MICROCOPY RESOLUTION TEST CHART

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 4218	2. GOVT ACCESSION NO. AD-A086725	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* HIGH ORDER "ZIP" DIFFERENCING OF CONVECTIVE TERMS		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) S. T. Zalesak		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62704H; 67-0889-0-0
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Nuclear Agency Washington, D.C. 20305		12. REPORT DATE May 8, 1980
		13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT *(of this Report)* Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*		
18. SUPPLEMENTARY NOTES This research was sponsored by the Defense Nuclear Agency under subtask S99QAXHC041, Work Unit Code 21, Title "Plasma Structure Evolution".		
19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)* Flux-corrected transport FCT Transport algorithms Convective transport algorithms Eulerian transport algorithms ZIP differencing		

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The ZIP flux form for differencing the term $(wv)_x$, where w is a convected quantity and v is a convective velocity, is observed to be equivalent to differencing the alternative expression $wv_x + v w_x$ using centered second order finite differences. Based on this observation, the extension of the ZIP flux concept to arbitrarily high order accuracy is given. Computational examples show the advantage both of the ZIP flux concept itself and of its higher order forms within the context of flux-corrected transport (FCT) algorithms.

DD , FORM 1473   EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

CONTENTS

DTIC
ELECTE
JUL 1 6 1980
S   D
B

ACCESSION for

NTIS	White Section ☑
DDC	Buff Section ☐
UNANNOUNCED	☐
JUSTIFICATION	

BY
DISTRIBUTION/AVAILABILITY CODES

| Dist. | AVAIL. and/or SPECIAL |
| A | |

iii

HIGH ORDER "ZIP" DIFFERENCING OF CONVECTIVE TERMS

I.   INTRODUCTION

Consider equations of the form

$$w_t + f_x = 0 \qquad (1)$$

where

$$f = wv + f' \qquad (2)$$

and hence

$$w_t + (wv)_x + f'_x = 0 \qquad (3)$$

Here w, f and v are functions of the independent variables x and t.

The second term in Eq. (3) is called a convective term and is the subject of this paper. We shall say that a finite difference approximation to Eq. (3) is in conservation or "flux" form when the approximation can be written

$$w_i^{n+1} = w_i^n - \Delta t \, \Delta x_i^{-1} \, [F_{i+\frac{1}{2}} - F_{i-\frac{1}{2}}] \qquad (4)$$

Here the subscripts refer to the spatial grid points x_i, the superscripts to the temporal grid points t^n, $\Delta t \equiv t^{n+1} - t^n$, and $\Delta x_i \equiv \frac{1}{2}(x_{i+1} - x_{i-1})$. We shall assume henceforth that Δx_i is independent of i, and denote the quantity simply by Δx. In this author's opinion, nonuniform meshes are best handled by coordinate transformation or mapping techniques[3,4,13]. The $F_{i+\frac{1}{2}}$ are called transportive fluxes, and are functions of the f_i at one or more of the time levels t^n. For a given time level, the functional dependence of F on f can be written to achieve any desired order of spatial accuracy (see [1, Appendix]).

For instance, centered second order differences require

$$F_{i+\frac{1}{2}} = \frac{1}{2} (f_{i+1} + f_i) \tag{5}$$

while centered fourth order differences give

$$F_{i+\frac{1}{2}} = \frac{7}{12} (f_{i+1} + f_i) - \frac{1}{12} (f_{i+2} + f_{i-1}) \tag{6}$$

For the purposes of this paper we wish to divide the net transportive flux $F_{i+\frac{1}{2}}$ into two components: $F^C_{i+\frac{1}{2}}$, the convective component, and $F'_{i+\frac{1}{2}}$, the non-convective component:

$$F_{i+\frac{1}{2}} \equiv F^C_{i+\frac{1}{2}} + F'_{i+\frac{1}{2}} \tag{7}$$

Thus $F^C_{i+\frac{1}{2}}$ and $F'_{i+\frac{1}{2}}$ are the fluxes corresponding to the second and third terms respectively of Eq. (3). We shall consider only $F^C_{i+\frac{1}{2}}$ here.

II.   SECOND ORDER ZIP FLUXES

A straightforward implementation of Eq. (5) for the convective flux would yield

$$F^C_{i+\frac{1}{2}} = \frac{1}{2} [w_{i+1} v_{i+1} + w_i v_i] \tag{8}$$

However, as is pointed out in the classic 1968 paper by Hirt [2], a better form for this convective flux is

2

$$F^c_{i+\frac{1}{2}} = \frac{1}{2} \left[v_{i+1} \, w_i + w_{i+1} \, v_i \right] \tag{9}$$

Hirt refers to this form as "ZIP" differencing, a convention we shall keep here. Hirt's "heuristic" stability analysis of difference equations entails expanding each term in the difference equation in a Taylor series to obtain the differential equation one is actually solving. Examination of the properties of this new differential equation sheds much light on the stability and error characteristics of the difference equation. Expanding our flux form representation for the second term in (3) we find

$$\left(\frac{\partial wv}{\partial x} \right)^{FD} \equiv \Delta x^{-1} \left[F^c_{i+\frac{1}{2}} - F^c_{i-\frac{1}{2}} \right] = \left(\frac{\partial wv}{\partial x} \right)_i + TE \tag{10}$$

where the superscript refers to the finite difference approximation and TE represents the truncation error terms.

For Eq. (8) we find that

$$TE = \frac{1}{6} \left(\frac{\partial^3 wv}{\partial x^3} \right)_i \Delta x^2 + \frac{1}{120} \left(\frac{\partial^5 wv}{\partial x^5} \right)_i \Delta x^4 + 0 \, (\Delta x^6) \tag{11}$$

while for the ZIP flux (9) we find

$$TE = \frac{1}{6} \left[w \frac{\partial^3 v}{\partial x^3} + v \frac{\partial^3 w}{\partial x^3} \right]_i \Delta x^2 + \frac{1}{120} \left[w \frac{\partial^5 v}{\partial x^5} + v \frac{\partial^5 w}{\partial x^5} \right]_i \Delta x^4 + 0(\Delta x^6)$$

$$\tag{12}$$

In Hirt's heuristic stability analysis of (3), one looks for truncation error terms of the form $\dfrac{\partial^2 w}{\partial x^2}$ since such terms will destabilize numerical solutions to Eq. (1) if they are negative and artificially damp the solutions if they are positive. It should be noted that for certain explicit non-dissipative schemes (leapfrog, for example) terms of this form are destabilizing _regardless of their sign._ A look at (12) shows that terms of this form are simply not present. One can extend Hirt's argument and look for terms involving _any_ even derivatives of w with respect to x, since any such terms could potentially be destabilizing, but these too are absent when ZIP fluxes are used. The odd order derivatives in the truncation error terms _will_ give rise to error, but these will be of a dispersive rather than of a dissipative or antidissipative nature.

By contrast, if we examine the truncation errors given by (11), we find that the leading term is

$$\frac{1}{6} \frac{\partial^3 wv}{\partial x^3} \Delta x^2 = [\frac{1}{2} \frac{\partial^2 w}{\partial x^2} \frac{\partial v}{\partial x} + \frac{1}{2} \frac{\partial^2 v}{\partial x^2} \frac{\partial w}{\partial x} + \frac{1}{6} w \frac{\partial^3 v}{\partial x^3} + \frac{1}{6} v \frac{\partial^3 w}{\partial x^3}] \Delta x^2$$

(13)

which will contribute a destabilizing or dissipative term except in the trivial case $\dfrac{\partial v}{\partial x} = 0$. Thus although both forms for the convective flux have the same formal order of accuracy in terms of Δx, we find the ZIP form preferable from stability considerations.

4

III. HIGH ORDER "ZIP" FLUXES

The extension of the ZIP concept to higher order can be seen by expanding $(wv)_x^{FD}$ for the second order ZIP flux (9)

$$\left(\frac{\partial wv}{\partial x}\right)_i^{FD} = \Delta x^{-1} \left[F_{i+\frac{1}{2}}^C - F_{i-\frac{1}{2}}^C \right]$$

$$= \frac{1}{2} \Delta x^{-1} \left[w_{i+1} v_i + w_i v_{i+1} - w_i v_{i-1} - w_{i-1} v_i \right]$$

$$= \frac{1}{2} \Delta x^{-1} \left[w_{i+1} - w_{i-1} \right] v_i + \frac{1}{2} \Delta x^{-1} \left[v_{i+1} - v_{i-1} \right] w_i$$

$$= v_i \left(\frac{\partial w}{\partial x}\right)_i^{FD} + w_i \left(\frac{\partial v}{\partial x}\right)_i^{FD} \tag{14}$$

So we see that ZIP differencing of the convective flux is equivalent to taking a central second order finite difference approximation to the term $wv_x + vw_x$ rather than $(wv)_x$. We point out that Cheng and Shubin [5] have also noted that second order central differencing of the term $wv_x + vw_x$ leads to a conservative scheme, something we have proven here by showing the ZIP form to be the equivalent convective flux. It would seem, then, that higher order forms for ZIP fluxes, if they exist at all, are equivalent to higher order central difference approximations to the form $wv_x + vw_x$. In fact, it is now quite clear why the ZIP fluxes work as they do: For central differences of all orders of accuracy, the truncation errors of approximations to first derivatives involve only odd order derivatives of the function. Hence, the form $wv_x + vw_x$ can never produce terms involving even order derivatives of w, as long as centered finite differences are used.

5

By way of contrast "straightforward" central differencing of the form $(wv)_x$ will still produce only odd order derivatives, but those derivatives will operate on the quantity wv, and can always be expanded to show that terms involving the undesirable even order derivatives of w are present. For example, the "straightforward" fourth order convective flux

$$F^c_{i+\frac{1}{2}} = \frac{7}{12} (w_i v_i + w_{i+1} v_{i+1}) - \frac{1}{12} (w_{i-1} v_{i-1} + w_{i+2} v_{i+2}) \quad (15)$$

gives the truncation error

$$TE = -\frac{1}{90} \frac{\partial^5 wv}{\partial x^5} \Delta x^4 + 0 (\Delta x^6) \quad (16)$$

Expansion of the leading term shows components involving both $\frac{\partial^2 w}{\partial x^2}$ and $\frac{\partial^4 w}{\partial x^4}$.

