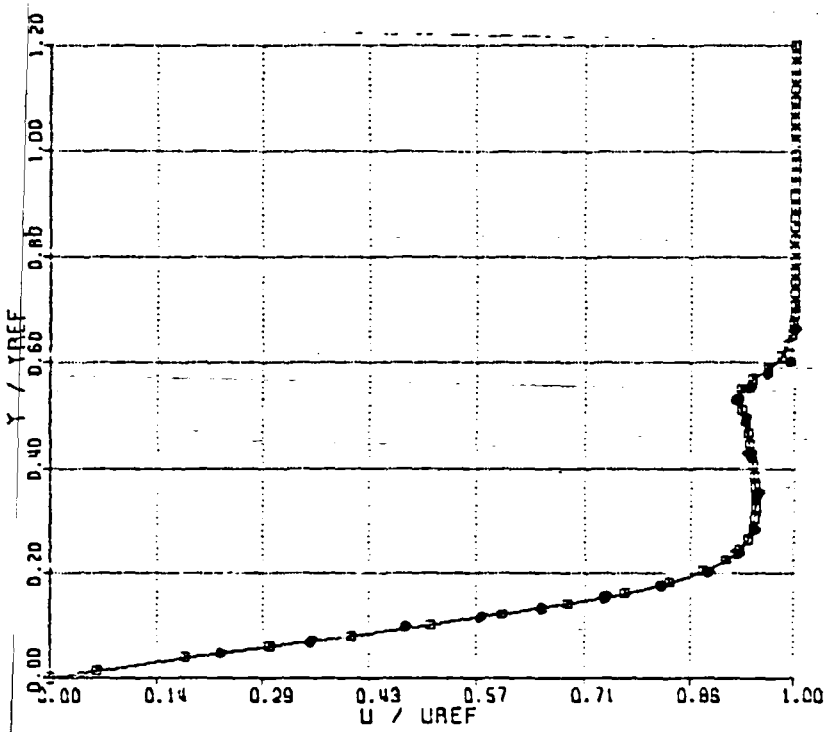
LAMINAR FLAT PLATE PROFILE
X STATION LOCATION = 40

RE	=	1000
M	=	3.0
PR	=	.72
GRID	=	60 × 60



● THEORY / CARTER
□ NUMERICAL

Figure 1

WEDV26
H2 SPECIEC CONTOUR
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Y
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
X
29-NOV-84 20:53:07

