GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[X] ORIGINAL [ ] REVISION NO. ______

Project No. E-19-636 (R-5757-2A0) GTRC/XXX DATE 6 / 20 / 85

Project Director: A. Yoganathan School/XXX Chem. Eng

Sponsor: American Heart Assoc.

Type Agreement: Grant in - aid agreement dated 7/1/85

Award Period: From 7/1/85 To ~~6/30/86~~ 12-1-86 (Performance) 8/30/86 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$
Funded:	$ 19,250	$ 19,250

Cost Sharing Amount: $ N/A Cost Sharing No: N/A

Title: Computer Simulation of Flow Through Trileaflet Heart Valve

ADMINISTRATIVE DATA

OCA Contact Ralph Grede x4820

1) Sponsor Technical Contact:

Ms. Charles Taylor
American Heart Association
Georgia Affiliate
Box 13589
Atlanta, GA 30324

2) Sponsor Admin/Contractual Matters:

Defense Priority Rating: N/A

Military Security Classification: N/A

(or) Company/Industrial Proprietary: N/A

RESTRICTIONS

See Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with N/A

COMMENTS:

Grant - Aid Agreement from Amer. Heart Assoc. See paragraph 10 of agreement for Publication restrictions, paragraph 7 for Patents and paragraph 12 for Personnel restrictions.

COPIES TO:

SPONSOR'S I. D. NO. 02.500.011.85.002

Project Director
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Accounting

Procurement/GTRI Supply Services
Research Security Services
Reports Coordinator (OCA)
Research Communications (2)

GTRC
Library
Project File
Other A. Jones

GEORGIA INSTITUTE OF TECHNOLOGY

OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date April 27, 1987

Project No. E-19-636

School/~~Lab~~ Chem. Engr

Includes Subproject No.(s) N/A

Project Director(s) A. Yoganathan

GTRC / ~~GIT~~

Sponsor American Heart Assoc.

Title Computer Simulation of Flow Through Trileaflet Heart Valve

Effective Completion Date: 12/1/86 (Performance) 1/2/87 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Continues Project No. E-19-666

Continued by Project No.

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Project File
Other Duane H.
Angela DuBose
M. Heyser
~~Russ Embry~~

FORM OCA 69.285

AHA, GEORGIA AFFILIATE
Broadview Plaza -Level C
2581 Piedmont Road, N.E.
Atlanta, Georgia 30324

FINANCIAL REPORT FORM for A.H.A. GRANT-IN-AID

TO: Fiscal Officer, William H. Borchert, Vice President for Finance

It will be appreciated if you will provide at your earliest convenience the information requested on the following project:

TITLE OF PROJECT: "Computer Simulation of Flow Through Trileaflet Heart Valves"

PRINCIPAL INVESTIGATOR: Ajit P. Yoganathan, Ph. D

AMOUNT OF GRANT:

Principal $ 17,500.00

Overhead $ 1,750.00 TOTAL $ 19,250.00

TO: American Heart Association, Georgia Affiliate

The following information submitted in accordance with conditions under which the above described grant was made.

EXPENDITURES FROM PRINCIPAL GRANT FROM JULY 1, 1985 TO JUNE 30, 1986.

Category	Amount	Category	Amount
Personnel	$ 12,499.99	Travel	$ - 0 -
Equipment	$ - 0 -	Other: Overhead	$ 1,715.43
Supplies	$ 4,654.06		$
(Computer Charges)		**TOTAL THROUGH JUNE 30**	$ 18,869.48

***BALANCE OF PRINCIPAL UNEXPENDED AS OF JUNE 30** .... $ 380.52

Comments:

Submitted by: Valeria D. Henderson

Institution: Georgia Institute of Technology

Date: September 19, 1986

E-19-636/R57572A0

AMERICAN HEART ASSOCIATION - GEORGIA AFFILIATE

COMPUTER SIMULATION OF FLOW THROUGH TRILIEAFLET HEART VALVES

(GRANT-IN-AID)