Without further ado, we give here the appropriate ZIP fluxes for the indicated spatial order of accuracy:

Second Order:

$$F^c_{i+\frac{1}{2}} = \frac{1}{2} [w_{i+1} v_i + w_i v_{i+1}] \quad (17)$$

Fourth Order:

$$F^c_{i+\frac{1}{2}} = \frac{2}{3} [w_{i+1} v_i + w_i v_{i+1}]$$

$$-\frac{1}{12}[w_{i+2} v_i + w_i v_{i+2} + w_{i+1} v_{i-1} + w_{i-1} v_{i+1}] \quad (18)$$

6

Sixth Order:

$$F^C_{i+\frac{1}{2}} = \frac{3}{4} \left[w_{i+1} v_i + w_i v_{i+1} \right]$$

$$- \frac{3}{20} \left[w_{i+2} v_i + w_i v_{i+2} + w_{i+1} v_{i-1} + w_{i-1} v_{i+1} \right] \tag{19}$$

$$+ \frac{1}{60} \left[w_{i+3} v_i + w_i v_{i+3} + w_{i+2} v_{i-1} + w_{i-1} v_{i+2} \right.$$

$$\left. + w_{i+1} v_{i-2} + w_{i-2} v_{i+1} \right]$$

In general

$$F^C_{i+\frac{1}{2}} = \sum_{k=1}^{N} \frac{1}{k} C^N_k P_{ki} \tag{20}$$

where N = order of approximation (even) ÷ 2

$$C^N_1 = \frac{N}{N+1} \tag{21}$$

$$C^N_k = - C^N_{k-1} \cdot \frac{N - k + 1}{N + k} \tag{22}$$

$$P_{ki} = \sum_{j=0}^{k-1} (w_{i-j+k} v_{i-j} + w_{i-j} v_{i-j+k}) \tag{23}$$

The reader can verify easily that the quantity $\left[F^C_{i+\frac{1}{2}} - F^C_{i-\frac{1}{2}} \right] \Delta x^{-1}$ does in fact reproduce the appropriate order finite difference approximation to the quantity $(w v_x + w_x v)_i$ when the above expressions are used.

IV. NUMERICAL EXAMPLE

We choose as our computational example the exploding diaphragm or Riemann problem for the one-dimensional equations of ideal inviscid compressible fluid flow:

7

$$
\begin{bmatrix} \rho \\ \rho v \\ \rho E \end{bmatrix}_t + \begin{bmatrix} \rho v \\ \rho v^2 \\ \rho E v \end{bmatrix}_x + \begin{bmatrix} 0 \\ P \\ Pv \end{bmatrix}_x = 0
$$

(24)

where ρ, v, P and E are the fluid density, velocity, pressure and specific total energy respectively. Also,

$P = (\gamma-1) \ (\rho E = \frac{1}{2} \ \rho v^2)$ (25)

where we will choose $\gamma = 1.4$. Our initial conditon consists of two constant states, one to the left and one to the right, separated by a discontinuity which is assumed to lie midway between two grid points, in this case points 50 and 51. For these calculations $\rho_{left} = P_{left} = 1.0$, $\rho_{right} = 10.0$, and $P_{right} = 100.0$. All calculations were done on a uniform mesh of 100 grid points using a Courant number of 0.1, and utilizing the second and fourth order leapfrog-trapezoidal flux-corrected transport (FCT) algorithms described in [1]. For simplicity the Boris-Book flux limiter [1,6] was used. Briefly, FCT algorithms solve Eq. (1) by forming a point by point weighted average of two transportive fluxes, one chosen to give monotone results (free of spurious oscillations) for the problem at hand, and the other to give formally high order accuracy. The high order fluxes are weighted as heavily as possible without violating monotonicity constraints, a process referred to as "flux limiting." In this example our monotone flux is given by the first order Rusanov scheme [7], while our high

8

order fluxes are given by the aforementioned second and fourth order

leapfrog trapezoidal schemes. The tests we will make of ZIP versus

non-ZIP differencing of convective terms refer only to the high order

portion of the FCT algorithm. FCT algorithms are extremely effective

in suppressing the numerical oscillations and instabilities which

would otherwise occur with the high order scheme. Because of this,

there may be a tendency on the part of the user to believe that great

care is not required in choosing the higher order portion of the total

FCT scheme since the flux limiting will "save" him. We shall show that

this is not always the case.

We have written Eq. (24) to show explicitly the convective terms

as the second terms in the (vector) equation. In Fig. 1 we show the

calculated (data points) and analytic (solid line) density profiles

after 500 time steps using the second order accurate convective fluxes

given by the "straightforward" evaluation Eq. (8) and by the ZIP

evaluation Eq. (17). We note that analytically we have a shock wave

moving to the left, followed by a contact discontinuity, and a rare-

faction fan moving to the right. The straightforward calculation is

seen to be afflicted by several large scale numerical oscillations while

the ZIP calculation yields a reasonably accurate and oscillation-free

profile, even though the implementation of FCT has kept both calculations

stable. From (3), (10), and (13) we see that straightforward differ-

encing is equivalent to adding a diffusion term with coefficient

$-(\partial v/\partial x)/2$ to the right hand side of (3). When $\partial v/\partial x$ is positive, as

in the rarefaction fan, we expect numerical instability; while in the

shock ($\partial v/\partial x < 0$) we expect artificial dissipation. We note that all

9

of the regions of roughness or oscillation in Fig. 1a represent fluid

elements that are, or at one time were, in the rarefaction fan; and

further that the density jump at the shock is smaller and occupies a

greater number of cells than in the corresponding ZIP calculation,

Fig. 1b. The ZIP calculation is obviously far superior. To be fair,

other procedures could have "fixed" the problem. In fact our choice

of the virtually non-dissipative leapfrog-trapezoidal scheme is

probably not a wise one for a calculation of this type, where discon-

tinuities abound. Nonetheless we do feel this example makes a valid

comparison of convective differencing schemes.

In Fig. 2 we show the same comparison as in Fig. 1, but this time

for the fourth order "straightforward" flux Eq. (15) and for the fourth

order ZIP flux Eq. (18). Again the "straightforward" calculation

gives numerical oscillations whereas ZIP differencing experiences no

apparent difficulties. Comparing Figures 1 and 2 we see an improvement

in the solution as we go from second to fourth order, a behavior

one would expect based on a linear dispersion analysis. Further

improvements in the ZIP solutions are seen as the order of the

approximation is increased to sixth and higher, but the oscillations

associated with the "straightforward" differencing remain intact.

In fact the improvement shown here is quite mild compared to

what we have seen in other types of calculations as we increase

the spatial order of the approximation. It now appears that the

"ultimate" FCT scheme will be either a very high order polynomial-based

approximation scheme or a pseudospectral scheme (see [8]). Both the

second and fourth order calculation smear the contact discontinuity more than is desirable. This is due to the overly conservative assumptions of the flux limiter used (the "clipping" problem – see [1]) at early times, and can be remedied by using a different flux limiter [1] and using monotonicity constraints whose description is beyond the scope of this paper.

Before leaving this section we briefly present several further calculations which may be of some interest to the reader.

Another very popular way of writing a second order convective flux is

$$F^c_{i+\frac{1}{2}} = \frac{1}{4} (w_{i+1} + w_i) (v_{i+1} + v_i) \qquad (26)$$

In fact MacCormack [14] has also concluded that the straightforward flux (8) is to be avoided in certain regions and is to be replaced by (26) there. Comparison of (8), (9), and (26) shows that (26) is nothing more than an average of second order ZIP and straightforward fluxes. The results for our Riemann test problem using (26) for the convective fluxes are shown in Fig. 3. We note that the results are far superior to those for the straightforward fluxes, Fig. 1a, but not quite as good as those for the ZIP fluxes, Fig. 1b.

We implied earlier that some of the problems associated with straightforward fluxes could be overcome by using a dissipative scheme. In Fig. 4, we show the results of using the fourth order straightforward flux (15) plus a dissipative flux of the form

$$F^D_{i+\frac{1}{2}} = \frac{1}{24} \left(\left| \frac{v_{i+1} + v_i}{2} \right| + \frac{c_{i+1} + c_i}{2} \right) \left[w_{i+2} - w_{i-1} - 3(w_{i+1} - w_i) \right]$$

(27)

which approximates a fourth order dissipation term involving the fourth derivative of w. Here c_i is the sound speed at grid point i. Note that the results are much improved over Fig 2a. In Fig 5 we show the results of adding the same dissipative flux (27) to the fourth order ZIP flux (18). The results are degraded only slightly. The idea of using fourth order dissipation with non-dissipative fourth order schemes is originally due to Kreiss and Oliger [15], and the obvious extension to even higher order schemes is the subject of study by the present author.

The reader may note that in the energy component of (24), the Pv term could easily have been treated using the ZIP format. In fact, by (25) P is proportional to one component of ρE and is therefore subject to the same kind of nonlinear instabilities as are the other convective terms. In Fig 6 we show the results of using the fourth order ZIP flux (18) for both the ρEv and the Pv terms in the energy equation. Although there is very little difference in this case from the straightforward treatment of Pv, the ZIP flux form is recommended on theoretical grounds.

V.   CONCLUSIONS

We have shown that ZIP differencing of the term $(wv)_x$ is the equivalent of a centered differencing of the alternative form $wv_x + w_xv$, both in the second order limit and with regard to the

12

kinds of truncation error terms that are produced for the higher orders. Explicit expressions for the calculation of arbitrarily high order ZIP fluxes have been given, and computational examples have been given to show the advantages of the ZIP flux form over the "straightforward" flux form within the context of FCT algorithms. It seems to us that the "heuristic" stability analysis of Hirt [2] has again proved to be a reliable tool in analyzing numerical schemes. We should point out to the reader that the ZIP flux concept is but one example of a class of numerical techniques based on Hirt's analysis known as truncation error cancellation (TEC) which are now quite highly developed and which have even been automated [9-11]. Similar, but not identical, techniques have been given by Warming and Hyett [12], Lerat and Peyret [16], Yanenko and Shokin [17], and by Cheng [18].

ACKNOWLEDGEMENT

REFERENCES

1. S. T. Zalesak, J. Comput. Phys. 31, (1979), 335.

2. C. W. Hirt, J. Comput. Phys. 2 (1968), 339.

3. P. J. Roache, Computational Fluid Dynamics, Hermosa Publishers, Albuquerque, 1976.

4. G. O. Roberts, "Computational Meshes for Boundary Layer Problems," in Proceedings of the Second International Conference on Numerical Methods in Fluid Dynamics, Lecture Notes in Physics, Vol. 8, Springer Verlag, New York, 1971.

5. S. I. Cheng and G. Shubin, J. Comput. Phys, 28 (1978), 315.

6. J. P. Boris and D. L. Book, "Solution of Continuity Equations by the Method of Flux-Corrected Transport," Methods in Computational Physics, Vol. 16, Academic Press, New York, 1976.

7. V. V. Rusanov, J. Comp. Math. Math. Phys. USSR, No. 2 (1962).

8. D. Gottlieb and S. A. Orszag, Numerical Analysis of Spectral Methods: Theory and Applications, SIAM, Philadelphia, 1977.

9. W. C. Rivard, O. A. Farmer, T. D. Butler and P. J. O'Rourke, "A Method for Increased Accuracy in Eulerian Fluid Dynamics Calculations," Los Alamos Scientific Laboratory Report LA-5426-MS, 1973.