Figure 2

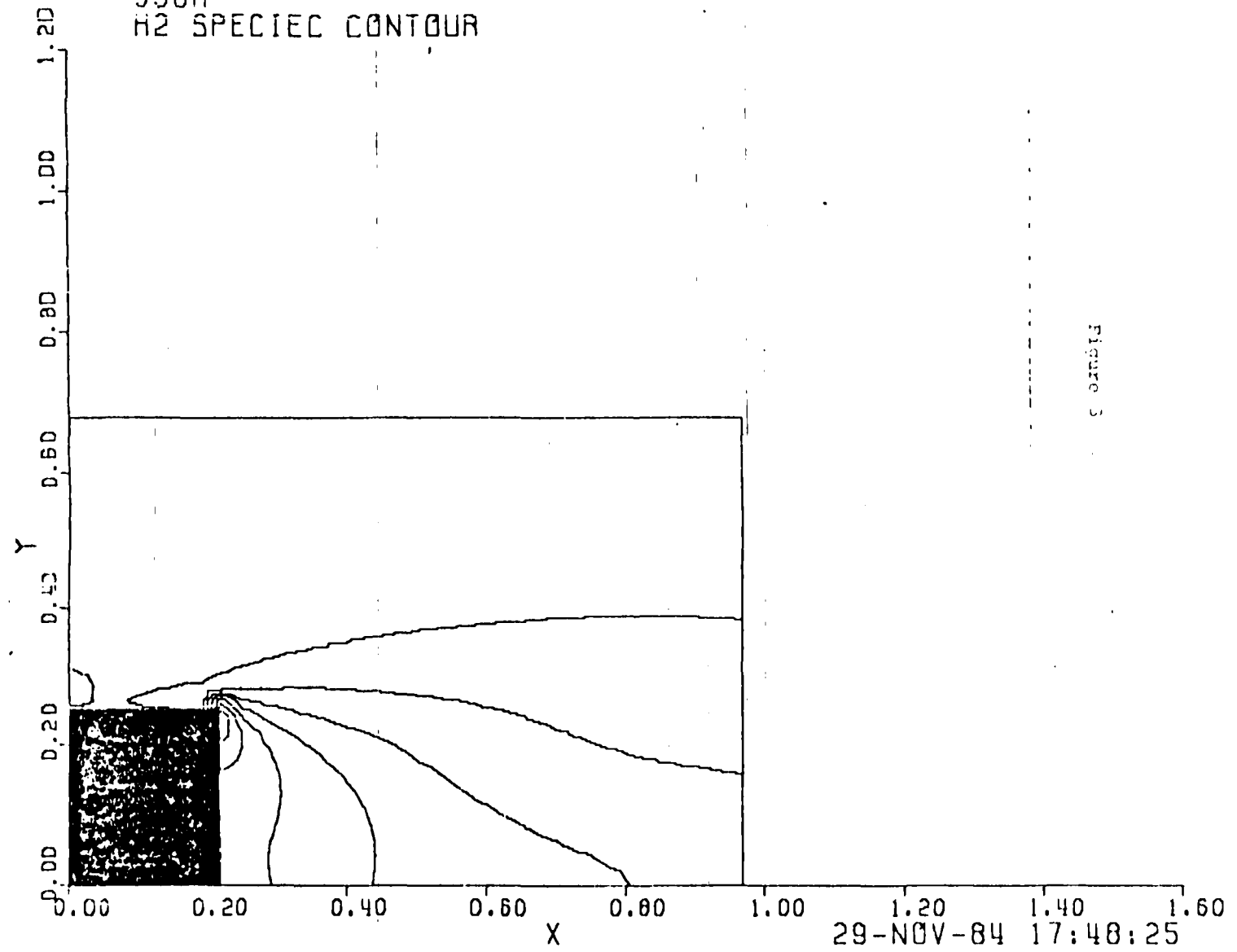

S50R
H2 SPECIEC CONTOUR
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Y
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
X
29-NOV-84 17:48:25

Figure 3

ABSTRACT

NUMERICAL INVESTIGATION OF 2-DIMENSIONAL H_2-AIR FLAME HOLDING OVER RAMPS AND REARWARD FACING STEPS

Thomas R. A. Bussing*
Earll M. Murman#

Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Over the past two decades Supersonic Combustion Ramjets (Scramjets) have received considerable attention. One critical element in the design of a Scramjet is the detailed understanding of the complex flow field in the engine during various phases of operation. One area of interest is the computation of chemically reacting flows in the vicinity of flame holders. The purpose of this proposed paper is to study the flame holding characteristics of simple ramps and rearward facing steps. Both of these configurations are considered candidates for Scramjet flame holders.

The flow field in a Scramjet is governed by the Navier-Stokes equations coupled to the finite rate chemistry equations. These equations represent different processes which can have their own characteristic time scales. In the problems of interest the time scales can be orders of magnitude different (Stiff) leading to severe time step restrictions on the computational procedure. If only the steady state solution is desired, several steps can be taken to accelerate the solution procedure. The details of these steps are given in Reference 1. The numerical procedure is based on a point implicit version of the Jameson, Schmidt and Turkel [Ref 2] finite volume/ multistage scheme coupled to a point implicit version of the Jameson multigrid method.

Briefly the idea behind the point implicit method involves modifying the original stiff set of equations to another set where the time stiffness

*Member AIAA. Research Assistant, Dept. of Aero and Astro
#Associate Fellow AIAA. Professor, Dept. of Aero and Astro

associated with the chemical time scales has been removed. This can be accomplished by multiplying the unsteady terms by a scaling matrix. For example, instead of solving the stiff given by

$$\frac{\partial \bar{U}}{\partial t} = - \frac{\partial \bar{F}}{\partial X} - \frac{\partial \bar{G}}{\partial Y} + \bar{H} \tag{1}$$

we could solve

$$\bar{\bar{S}} \frac{\partial \bar{U}}{\partial t} = - \frac{\partial \bar{F}}{\partial X} - \frac{\partial \bar{G}}{\partial Y} + \bar{H} \tag{2}$$

where S is picked to be the desired scaling matrix. A convenient choice for S is the matrix obtained by numerically treating the chemical source terms implicitly. Hence the term point implicit. The technique translates to solving the equations in pseudo time marching each state quantity at its own respective characteristic time scale. Note equations (1) and (2) have the same steady state solutions.

Two flame holder configurations are considered in this study using the compressible flow equations with H_2-Air finite rate chemistry. The first uses a wall-generated, oblique shock (ramp) to initiate and hold a flame. Examples of this type of reacting flow are shown in Figures 1 and 2. Figure 1 shows the H_2 species contours for a reaction initiated by an oblique shock ($M_{in} = 3.5$, HR = 0.026, $\phi = 0.1$, $T_{in} = 900K$, $T_{ig} = 1000K$, with 62% of the available H_2 burned). Note the flow is entirely supersonic. If as shown in Figure 2 the Mach number is reduced to 2.6 (HR = 0.1, $\phi = 0.1$, 89% H_2 burn) the flow field takes on a different phenomenology. Here a subsonic bubble forms behind the normal Mach stem. The calculations were done inviscidly as the Reynolds number typical of the ramp flows of interest is 10^7. Using the point implicit/rescaling method discussed above, convergence was achieved in 200 iterations compared to 2×10^8 iterations for a purely explicit scheme.