FINAL REPORT (7/1/85 - 11/30/86)

I. Principal Investigator

Professor Ajit P. Yoganathan, Ph.D., Georgia Tech

II. Project Report

Both *in vivo* and *in vitro* hemodynamic studies indicate that the trileaflet tissue valves in current clinical use have inferior fluid dynamic characteristics, especially in the smaller sizes. The perceived increased use of the new low-pressure fixed tissue valves for heart valve replacement and in valved conduits, together with the need for cheap, disposable and fluid mechanically efficient trileaflet valves in short and long term LVADs require detailed fundamental studies of the trileaflet design concept. *In vitro* studies indicate that the fluid dynamic characteristics of some of the current trileaflet designs can be improved by improving the design characteristics of the valve leaflets and supporting stent structures.

The aim of the present study is to provide a relatively realistic simulation of blood flow through trileaflet tissue valves. The ultimate goal of this research effort is to develop the means for designing trileaflet valves which are more fluid dynamically efficient and clinically useful. The aortic trileaflet tissue valve design was chosen as the subject of this study, since it is the only popular valve in current clinical use which is approximately axisymmetric. An axisymmetric geometry is computationally more convenient since it involves only two dimensional equations. An extension to three dimensions may be conceptually simple, but the actual implementation is very difficult.

The problem of numerically modeling flow through heart valves must first be characterized before choosing a solution algorithm (method). A thorough review of the literature on previous modeling attempts revealed that the unsteady character of the flow had not been investigated with a solver capable of resolving the viscous shear layer at realistic Reynolds numbers. Therefore, an algorithm was sought which would accomplish this goal. In addition, it was decided that only primitive variable formulations would be considered for ease of boundary conditions, as well as future upgrading to three dimensional studies. In the short term, this was a difficult choice since these types of algorithms have not been widely applied to unsteady, incompessible, internal flow fields, as encountered with a heart valve.

The first algorithm which we chose to study was the method of pseudocompressibility (MOP). Some recent work of Kwak, Chang and co-workers, and Choi, Merkel and co-workers had successfully used this for asymptotic steady state solutions for internal and incompressible flow problems. MOP is a slight modification of the Beam-Warning algorithm which has been widely used by the aerospace industry for over a decade in complex compressible flow predictions. This experience, plus the recent success in internal and incompressible flow problems, led us to try to adapt it for our problem. In order to use MOP for unsteady flow, the incompressibility condition (zero velocity divergence) must be enforced at every time step. We attempted to do this using successive overrelaxation to solve for pressure so that the divergence at each node deceased below a convergence criteria. Axial and radial velociteis were simultaneously updated. This technique was borrowed from the marker and cell algorithm, and adapted so that pressure and velocity variables were all located at the same physical location.

This MOP algorithm was coded in Fortran in genral curvilinear coordinates for use in complex geometries. Since it involved the solution of a block tridiagonal matrix and an iterative pressure solution for each time step, it was quite expensive to run. This, plus large memory requirements, required the use of Georgia Tech's Cyber 990 with a virtual memory operating system. The program was also run on a supercomputer in Seattle, WA.

The MOP solver was then used for flow fields through stenosis geometries for which experimental measurements existed. At low Reynolds numbers or mild stenoses the results were similar to the measurements. However, for higher Reynolds numbers or more severe stenoses, convegence was not achieved. In addition, due to the size and complexity of the cord, modification and testing were very time consuming. Since the asymptotic solutions to steady state were not acceptable, we decided not to attempt unsteady solutions at that time. Instead, we sought a simpler algorithm which would allow rapid modification and testing, even if it was limited to slower convergence than the implicit MOP scheme.

The marker and cell algorithm (MAC) was developed at Los Alamos in the 1960's. It uses an explicit guess for axial and radial velocity, and then uses the pressure/velocity iteration schemem described above. However, MAC uses a staggered grid in which the two velocity components and pressure are all located at different points in each finite different cell (See Figure 1). This is in contrast to the MOP where we tried an MAC type update, but on a "classic" grid where all variables are identically located.