10. L. D. Cloutman and L. W. Fullerton, "Automated Heuristic Stability Analysis for Nonlinear Equations," Los Alamos Scientific Laboratory Report LA-6885-MS, 1977.

11. L. D. Cloutman and L. W. Fullerton, J. Comput. Phys. $\underline{29}$ (1978) 141.

12. R. F. Warming and B. J. Hyett, J. Comput. Phys. $\underline{14}$ (1974), 159.

13. F. G. Blottner "Nonuniform Grid Method for Turbulent Boundary Layers," in <u>Proceedings of the Fourth International Conference on Numerical Methods in Fluid Dynamics</u>, Lecture Notes in Physics, Vol. 35, Springer Verlag, New York, 1975.

14. R. W. MacCormack "Numerical Solution of the Interaction of a Shock Wave with a Laminar Boundary Layer," in <u>Proceedings of the Second International Conference on Numerical Methods in Fluid Dynamics</u>, Lecture Notes in Physics, Vol. 8, Springer Verlag, New York, 1971.

15. H. - O. Kreiss and J. Oliger, Tellus $\underline{24}$ (1972), 199.

16. A. Lerat and R. Peyret "The Problem of Spurious Oscillations in the Numerical Solution of the Equations of Gas Dynamics," in <u>Proceedings of the Fourth International Conference on Numerical Methods in Fluid Dynamics</u>, Lecture Notes in Physics, Vol. 35, Springer Verlag, New York, 1975.

17. N. N. Yanenko and Yu. I. Shokin, Phys. Fluids, $\underline{12}$, (1969), II 28.

18. S. I. Cheng, Phys. Fluids, $\underline{12}$, (1969), II 34.

Fig. 1a - Comparison of analytic and computed density profiles (solid lines and data points respectively) for the exploding diaphragm problem given in the text for second order straightforward convective fluxes Eq. (8)
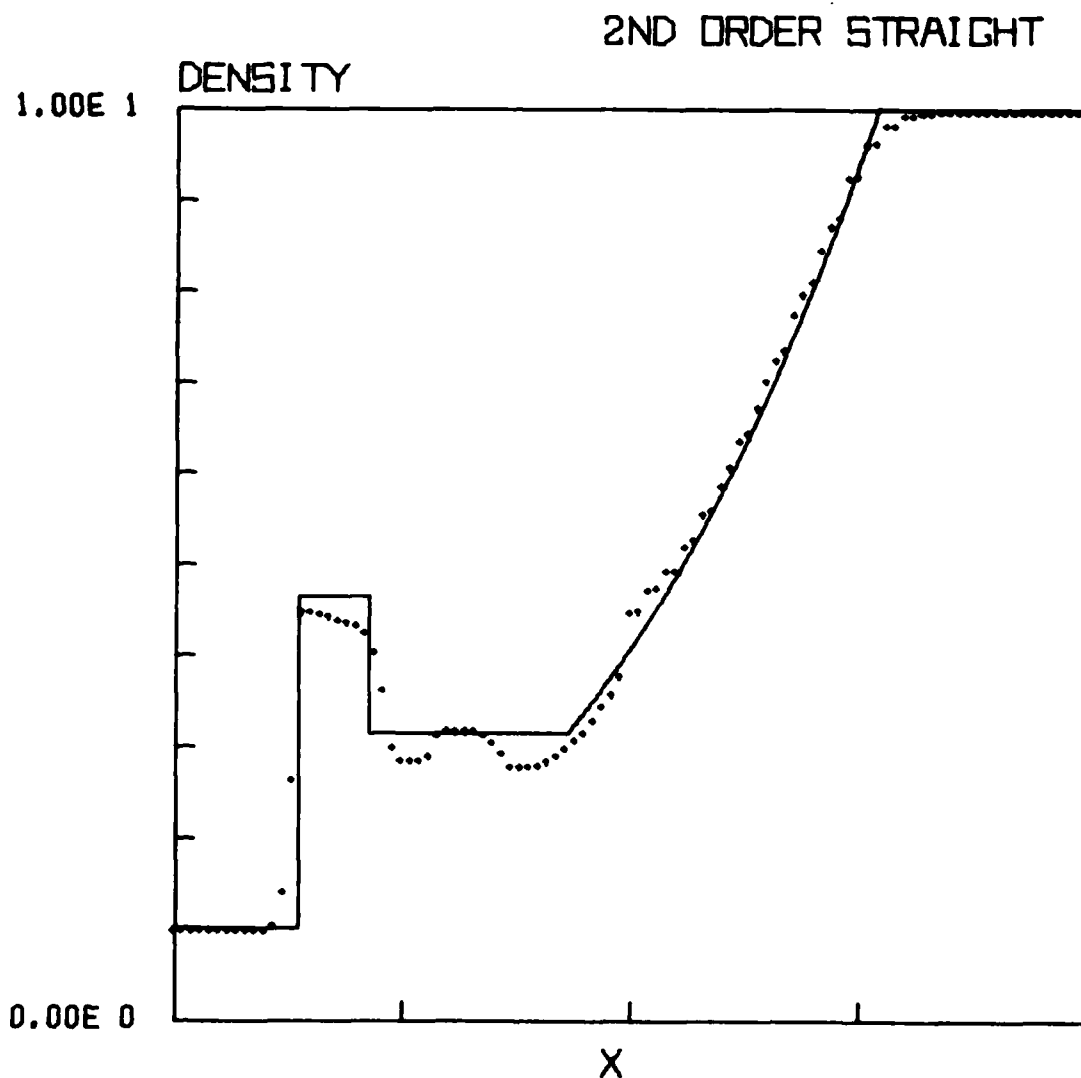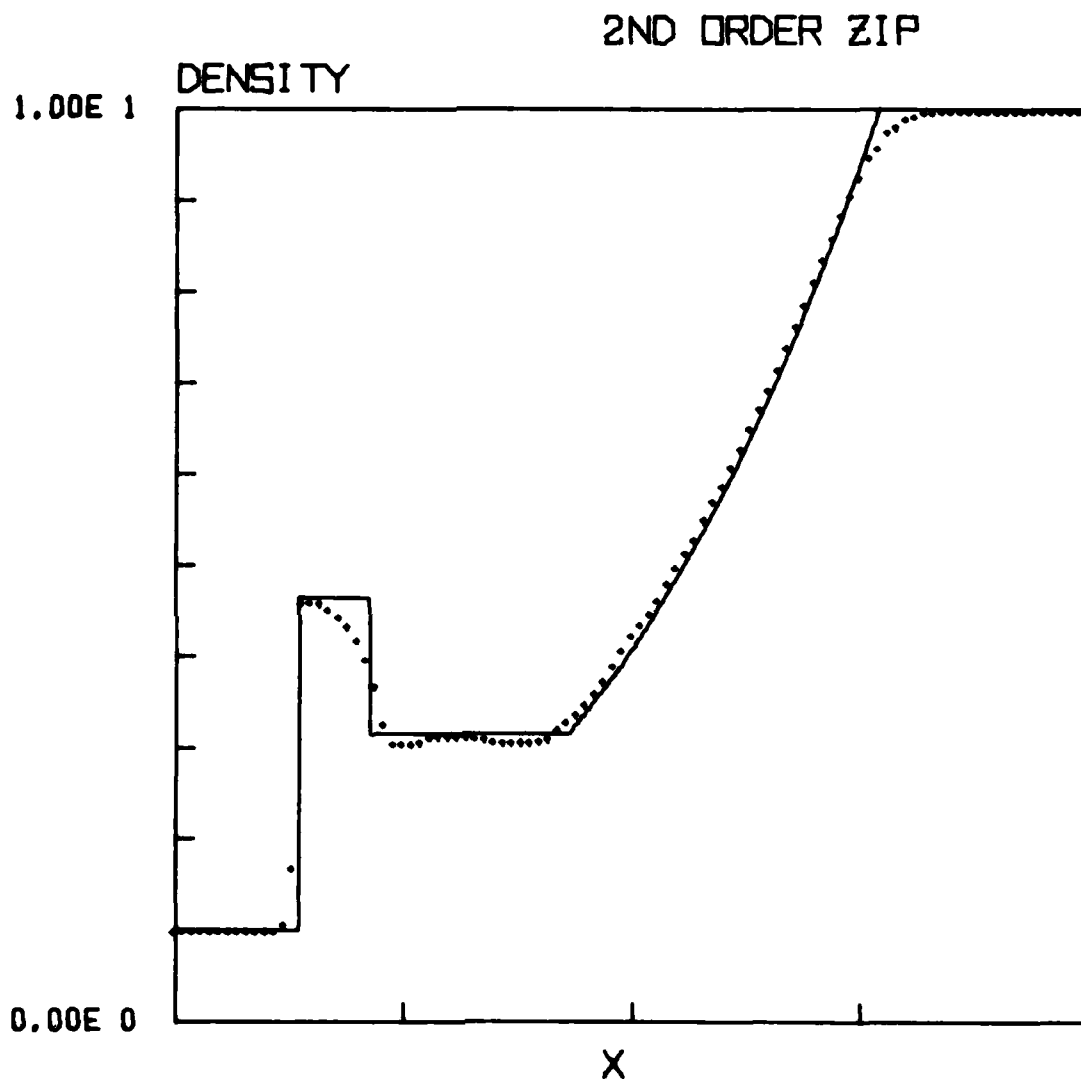
Fig. 1b - Comparison of analytic and computed density profiles (solid lines and data points respectively) for the exploding diaphragm problem given in the text for second order ZIP fluxes Eq. (17)