The second class of problems involves flame holding behind a rearward facing step. Here the recirculation zone acts to anchor the flame. In this case the viscous effects are significant and the full Navier-Stokes equations are needed. At the time of the writing of this abstract the rearward facing step calculations were not completed, but they would be included in the paper. For both flame holder configurations many phenomenologies are expected, and an attempt will be made to characterize them.

Table of Symbols

HR	$\sum_i Y \times HF_i / (Cv_{in} \times T_{in} + 0.8 \times U^2)$
ϕ	Stochiometric mixture ratio
Y_i	ρ of species i/mixture density
HF	Heat of formation

References

[1] Bussing, T.R.A., Murman, E.M., "A finite volume method for the calculation of compressible chemically reacting flows," AIAA Paper 85-0331, Aerospace Meeting, Reno.

[2] Jameson, A., Schmidt, W., Turkel, E., "Numerical solution of the Euler equations by finite volume methods using Runga-Kutta time-stepping schemes," AIAA 81-1259.

[3] Jameson, A., "Solution of the Euler equations for two-dimensional transonic flow by a multigrid method," Princeton University MAE Report No. 1613, June 198[illegible].

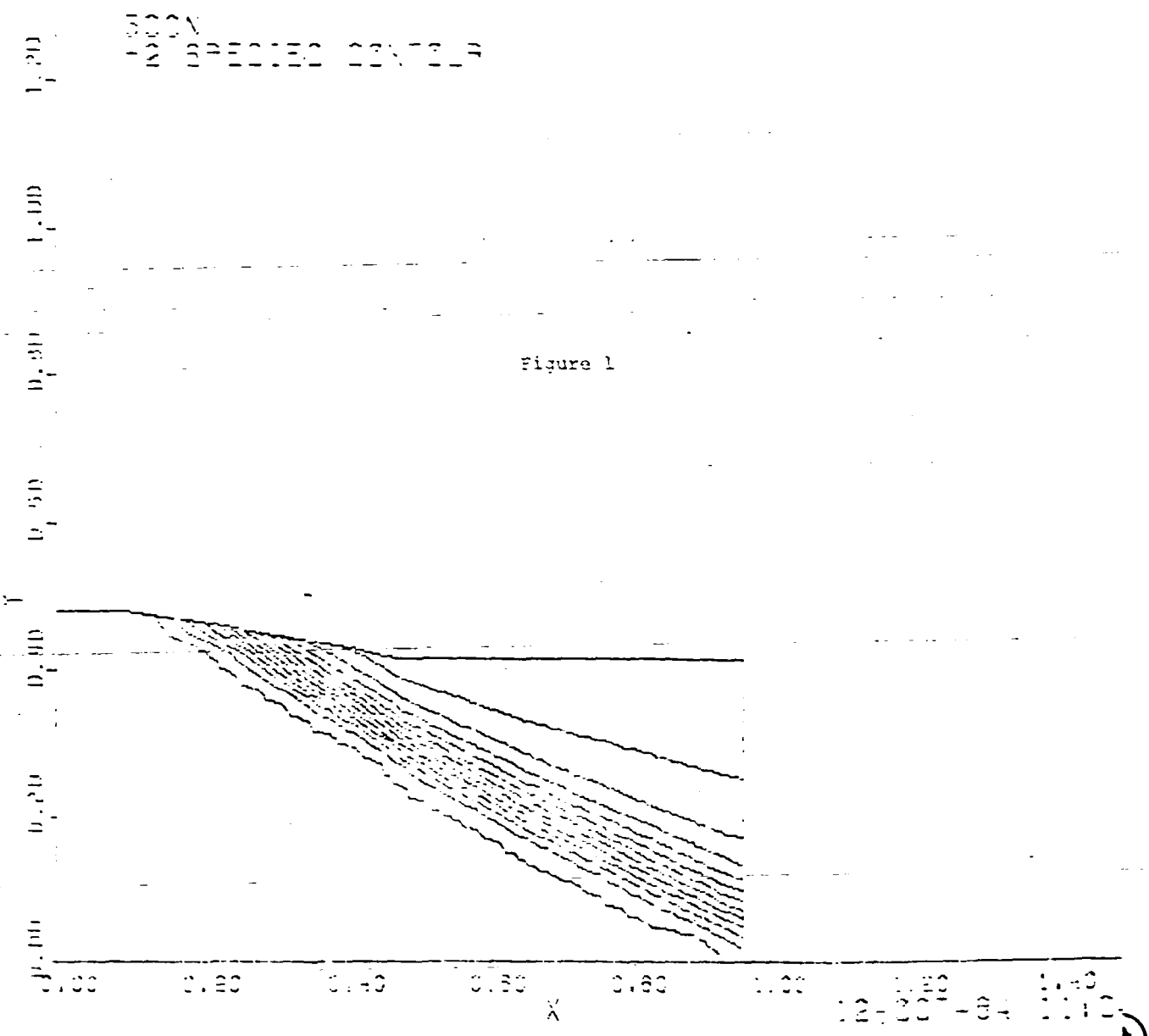


Figure 1

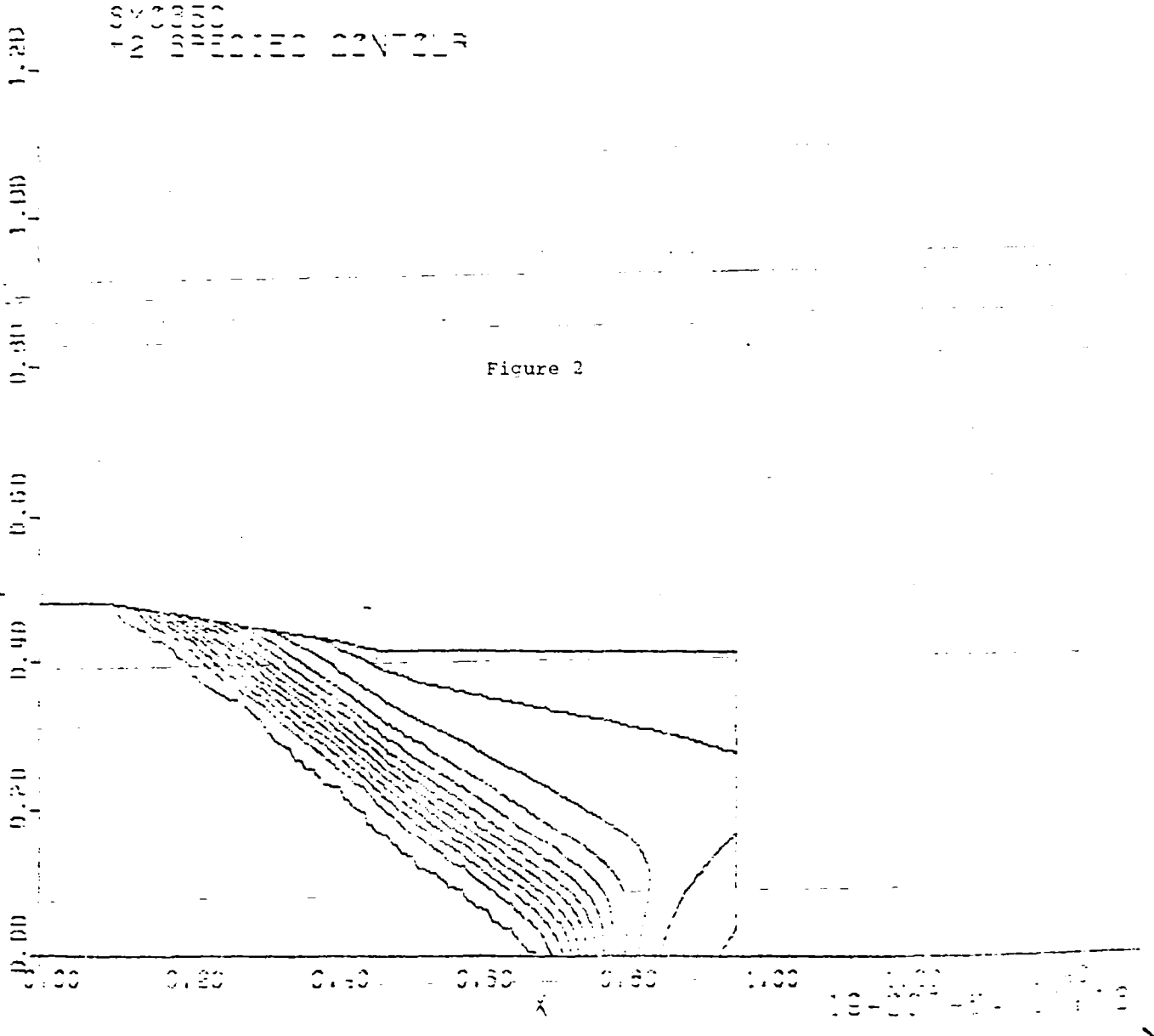


Figure 2