This scheme was coded in Fortran for a cartesian grid representing an axisymmetric geometry. It was decided that many of the features of flow in the vicinity of heart valves could be initially studied without resorting to the much more complicated curvilinear coordinates. The algorithm has been validated for unsteady and physiological boundary conditions, sudden expansions, sudden contractions, larminar vortex shedding and time accuracy. The algorithm has been successfully tested for the following:

(i) Time accuracy and pressure driving force-axisymmetric startup flow

(ii) Time accuracy and separated regions - Issa et al., test case (see figure 2)

(iii) Vortex shedding phenomena - Issa et al., test case but at Re = 1000 (See figure 3).

The pulsatile flow computer simulation algorithm has been coded and debugged on a Vax 780 computer system. The program, however, has to be run on a super computer system, for time and cost effectiveness. The program uses the following phyiologic parameters: (i) heart rate of 70 beats/min; (ii) systolic duration of 300 ms; and (iii) cardiac ouputs of 2 and 5 liters/min. At this point the turbulence algorithm has not been coded due to problems encountered with numerical instabilities. We have concentrated our efforts during the past year to develop the best flow simulation model. Without the appropriate flow simulation model, the use of a turbulence model would be worthless. With industrial funding we have obtained for the current year we will pursue the turbulence model. In the simulation the leaflet is moved from the closed to fully open position in five discrete steps as shown in Figure 4. The flow fields at these time steps (at a cardiac ouput of 2 liters/min) are shown in schematic form in Figure 4. These results indicate that the flow simulation model is functioning properly. The model is numerically stable, even though it is slow and time consuming at present. Further refinement of the model in our future work should make it more time efficient. Our main priortiy during the initial development of the model was to obtain numerical convergence and stability.

Lay Summary

This research work is mainly directed towards understanding the flow of blood through various designs of trileaflet heart valve prostheses. It is proposed to use a sophisticated computer model to evaluate how various parameters of trileaflet valve designs affect their performance. Such parameters are: (i) leaflet shape, (ii) leaflet size, (iii) stent design and (iv) orifice design. These parameters will be varied in the computer model in order to optimize the designs of trileaflet valves.

Trileaflet valves in current clinical use do not possess good hemodynamic (fluid mechanic) characteristics, especially in the smaller sizes. It is our opinion these poor performance characteristics are due to poor design criteria. With the proposed computer model it is planned to study a variety of trileaflet valve designs which could be used: (i) for heart valve replacement, (ii) in short and long term left ventricular assist devices, (iii) in a total artificial heart.

III. Collaborators

Frank P. Williams, M.S.,

Dana M. Stevenson, Ph.D.

Both collaborators worked on the computer algorithms used in this research work

IV. Publications

(A) Abstracts and Presentations

1. Williams, F.P. and Yoganathan, A.P., "Numerical Cardiovascular Studies", Scientific Meeting, Georgia Heart Association, Athens, GA, August 1986.

2. Yoganathan, A.P., and Williams, F.P., "Numerical Simulation of Fluid Flow Through on Axisymmetric Aortic Valve - Like Geometry" Annual Meeting American Institute of Chemical Engineers, Miami, FL, November 1986.

(B) Manuscripts

1. Stevenson, D.M., Yoganathan, A.P. and Williams, F.P., "Numerical Simulation of Steady Turbulent Flow Through Trileaflet Aortic Heart Valves - Results on Five Models" Journal of Biomechanics 19, pp. 909-926 (1985).

V. Research Continuation

(A) Work on this project is continuing in order to implement turbulence into the unsteady flow model.

(B) Funding from industrial sources ($15000) has been obtained for the period 7/1/86-6/60/87. We also plan to submit a NIH proposal in June 1987.