18
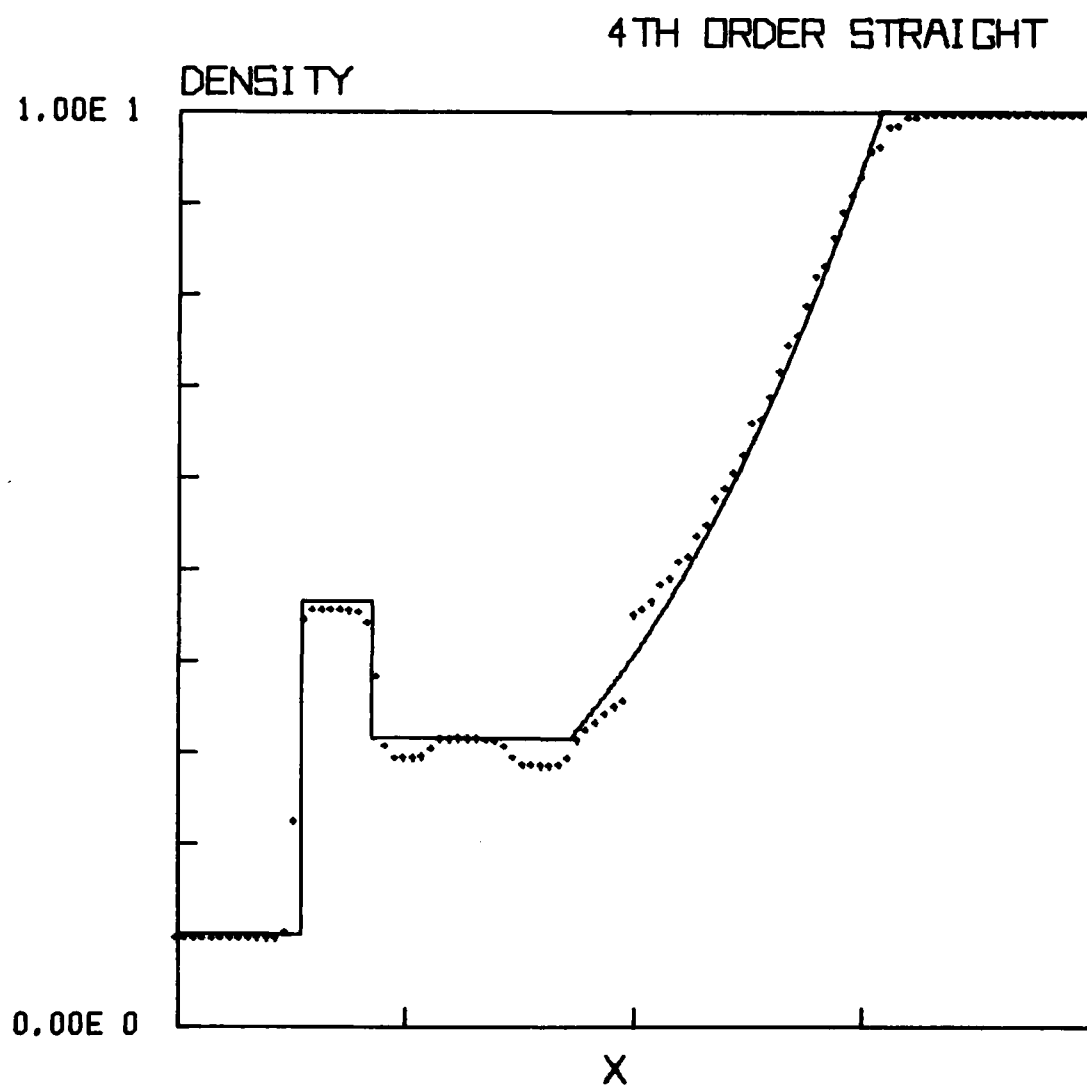
Fig. 2a - Same as Fig. 1 but for fourth order straightforward
convective fluxes Eq. (15)

4TH ORDER ZIP

DENSITY

1.00E 1

0.00E 0

X
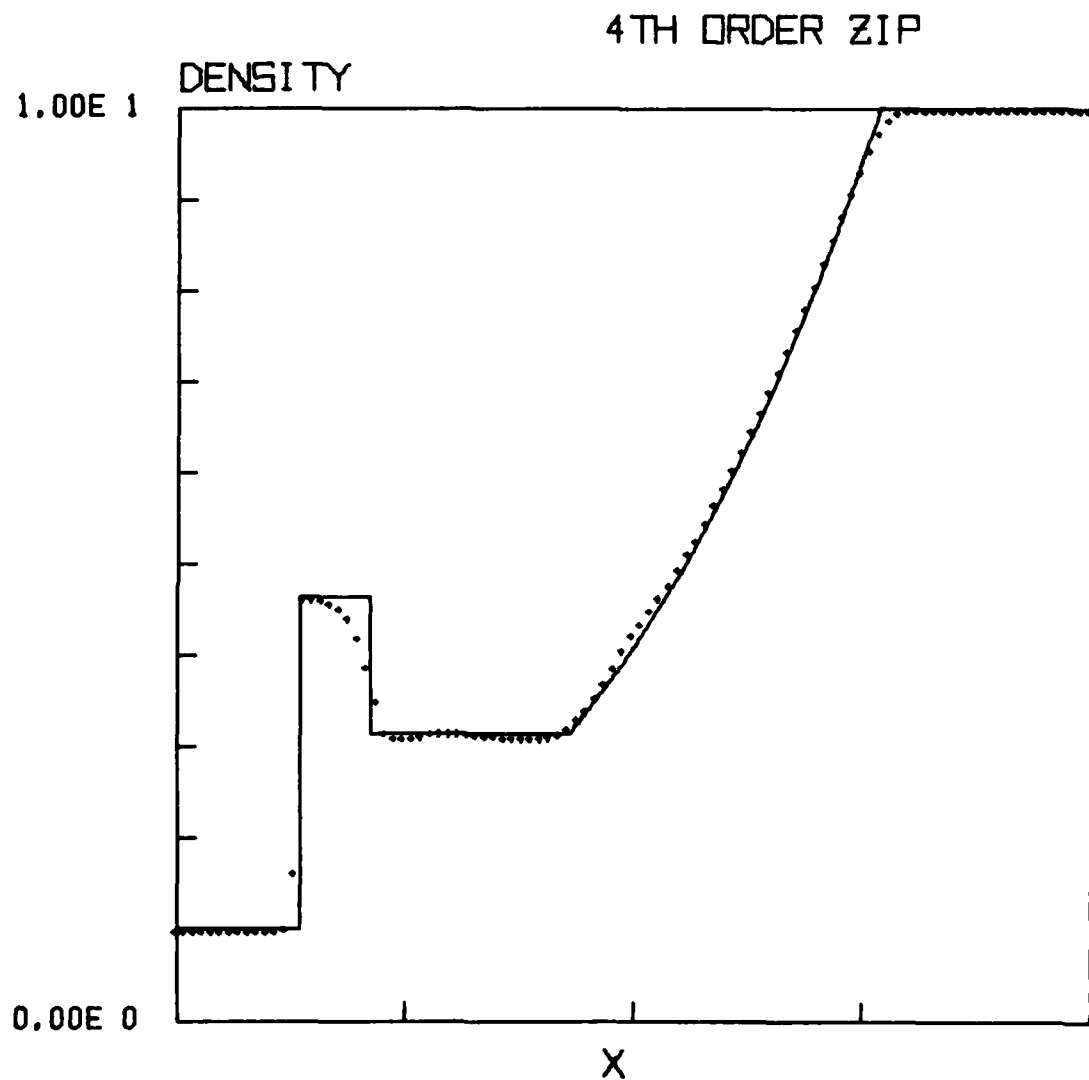
Fig. 2b - Same as Fig. 1 but for fourth order ZIP fluxes Eq. (18)

20

2ND ORDER VHAF

DENSITY
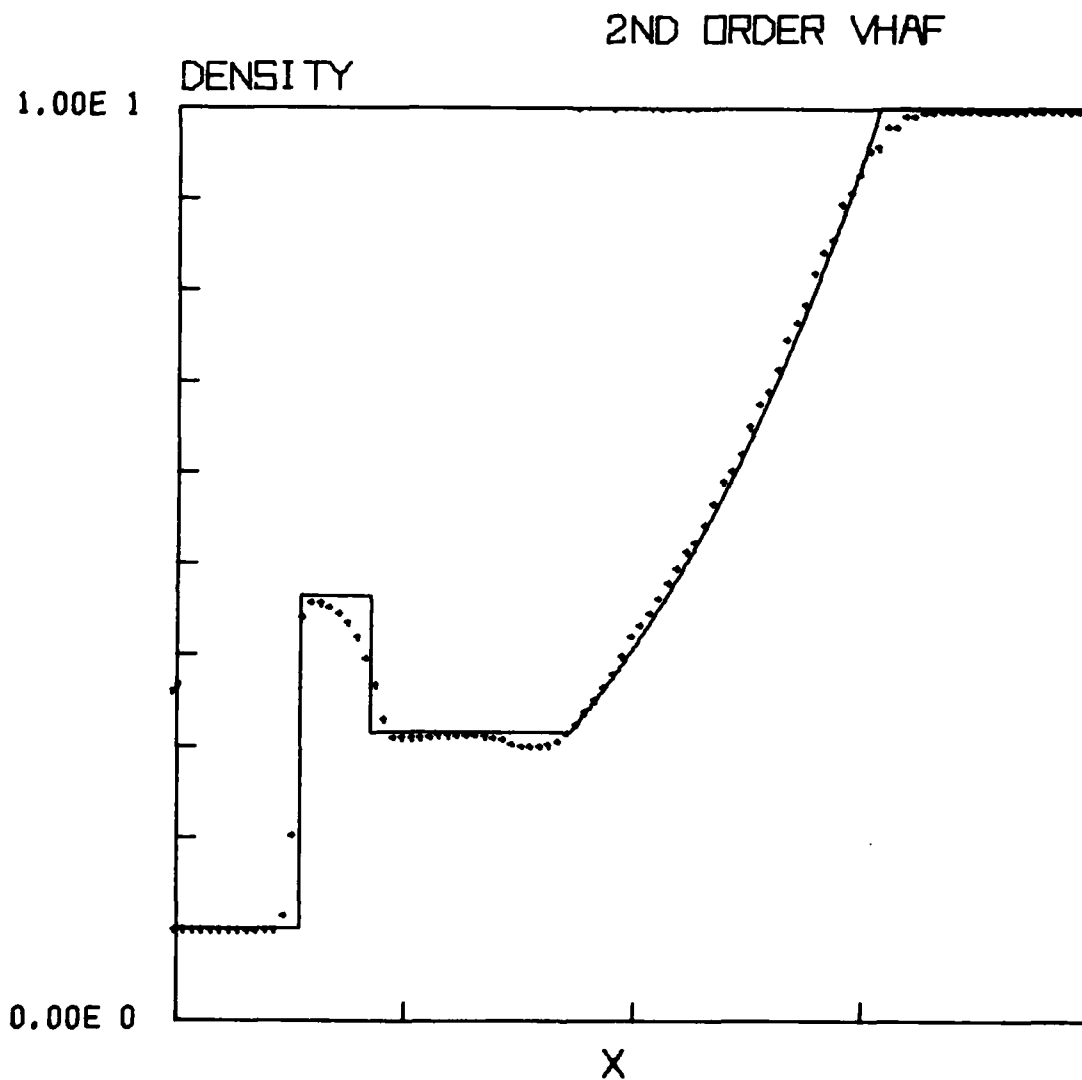
Fig. 3 - Same as Fig. 1 but for the second order convective
flux given by Eq. (26)

4TH STR D=1/12
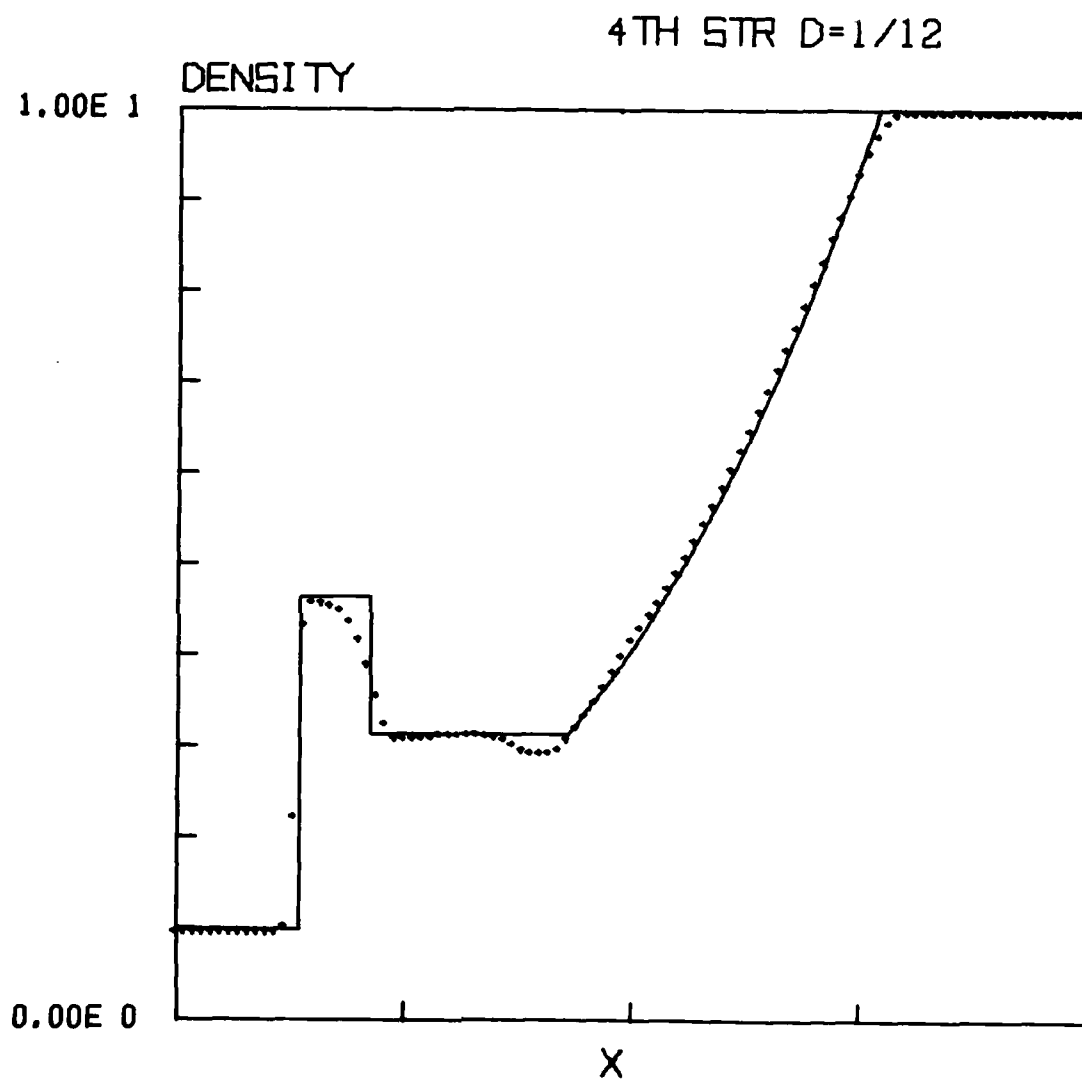
Fig. 4 — Same as Fig. 2a but with the addition of a fourth order
dissipation term given by Eq. (27)

Fig. 5 - Same as Fig. 2b but with the addition of a fourth order
dissipation term given by Eq. (27)

23

4TH ZIP + PV ZIP

DENSITY

1.00E 1

0.00E 0

X

Fig. 6 – Same as Fig. 2b but using the ZIP format for the term Pv
in the energy equation of (24)

DISTRIBUTION LIST

DEPARTMENT OF DEFENSE

ASSISTANT SECRETARY OF DEFENSE
COMM, CMD, CONT & INTELL
WASHINGTON, D.C. 20301
    01CY ATTN J. BABCOCK
    01CY ATTN M. EPSTEIN

ASSISTANT TO THE SECRETARY OF DEFENSE
ATOMIC ENERGY
WASHINGTON, D.C. 20301
    01CY ATTN EXECUTIVE ASSISTANT

DIRECTOR
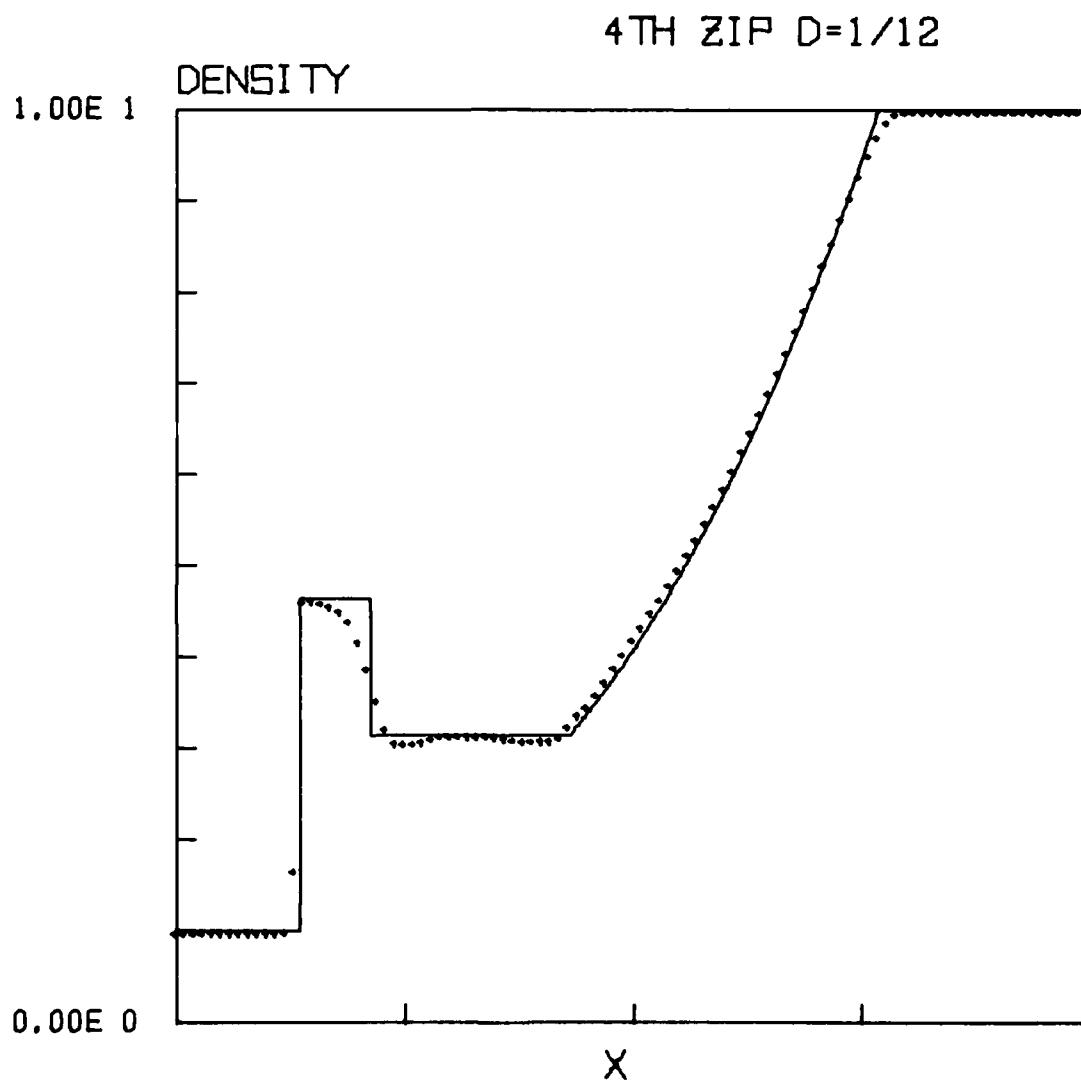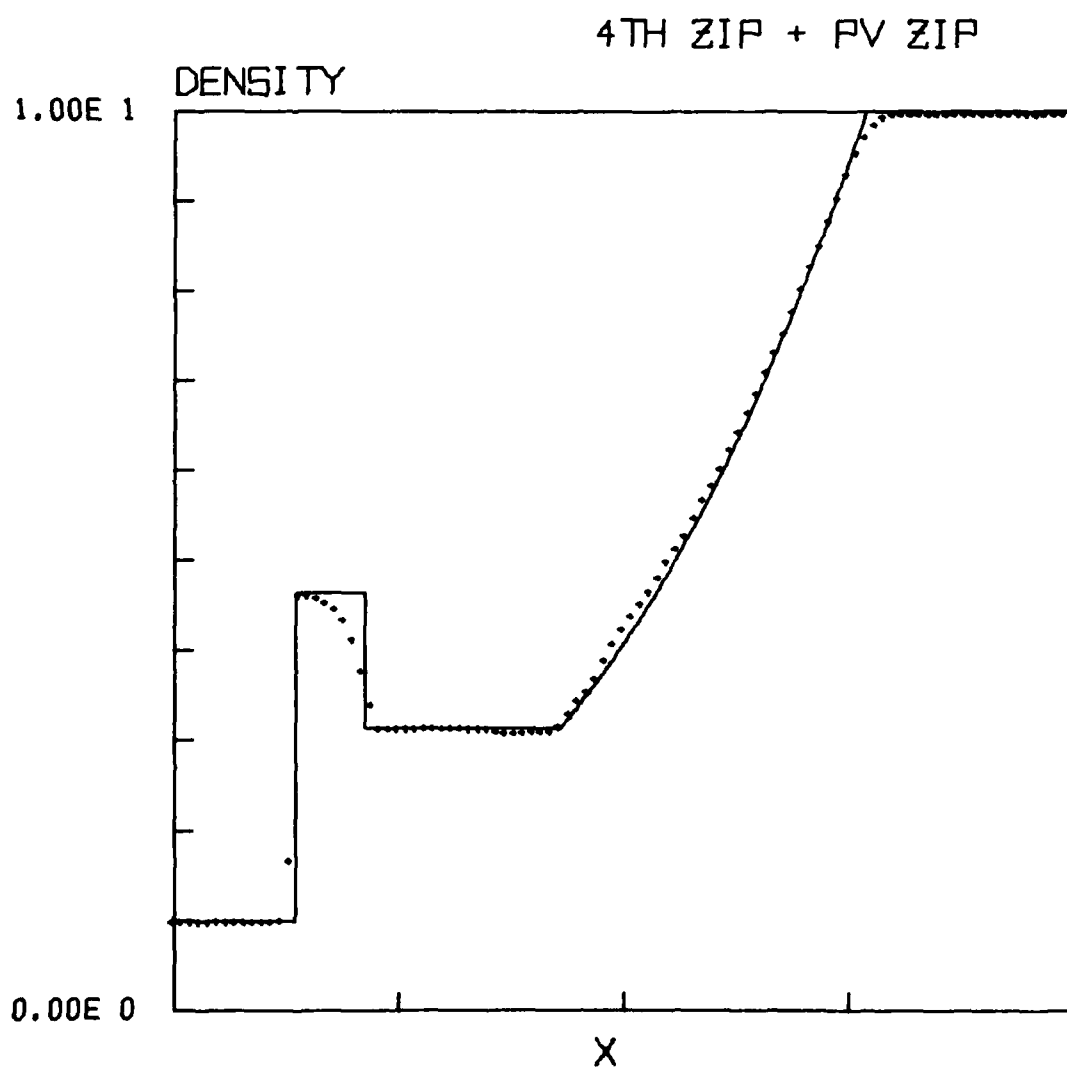COMMAND CONTROL TECHNICAL CENTER
PENTAGON RM BE 685
WASHINGTON, D.C. 20301
    01CY ATTN C-650
    01CY ATTN C-312 R. MASON