MARKER AND CELL ALGORITHM (MAC)

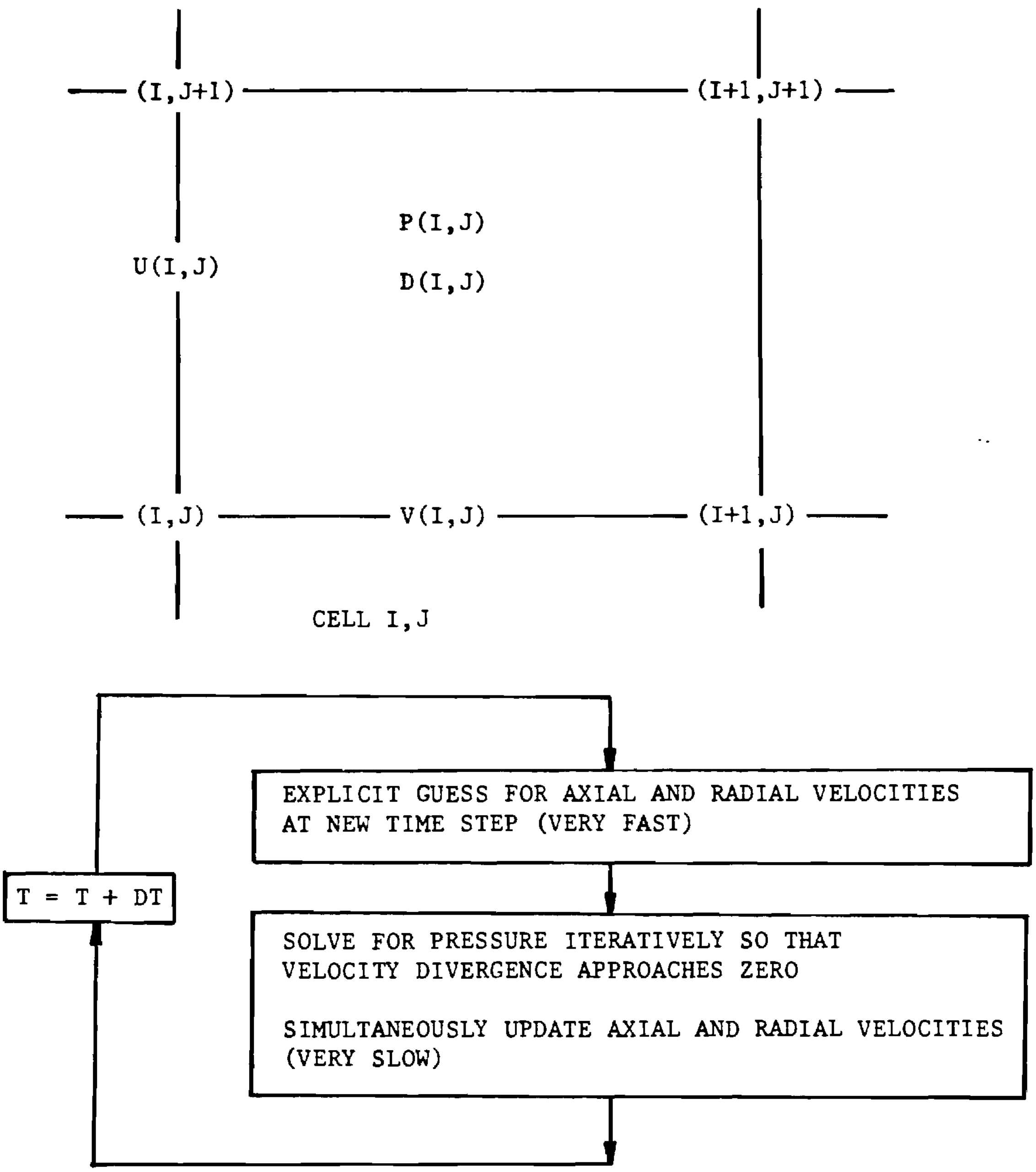

Figure 1

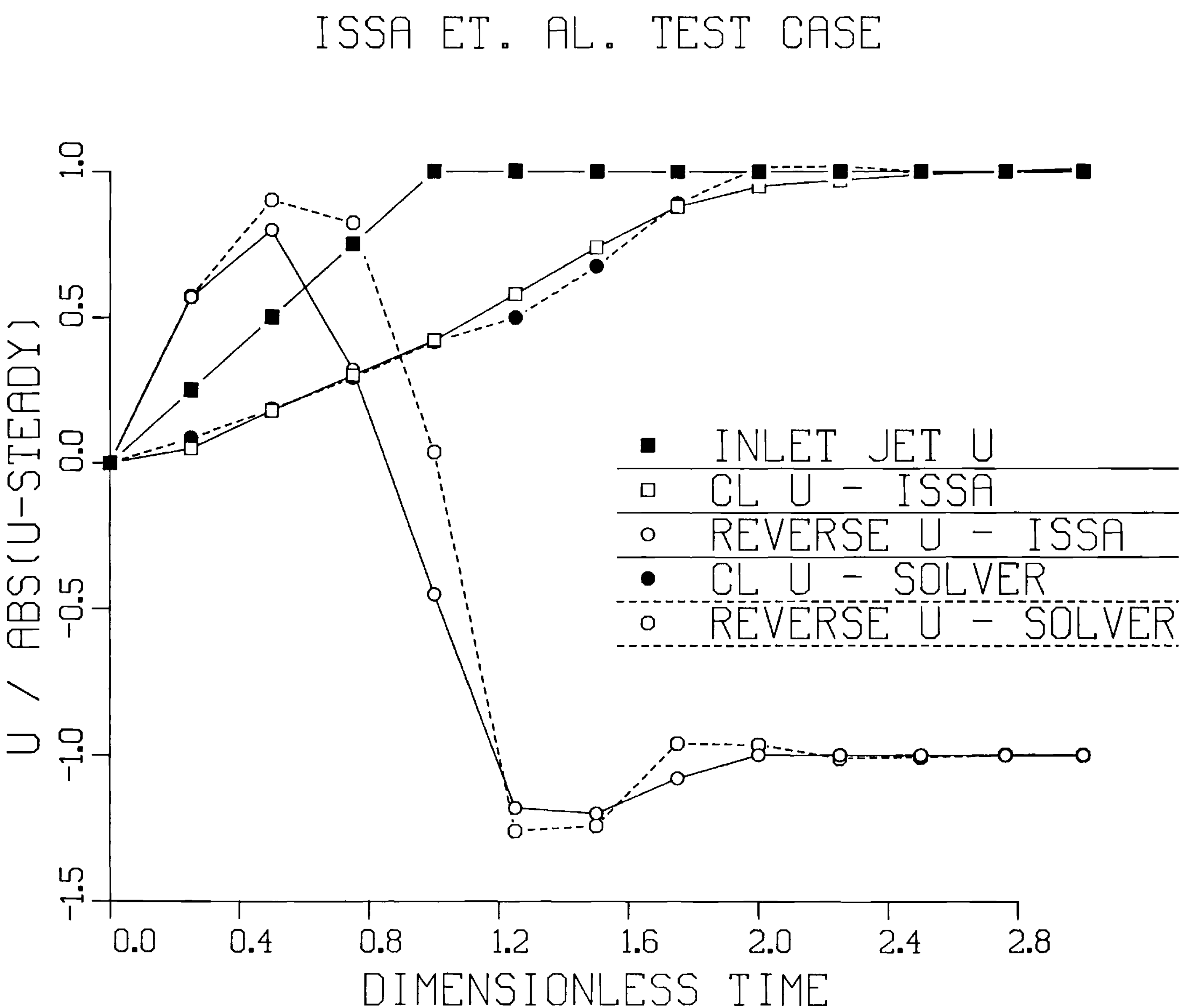
ISSA ET. AL. TEST CASE
U / ABS(U-STEADY)
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
DIMENSIONLESS TIME
INLET JET U
CL U - ISSA
REVERSE U - ISSA
CL U - SOLVER
REVERSE U - SOLVER

Figure 2

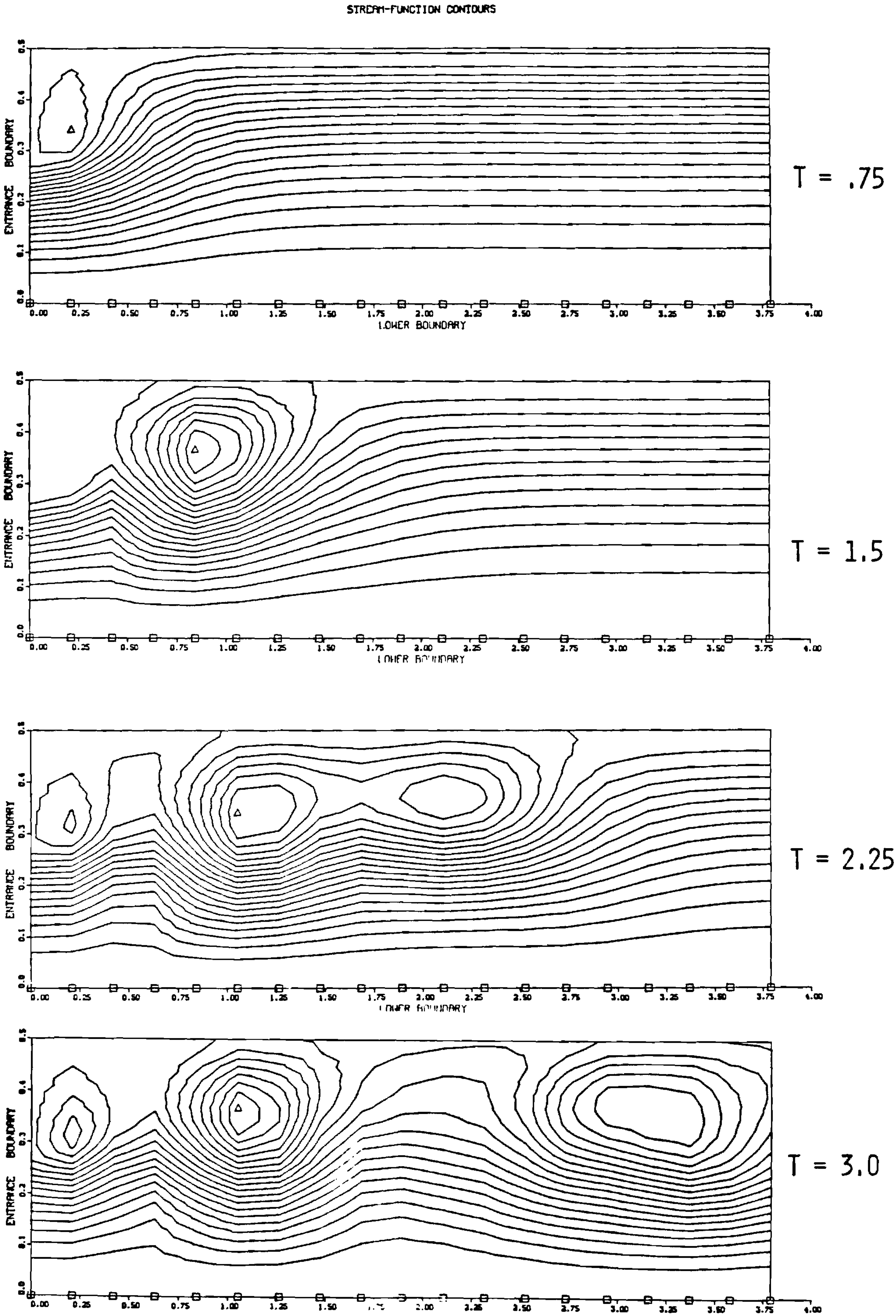
STREAM-FUNCTION CONTOURS
ENTRANCE BOUNDARY
LOWER BOUNDARY
T = .75
T = 1.5
T = 2.25
T = 3.0