DIRECTOR
DEFENSE ADVANCED RSCH PROJ AGENCY
ARCHITECT BUILDING
1400 WILSON BLVD.
ARLINGTON, VA. 22209
    01CY ATTN NUCLEAR MONITORING RESEARCH
    01CY ATTN STRATEGIC TECH OFFICE

DEFENSE COMMUNICATION ENGINEER CENTER
1860 WIEHLE AVENUE
RESTON, VA. 22090
    01CY ATTN CODE R820
    01CY ATTN CODE R410 JAMES W. MCLEAN
    01CY ATTN CODE R720 J. WORTHINGTON

DIRECTOR
DEFENSE COMMUNICATIONS AGENCY
WASHINGTON, D.C. 20305
      (ADR CNWDI: ATTN CODE 240 FOR)
    01CY ATTN CODE 101B

DEFENSE DOCUMENTATION CENTER
CAMERON STATION
ALEXANDRIA, VA. 22314
    (12 COPIES IF OPEN PUBLICATION, OTHERWISE 2 COPIES)
    12CY ATTN TC

DIRECTOR
DEFENSE INTELLIGENCE AGENCY
WASHINGTON, D.C. 20301
    01CY ATTN DT-1B
    01CY ATTN DB-4C E. O'FARRELL
    01CY ATTN DIAAP A. WISE
    01CY ATTN DIAST-5
    01CY ATTN DT-1BZ R. MORTON
    01CY ATTN HQ-TR J. STEWART
    01CY ATTN W. WITTIG DC-7D

DIRECTOR
DEFENSE NUCLEAR AGENCY
WASHINGTON, D.C. 20305
    01CY ATTN STVL
    04CY ATTN TITL
    01CY ATTN DDST
    03CY ATTN RAAE

COMMANDER
FIELD COMMAND
DEFENSE NUCLEAR AGENCY
KIRTLAND AFB, NM 87115
    01CY ATTN FCPR

DIRECTOR
INTERSERVICE NUCLEAR WEAPONS SCHOOL
KIRTLAND AFB, NM 87115
    01CY ATTN DOCUMENT CONTROL

JOINT CHIEFS OF STAFF
WASHINGTON, D.C. 20301
    01CY ATTN J-3 WWMCCS EVALUATION OFFICE

DIRECTOR
JOINT STRAT TGT PLANNING STAFF
OFFUTT AFB
OMAHA, NB 68113
    01CY ATTN JLTW-2
    01CY ATTN JPST G. GOETZ

CHIEF
LIVERMORE DIVISION FLD COMMAND DNA
DEPARTMENT OF DEFENSE
LAWRENCE LIVERMORE LABORATORY
P. O. BOX 808
LIVERMORE, CA 94550
    01CY ATTN FCPRL

DIRECTOR
NATIONAL SECURITY AGENCY
DEPARTMENT OF DEFENSE
FT. GEORGE G. MEADE, MD 20755
    01CY ATTN JOHN SKILLMAN R52
    01CY ATTN FRANK LEONARD
    01CY ATTN W14 PAT CLARK
    01CY ATTN OLIVER H. BARTLETT W32
    01CY ATTN R5

COMMANDANT
NATO SCHOOL (SHAPE)
APO NEW YORK 09172
    01CY ATTN U.S. DOCUMENTS OFFICER

UNDER SECY OF DEF FOR RSCH & ENGRG
DEPARTMENT OF DEFENSE
WASHINGTON, D.C. 20301
    01CY ATTN STRATEGIC & SPACE SYSTEMS (OS)

WWMCCS SYSTEM ENGINEERING ORG
WASHINGTON, D.C. 20305
    01CY ATTN R. CRAWFORD

COMMANDER/DIRECTOR
ATMOSPHERIC SCIENCES LABORATORY
U.S. ARMY ELECTRONICS COMMAND
WHITE SANDS MISSILE RANGE, NM 88002
    01CY ATTN DELAS-EO F. NILES

DIRECTOR
BMD ADVANCED TECH CTR
HUNTSVILLE OFFICE
P. O. BOX 1500
HUNTSVILLE, AL 35807
    01CY ATTN ATC-T MELVIN T. CAPPS
    01CY ATTN ATC-O W. DAVIES
    01CY ATTN ATC-R DON RUSS

PROGRAM MANAGER
BMD PROGRAM OFFICE
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333
    01CY ATTN DACS-BMT J. SHEA

CHIEF C-E SERVICES DIVISION
U.S. ARMY COMMUNICATIONS CMD
PENTAGON RM 1B269
WASHINGTON, D.C. 20310
    01CY ATTN C-E-SERVICES DIVISION

COMMANDER
FRADCOM TECHNICAL SUPPORT ACTIVITY
DEPARTMENT OF THE ARMY.
FORT MONMOUTH, N.J. 07703
    01CY ATTN DRSEL-NL-RD H. BENNET
    01CY ATTN DRSEL-PL-ENV M. BOMKE
    01CY ATTN J. E. QUIGLEY

COMMANDER
HARRY DIAMOND LABORATORIES
DEPARTMENT OF THE ARMY
2800 POWDER MILL ROAD
ADELPHI, MD 20783
        (CNWDI-INNER ENVELOPE: ATTN: DELHD-RBH)
    01CY ATTN DELHD-TI M. WEINER
    01CY ATTN DELHD-RB R. WILLIAMS
    01CY ATTN DELHD-NP F. WIMENITZ
    01CY ATTN DELHD-NP C. MOAZED

COMMANDER
U.S. ARMY COMM-ELEC ENGRG INSTAL AGY
FT. HUACHUCA, AZ 85613

    01CY ATTN CCC-EMEO GEORGE LANE

COMMANDER
U.S. ARMY FOREIGN SCIENCE & TECH CTR
220 7TH STREET, NE
CHARLOTTESVILLE, VA 22901
    01CY ATTN DRXST-SD
    01CY ATTN R. JONES

COMMANDER
U.S. ARMY MATERIEL DEV & READINESS CMD
5001 EISENHOWER AVENUE
ALEXANDRIA, VA 22333
    01CY ATTN DRCLDC J. A. BENDER

COMMANDER
U.S. ARMY NUCLEAR AND CHEMICAL AGENCY
7500 BACKLICK ROAD
BLDG 2073
SPRINGFIELD, VA 22150
    01CY ATTN LIBRARY

DIRECTOR
U.S. ARMY BALLISTIC RESEARCH LABS
ABERDEEN PROVING GROUND, MD 21005
    01CY ATTN TECH LIB EDWARD BAICY

COMMANDER
U.S. ARMY SATCOM AGENCY
FT. MONMOUTH, NJ 07703
    01CY ATTN DOCUMENT CONTROL

COMMANDER
U.S. ARMY MISSILE INTELLIGENCE AGENCY
REDSTONE ARSENAL, AL 35809
    01CY ATTN JIM GAMBLE

DIRECTOR
U.S. ARMY TRADOC SYSTEMS ANALYSIS ACTIVITY
WHITE SANDS MISSILE RANGE, NM 88002
    01CY ATTN ATAA-SA
    01CY ATTN TCC/F. PAYAN JR.
    01CY ATTN ATAA-TAC LTC J. HESSE

COMMANDER
NAVAL ELECTRONIC SYSTEMS COMMAND
WASHINGTON, D.C. 20360
    01CY ATTN NAVALEX 034 T. HUGHES
    01CY ATTN PME 117
    01CY ATTN PME 117-T
    01CY ATTN CODE 5011

COMMANDING OFFICER
NAVAL INTELLIGENCE SUPPORT CTR
4301 SUITLAND ROAD, BLDG. 5
WASHINGTON, D.C. 20390
    01CY ATTN MR. DUBBIN STIC 12
    01CY ATTN NISC-50
    01CY ATTN CODE 5404 J. GALET

COMMANDER
NAVAL OCEAN SYSTEMS CENTER
SAN DIEGO, CA 92152
    03CY ATTN CODE 532 W. MOLER
    01CY ATTN CODE 0230 C. BAGGETT
    01CY ATTN CODE 81 R. EASTMAN

DIRECTOR
NAVAL RESEARCH LABORATORY
WASHINGTON, D.C. 20375
    01CY ATTN CODE 4700 TIMOTHY P. COFFEY (25 CYS
                            IF UNCLASS, 1 CY IF CLASS)
    01CY ATTN CODE 4701 JACK D. BROWN
    01CY ATTN CODE 4780 BRANCH HEAD (150 CYS
                            IF UNCLASS, 1 CY IF CLASS)
    01CY ATTN CODE 7500 HQ COMM DIR BRUCE WALD
    01CY ATTN CODE 7550 J. DAVIS
    01CY ATTN CODE 7580
    01CY ATTN CODE 7551
    01CY ATTN CODE 7555
    01CY ATTN CODE 4730 E. MCLEAN
    01CY ATTN CODE 4127 C. JOHNSON

COMMANDER
NAVAL SEA SYSTEMS COMMAND
WASHINGTON, D.C. 20362
    01CY ATTN CAPT R. PITKIN

COMMANDER
NAVAL SPACE SURVEILLANCE SYSTEM
DAHLGREN, VA 22448
    01CY ATTN CAPT J. H. BURTON

OFFICER-IN-CHARGE
NAVAL SURFACE WEAPONS CENTER
WHITE OAK, SILVER SPRING, MD 20910
    01CY ATTN CODE F31

DIRECTOR
STRATEGIC SYSTEMS PROJECT OFFICE
DEPARTMENT OF THE NAVY
WASHINGTON, D.C. 20376
    01CY ATTN NSP-2141
    01CY ATTN NSSP-2722 FRED WIMBERLY

NAVAL SPACE SYSTEM ACTIVITY
P. O. BOX 92960
WORLDWAY POSTAL CENTER
LOS ANGELES, CALIF. 90009
    01CY ATTN A. B. HAZZARD

COMMANDER
NAVAL SURFACE WEAPONS CENTER
DAHLGREN LABORATORY
DAHLGREN, VA 22448
    01CY ATTN CODE DF-14 R. BUTLER

COMMANDING OFFICER
NAVY SPACE SYSTEMS ACTIVITY
P.O. BOX 92960
WORLDWAY POSTAL CENTER
LOS ANGELES, CA. 90009
    01CY ATTN CODE 52

OFFICE OF NAVAL RESEARCH
ARLINGTON, VA 22217
    01CY ATTN CODE 465
    01CY ATTN CODE 461
    01CY ATTN CODE 402
    01CY ATTN CODE 420
    01CY ATTN CODE 421

COMMANDER
AEROSPACE DEFENSE COMMAND/DC
DEPARTMENT OF THE AIR FORCE
ENT AFB, CO 80912
    01CY ATTN DC MR. LONG

COMMANDER
AEROSPACE DEFENSE COMMAND/XPD
DEPARTMENT OF THE AIR FORCE
ENT AFB, CO 80912
    01CY ATTN XPDQQ
    01CY ATTN XP

AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MA 01731
    01CY ATTN OPR HAROLD GARDNER
    01CY ATTN OPR-1 JAMES C. ULWICK
    01CY ATTN LKB KENNETH S. W. CHAMPION
    01CY ATTN OPR ALVA T. STAIR
    01CY ATTN PHP JULES AARONS
    01CY ATTN PHD JURGEN BUCHAU
    01CY ATTN PHD JOHN P. MULLEN

AF WEAPONS LABORATORY
KIRTLAND AFB, NM 87117
    01CY ATTN SUL
    01CY ATTN CA ARTHUR H. GUENTHER
    01CY ATTN DYC CAPT J. BARRY
    01CY ATTN DYC JOHN M. KAMM
    01CY ATTN DYT CAPT MARK A. FRY
    01CY ATTN DES MAJ GARY GANONG
    01CY ATTN DYC J. JANNI

AFTAC
PATRICK AFB, FL 32925
    01CY ATTN TF/MAJ WILEY
    01CY ATTN TN

AIR FORCE AVIONICS LABORATORY
WRIGHT-PATTERSON AFB, OH 45433
    01CY ATTN AAD WADE HUNT
    01CY ATTN AAD ALLEN JOHNSON

DEPUTY CHIEF OF STAFF
RESEARCH, DEVELOPMENT, & ACQ
DEPARTMENT OF THE AIR FORCE
WASHINGTON, D.C. 20330
    01CY ATTN AFRDQ

HEADQUARTERS
ELECTRONIC SYSTEMS DIVISION/XR
DEPARTMENT OF THE AIR FORCE
HANSCOM AFB, MA 01731
    01CY ATTN XR J. DEAS

HEADQUARTERS
ELECTRONIC SYSTEMS DIVISION/YSEA
DEPARTMENT OF THE AIR FORCE
HANSCOM AFB, MA 01731
    01CY ATTN YSEA

HEADQUARTERS
ELECTRONIC SYSTEMS DIVISION/DC
DEPARTMENT OF THE AIR FORCE
HANSCOM AFB, MA 01731
    01CY ATTN DCKC MAJ J.C. CLARK

COMMANDER
FOREIGN TECHNOLOGY DIVISION, AFSC
WRIGHT-PATTERSON AFB, OH 45433
    01CY ATTN NICD LIBRARY
    01CY ATTN ETDP B. BALLARD

COMMANDER
ROME AIR DEVELOPMENT CENTER, AFSC
GRIFFISS AFB, NY 13441
    01CY ATTN DOC LIBRARY/TSLD
    01CY ATTN OCSE V. COYNE

SAMSO/SZ
POST OFFICE BOX 92960
WORLDWAY POSTAL CENTER
LOS ANGELES, CA 90009
(SPACE DEFENSE SYSTEMS)
    01CY ATTN SZJ

STRATEGIC AIR COMMAND/XPFS
OFFUTT AFB, NB 68113
    01CY ATTN XPFS MAJ B. STEPHAN
    01CY ATTN ADWATE MAJ BRUCE BAUER
    01CY ATTN NRT
    01CY ATTN DOK CHIEF SCIENTIST

SAMSO/YA
P. O. BOX 92960
WORLDWAY POSTAL CENTER
LOS ANGELES, CA 90009
    01CY ATTN YAT CAPT L. BLACKWELDER

SAMSO/SK
P. O. BOX 92960
WORLDWAY POSTAL CENTER
LOS ANGELES, CA 90009
    01CY ATTN SKA (SPACE COMM SYSTEMS) M. CLAVIN

SAMSO/MN
NORTON AFB, CA 92409
(MINUTEMAN)
    01CY ATTN MNNL LTC KENNEDY

COMMANDER
ROME AIR DEVELOPMENT CENTER, AFSC
HANSCOM AFB, MA 01731
    01CY ATTN EEP A. LORENTZEN

DEPARTMENT OF ENERGY
ALBUQUERQUE OPERATIONS OFFICE
P. O. BOX 5400
ALBUQUERQUE, NM 87115
    01CY ATTN DOC CON FOR D. SHERWOOD

DEPARTMENT OF ENERGY
LIBRARY ROOM G-042
WASHINGTON, D.C. 20545
    01CY ATTN DOC CON FOR A. LABOWITZ

EG&G, INC.
LOS ALAMOS DIVISION
P. O. BOX 809
LOS ALAMOS, NM 85544
    01CY ATTN DOC CON FOR J. BREEDLOVE

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE LABORATORY
P. O. BOX 808
LIVERMORE, CA 94550
    01CY ATTN DOC CON FOR TECH INFO DEPT
    01CY ATTN DOC CON FOR L-389 R. OTT
    01CY ATTN DOC CON FOR L-31 R. HAGER
    01CY ATTN DOC CON FOR L-46 F. SEWARD

LOS ALAMOS SCIENTIFIC LABORATORY
P. O. BOX 1663
LOS ALAMOS, NM 87545
    01CY ATTN DOC CON FOR J. WOLCOTT
    01CY ATTN DOC CON FOR R. F. TASCHEK
    01CY ATTN DOC CON FOR E. JONES
    01CY ATTN DOC CON FOR J. MALIK
    01CY ATTN DOC CON FOR R. JEFFRIES
    01CY ATTN DOC CON FOR J. ZINN
    01CY ATTN DOC CON FOR P. KEATON
    01CY ATTN DOC CON FOR D. WESTERVELT

SANDIA LABORATORIES
P. O. BOX 5800
ALBUQUERQUE, NM 87115
    01CY ATTN DOC CON FOR J. MARTIN
    01CY ATTN DOC CON FOR W. BROWN
    01CY ATTN DOC CON FOR A. THORNBROUGH
    01CY ATTN DOC CON FOR T. WRIGHT
    01CY ATTN DOC CON FOR D. DAHLGREN
    01CY ATTN DOC CON FOR 3141
    01CY ATTN DOC CON FOR SPACE PROJECT DIV

SANDIA LABORATORIES
LIVERMORE LABORATORY
P. O. BOX 969
LIVERMORE, CA 94550
    01CY ATTN DOC CON FOR B. MURPHEY
    01CY ATTN DOC CON FOR T. COOK

OFFICE OF MILITARY APPLICATION
DEPARTMENT OF ENERGY
WASHINGTON, D.C. 20545
    01CY ATTN DOC CON FOR D. GALE

OTHER GOVERNMENT

CENTRAL INTELLIGENCE AGENCY
ATTN RD/SI, RM 5G48, HQ BLDG
WASHINGTON, D.C. 20505
    01CY ATTN OSI/PSID RM 5F 19

DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234
    (ALL CORRES: ATTN SEC OFFICER FOR)
    01CY ATTN R. MOORE

INSTITUTE FOR TELECOM SCIENCES
NATIONAL TELECOMMUNICATIONS & INFO ADMIN
BOULDER, CO 80303
    01CY ATTN A. JEAN (UNCLASS ONLY)
    01CY ATTN W. UTLAUT
    01CY ATTN D. CROMBIE
    01CY ATTN L. BERRY

NATIONAL OCEANIC & ATMOSPHERIC ADMIN
ENVIRONMENTAL RESEARCH LABORATORIES
DEPARTMENT OF COMMERCE
BOULDER, CO 80302
    01CY ATTN R. GRUBB
    01CY ATTN AERONOMY LAB G. REID

DEPARTMENT OF DEFENSE CONTRACTORS

AEROSPACE CORPORATION
P. O. BOX 92957
LOS ANGELES, CA 90009
    01CY ATTN I. GARFUNKEL
    01CY ATTN T. SALMI
    01CY ATTN V. JOSEPHSON
    01CY ATTN S. BOWER
    01CY ATTN N. STOCKWELL
    01CY ATTN D. OLSEN
    01CY ATTN J. CARTER
    01CY ATTN F. MORSE
    01CY ATTN SMFA FOR PWW

ANALYTICAL SYSTEMS ENGINEERING CORP
5 OLD CONCORD ROAD
BURLINGTON, MA 01803
    01CY ATTN RADIO SCIENCES

BERKELEY RESEARCH ASSOCIATES, INC.
P. O. BOX 983
BERKELEY, CA 94701
    01CY ATTN J. WORKMAN

BOEING COMPANY, THE
P. O. BOX 3707
SEATTLE, WA 98124
    01CY ATTN G. KEISTER
    01CY ATTN D. MURRAY
    01CY ATTN G. HALL
    01CY ATTN J. KENNEY

CALIFORNIA AT SAN DIEGO, UNIV OF
IPAPS, B-019
LA JOLLA, CA 92093
    01CY ATTN HENRY G. BOOKER

BROWN ENGINEERING COMPANY, INC.
CUMMINGS RESEARCH PARK
HUNTSVILLE, AL 35807
    01CY ATTN ROMEO A. DELIBERIS

CHARLES STARK DRAPER LABORATORY, INC.
555 TECHNOLOGY SQUARE
CAMBRIDGE, MA 02139
    01CY ATTN D. B. COX
    01CY ATTN J. P. GILMORE

COMPUTER SCIENCES CORPORATION
6565 ARLINGTON BLVD
FALLS CHURCH, VA 22046
    01CY ATTN H. BLANK
    01CY ATTN JOHN SPOOR
    01CY ATTN C. NAIL

COMSAT LABORATORIES
LINTHICUM ROAD
CLARKSBURG, MD 20734
    01CY ATTN G. HYDE

CORNELL UNIVERSITY
DEPARTMENT OF ELECTRICAL ENGINEERING
ITHACA, NY 14850
    01CY ATTN D. T. FARLEY JR

ELECTROSPACE SYSTEMS, INC.
BOX 1359
RICHARDSON, TX 75080
    01CY ATTN H. LOGSTON
    01CY ATTN SECURITY (PAUL PHILLIPS)