Figure 3

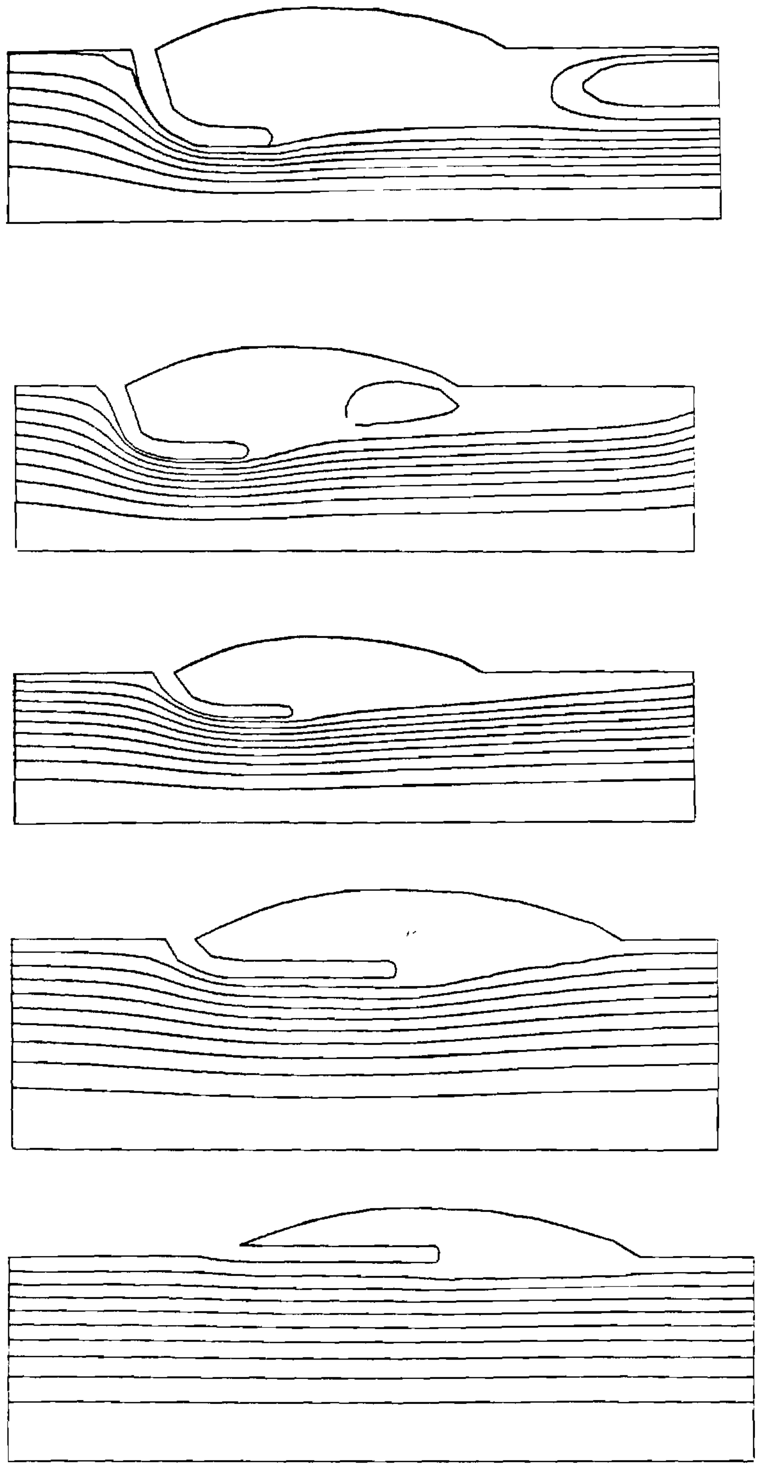

Figure 4