ESL INC.
495 JAVA DRIVE
SUNNYVALE, CA 94086
    01CY ATTN J. ROBERTS
    01CY ATTN JAMES MARSHALL
    01CY ATTN C. W. PRETTIE

FORD AEROSPACE & COMMUNICATIONS CORP
3939 FABIAN WAY
PALO ALTO, CA 94303
    01CY ATTN J. T. MATTINGLEY

GENERAL ELECTRIC COMPANY
SPACE DIVISION
VALLEY FORGE SPACE CENTER
GODDARD BLVD KING OF PRUSSIA
P. O. BOX 8555
PHILADELPHIA, PA 19101
    01CY ATTN M. H. BORTNER SPACE SCI LAB

GENERAL ELECTRIC COMPANY
P. O. BOX 1122
SYRACUSE, NY 13201
    01CY ATTN F. REIBERT

GENERAL ELECTRIC COMPANY
TEMPO-CENTER FOR ADVANCED STUDIES
816 STATE STREET (P.O. DRAWER QQ)
SANTA BARBARA, CA 93102
    01CY ATTN DASIAC
    01CY ATTN DON CHANDLER
    01CY ATTN TOM BARRETT
    01CY ATTN TIM STEPHANS
    01CY ATTN WARREN S. KNAPP
    01CY ATTN WILLIAM MCNAMARA
    01CY ATTN B. GAMBILL
    01CY ATTN MACK STANTON

GENERAL ELECTRIC TECH SERVICES CO., INC.
HMES
COURT STREET
SYRACUSE, NY 13201
    01CY ATTN G. MILLMAN

GENERAL RESEARCH CORPORATION
SANTA BARBARA DIVISION
P. O. BOX 6770
SANTA BARBARA, CA 93111
    01CY ATTN JOHN ISE JR
    01CY ATTN JOEL GARBARINO

GEOPHYSICAL INSTITUTE
UNIVERSITY OF ALASKA
FAIRBANKS, AK 99701
    (ALL CLASS ATTN: SECURITY OFFICER)
    01CY ATTN T. N. DAVIS (UNCL ONLY)
    01CY ATTN NEAL BROWN (UNCL ONLY)
    01CY ATTN TECHNICAL LIBRARY

GTE SYLVANIA, INC.
ELECTRONICS SYSTEMS GRP-EASTERN DIV
77 A STREET
NEEDHAM, MA 02194
    01CY ATTN MARSHAL CROSS

ILLINOIS, UNIVERSITY OF
DEPARTMENT OF ELECTRICAL ENGINEERING
URBANA, IL 61803
    01CY ATTN K. YEH

ILLINOIS, UNIVERSITY OF
107 COBLE HALL
801 S. WRIGHT STREET
URBANA, IL 60680
    (ALL CORRES ATTN SECURITY SUPERVISOR FOR)
    01CY ATTN K. YEH

INSTITUTE FOR DEFENSE ANALYSES
400 ARMY-NAVY DRIVE
ARLINGTON, VA 22202
    01CY ATTN J. M. AEIN
    01CY ATTN ERNEST BAUER
    01CY ATTN HANS WOLFHARD
    01CY ATTN JOEL BENGSTON

HSS, INC.
2 ALFRED CIRCLE
BEDFORD, MA 01730
    01CY ATTN DONALD HANSEN

INTL TEL & TELEGRAPH CORPORATION
500 WASHINGTON AVENUE
NUTLEY, NJ 07110
    01CY ATTN TECHNICAL LIBRARY

JAYCOR
1401 CAMINO DEL MAR
DEL MAR, CA 92014

JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
JOHNS HOPKINS ROAD
LAUREL, MD 20810
    01CY ATTN DOCUMENT LIBRARIAN
    01CY ATTN THOMAS POTEMRA
    01CY ATTN JOHN DASSOULAS

LOCKHEED MISSILES & SPACE CO INC
P. O. BOX 504
SUNNYVALE, CA 94088
    01CY ATTN DEPT 60-12
    01CY ATTN D. R. CHURCHILL

LOCKHEED MISSILES AND SPACE CO INC
3251 HANOVER STREET
PALO ALTO, CA 94304
    01CY ATTN MARTIN WALT DEPT 52-10
    01CY ATTN RICHARD G. JOHNSON DEPT 52-12
    01CY ATTN W. L. IMHOF DEPT 52-12

KAMAN SCIENCES CORP
P. O. BOX 7463
COLORADO SPRINGS, CO 80933
    01CY ATTN T. MEAGHER

LINKABIT CORP
10453 ROSELLE
SAN DIEGO, CA 92121
    01CY ATTN IRWIN JACOBS

M.I.T. LINCOLN LABORATORY
P. O. BOX 73
LEXINGTON, MA 02173
    01CY ATTN DAVID M. TOWLE
    01CY ATTN P. WALDRON
    01CY ATTN L. LOUGHLIN
    01CY ATTN D. CLARK

MARTIN MARIETTA CORP
ORLANDO DIVISION
P. O. BOX 5837
ORLANDO, FL 32805
    01CY ATTN R. HEFFNER

MCDONNELL DOUGLAS CORPORATION
5301 BOLSA AVENUE
HUNTINGTON BEACH, CA 92647
    01CY   ATTN N. HARRIS
    01CY   ATTN J. MOULE
    01CY   ATTN GEORGE MROZ
    01CY   ATTN W. OLSON
    01CY   ATTN R. W. HALPRIN
    01CY   ATTN TECHNICAL LIBRARY SERVICES

MISSION RESEARCH CORPORATION
735 STATE STREET
SANTA BARBARA, CA 93101
    01CY   ATTN P. FISCHER
    01CY   ATTN W. F. CREVIER
    01CY   ATTN STEVEN L. GUTSCHE
    01CY   ATTN D. SAPPENFIELD
    01CY   ATTN R. BOGUSCH
    01CY   ATTN R. HENDRICK
    01CY   ATTN RALPH KILB
    01CY   ATTN DAVE SOWLE
    01CY   ATTN F. FAJEN
    01CY   ATTN M. SCHEIBE
    01CY   ATTN CONRAD L. LONGMIRE
    01CY   ATTN WARREN A. SCHLUETER

MITRE CORPORATION, THE
P. O. BOX 208
BEDFORD, MA 01730
    01CY   ATTN JOHN MORGANSTERN
    01CY   ATTN G. HARDING
    01CY   ATTN C. E. CALLAHAN

MITRE CORP
WESTGATE RESEARCH PARK
1820 DOLLY MADISON BLVD
MCLEAN, VA 22101
    01CY   ATTN W. HALL
    01CY   ATTN W. FOSTER

PACIFIC-SIERRA RESEARCH CORP
1456 CLOVERFIELD BLVD.
SANTA MONICA, CA 90404
    01CY   ATTN E. C. FIELD JR

PENNSYLVANIA STATE UNIVERSITY
IONOSPHERE RESEARCH LAB
318 ELECTRICAL ENGINEERING EAST
UNIVERSITY PARK, PA 16802
    (NO CLASSIFIED TO THIS ADDRESS)
    01CY   ATTN IONOSPHERIC RESEARCH LAB

PHOTOMETRICS, INC.
442 MARRETT ROAD
LEXINGTON, MA 02173
    01CY   ATTN IRVING L. KOFSKY

PHYSICAL DYNAMICS INC.
P. O. BOX 3027
BELLEVUE, WA 98009
    01CY   ATTN E. J. FREMOUW

PHYSICAL DYNAMICS INC.
P. O. BOX 1069
BERKELEY, CA 94701
    01CY   ATTN A. THOMPSON

R & D ASSOCIATES
P. O. BOX 9695
MARINA DEL REY, CA 90291
    01CY   ATTN FORREST GILMORE
    01CY   ATTN BRYAN GABBARD
    01CY   ATTN WILLIAM B. WRIGHT JR
    01CY   ATTN ROBERT F. LELEVIER
    01CY   ATTN WILLIAM J. KARZAS
    01CY   ATTN H. ORY
    01CY   ATTN C. MACDONALD
    01CY   ATTN R. TURCO

RAND CORPORATION, THE
1700 MAIN STREET
SANTA MONICA, CA 90406
    01CY   ATTN CULLEN CRAIN
    01CY   ATTN ED BEDROZIAN

RIVERSIDE RESEARCH INSTITUTE
80 WEST END AVENUE
NEW YORK, NY 10023
    01CY   ATTN VINCE TRAPANI

SCIENCE APPLICATIONS, INC.
P. O. BOX 2351
LA JOLLA, CA 92038
    01CY   ATTN LEWIS M. LINSON
    01CY   ATTN DANIEL A. HAMLIN
    01CY   ATTN D. SACHS
    01CY   ATTN E. A. STRAKER
    01CY   ATTN CURTIS A. SMITH
    01CY   ATTN JACK MCDOUGALL

RAYTHEON CO.
528 BOSTON POST ROAD
SUDBURY, MA 01776
    01CY   ATTN BARBARA ADAMS

SCIENCE APPLICATIONS, INC.
HUNTSVILLE DIVISION
2109 W. CLINTON AVENUE
SUITE 700
HUNTSVILLE, AL 35805
    01CY   ATTN DALE H. DIVIS

SCIENCE APPLICATIONS, INCORPORATED
8400 WESTPARK DRIVE
MCLEAN, VA 22101
    01CY   ATTN J. COCKAYNE

SCIENCE APPLICATIONS, INC.
80 MISSION DRIVE
PLEASANTON, CA 94566
    01CY   ATTN SZ

SRI INTERNATIONAL
333 RAVENSWOOD AVENUE
MENLO PARK, CA 94025
    01CY   ATTN DONALD NEILSON
    01CY   ATTN ALAN BURNS
    01CY   ATTN G. SMITH
    01CY   ATTN L. L. COBB
    01CY   ATTN DAVID A. JOHNSON
    01CY   ATTN WALTER G. CHESNUT
    01CY   ATTN CHARLES L. RINO
    01CY   ATTN WALTER JAYE
    01CY   ATTN M. BARON
    01CY   ATTN RAY L. LEADABRAND
    01CY   ATTN G. CARPENTER
    01CY   ATTN G. PRICE
    01CY   ATTN J. PETERSON
    01CY   ATTN R. HAKE, JR.
    01CY   ATTN V. GONZALES
    01CY   ATTN D. MCDANIEL

TECHNOLOGY INTERNATIONAL CORP
75 WIGGINS AVENUE
BEDFORD, MA 01730
    01CY ATTN W. P. BOQUIST

TRW DEFENSE & SPACE SYS GROUP
ONE SPACE PARK
REDONDO BEACH, CA 90278
    01CY ATTN R. K. PLEBUCH
    01CY ATTN S. ALTSCHULER
    01CY ATTN D. DEE

VISIDYNE, INC.
19 THIRD AVENUE
NORTH WEST INDUSTRIAL PARK
BURLINGTON, MA 01803
    01CY ATTN CHARLES HUMPHREY
    01CY ATTN J. W. CARPENTER