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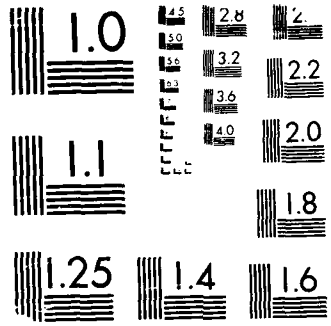

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A USERS'/PROGRAMMERS' MANUAL FOR TWAKE

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Center for Hydrodynamic Developments
Laboratory for Computational Physics and Fluid Dynamics

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A detailed description is given of the procedures required to initialize the computer code TWAKE for a class of surface ship wake problems. The code is a modified combination of variants of the CMC-3DPNS finite-element solver and is applicable to the steady, Reynolds-averaged, parabolic Navier-Stokes equations with a k,ϵ turbulence closure model. General descriptions are given of the computational model and the logical path through the execution modules. Samples are given of data resulting from all output units. The program has been executed for the given data on Cray, Hewlett-Packard, and Digital Equipment computer systems with identical results to 4 significant figures for single precision computations.

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A USERS'/PROGRAMMERS' MANUAL FOR TWAKE

1. INTRODUCTION

The computer program TWAKE is a modified version of the CMC-3DPNS program described in Refs. [1-4]. The parent code is available in the NASA/COSMIC software library (Ref. [8]) and, under separate contracts, variations of the original code have been acquired by the Naval Research Laboratory and the David Taylor Research Center. At NRL the program has been used to simulate a variety of turbulent, two and three-dimensional, self-propelled and drag wakes (Refs. [5-7]). In addition, several unpublished calculations of surface ship wakes and two-dimensional turbulent jets have been completed. Comparisons of the calculations with experimental data have consistently shown good quantitative agreement with respect to axial evolutions of characteristic (single-point) flow parameters such as maximum velocity deficit (excess) and maximum turbulence kinetic energy. In addition, the simulations of the experiments of Ref. [9] reproduced the qualitative behavior of major flow structures in the cross-plane.

In order to complete these numerical simulations, it has on occasion been necessary to alter and merge portions of the Navy-procured variants mentioned above. From these efforts has evolved a version of CMC-3DPNS which may be described as being "ship wake specific" while retaining the flexibility of the original program through the use of parameters defined during input.

NRL has been tasked to deliver the modified software to the OCNR (Code 12) Ship Wake Detection Program. This report is intended to serve as a programmers'/users' manual in support of that task. It should be considered as supplemental to Refs. [2-3] and this report will assume advance familiarity with that literature. The subsequent sections will describe the fundamentals of using TWAKE to simulate a class of self-propelled wake flows near a free surface. The physical approximations employed to derive the conservation equations as well as the mathematical concepts involved in their discretization are described in Refs. [1,4] and will not be repeated herein.

2. OVERVIEW OF THE COMPUTATIONAL MODEL

The conservation equations to be considered are the steady, three-dimensional, time-averaged (in the turbulence sense) parabolic Navier-Stokes equations. The effects of turbulence are described using modelled transport equations for the turbulence kinetic energy and the isotropic dissipation function along with an anisotropic closure for the turbulent stresses. Since the continuity equation is not parabolic, additional formulational steps are necessary to render the equation set amenable to a streamwise-marching numerical solution technique. As is usual the divergence of the transverse momentum equations provides an equation for the static pressure. The pressure field that satisfies this Poisson equation consists of complementary and particular parts with the complementary solution satisfying the homogeneous part of the original equation. An additional equation is provided by the definition of a harmonic function which is forced to zero (within a defined tolerance) as the continuity equation is satisfied. These equations and the ordering analysis leading to their derivation may be found in Ref. [4].

The computer program has been designed to consider the simultaneous convection and diffusion of up to 30 arbitrary scalar field variables, q_i. The general form of the equation system is

$$L(q_i) = u_1 \frac{\partial q_i}{\partial x_1} + c_i u_l \frac{\partial q_i}{\partial x_l} - d_i \frac{\partial}{\partial x_l}\left(\kappa_i \frac{\partial q_i}{\partial x_l}\right) + s_i = 0, \qquad (1)$$

with boundary conditions

$$l(q_i) = a_{1il} q_i + a_{2il} \frac{\partial q_i}{\partial x_l} \vec{n}_l + a_{3il} = 0, \qquad (2)$$

and initial conditions

$$q_i(0, x_l) \equiv q_i^0(x_l). \qquad (3)$$

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In these equations x_1 is the primary flow (marching) direction, the subscript l, $2 \leq l \leq 3$. denotes the coordinate directions defining the transverse solution plane, and $\vec{n}_l$ is the outward unit normal vector. In Eq. (1) s_i is a source or sink term for q_i and κ_i is the diffusion coefficient. The constants a_{nil} in Eq. (2) allow the specification of the appropriate boundary conditions on each boundary of the solution domain. The coefficients c_i and d_i as well as parametric or functional representations of the diffusion coefficients and source terms are supplied by the user as part of the input process and by providing additional coding as necessary.

The turbulent PNS equations and modelled equations described in the first paragraph are a subset of the general equation system and appropriate specifications of the coefficients, functionals, and source terms have been programmed. Nevertheless, there remains considerable latitude for the user, through the use of parameters specified on input, to further tailor the equation set for specific applications, especially with regard to the treatment of source and diffusion terms. Several of the original parameters are not described in Refs. [2-3] and some additional choices have been added by this author. The full equation set in a hybrid, as coded, form is included as Appendix A of this report and should serve to clarify and complete the descriptions in the above references.

The numerical solution of the governing equation set is accomplished by means of a finite-element algorithm. The particular algorithm employed by TWAKE is derived in Chapter 4 of Ref. [4] using the Galerkin-Weighted Residuals formulation. A brief outline of the algorithm is useful to introduce necessary terminology and for reference in subsequent sections of this report.

To a degree the finite-element algorithm is an integral transformation, transforming an initial value partial differential equation into a larger order system of ordinary differential equations. The algorithm is established by first sub-dividing the flow domain into a number of sub-domains or finite elements. Each element is associated with a number of discrete nodes located on (or within) the element boundary. The spatial variation within the element of any flow variable, q_e, is assumed in terms of interpolation polynomials, N, and the values (unknown) of the variable at the node points, Q, for example,

$$q_e(x_1, x_l) = \{N_k(x_l)\}^T \{Q(x_1)\}_e . \tag{4}$$

The curley braces denote column matrices whose order is equal to the number of nodes comprising the element and the elements of $\{N_k\}$ are polynomial functions complete to degree k. The numerically determined finite element approximation q^h, to the true solution q, is the summation of the independent solutions q_e,

$$q(x_1, x_l) \approx q^h(x_1, x_l) \equiv \sum_{e=1}^{M} q_e(x_1, x_l), \tag{5}$$

where M equals the number of finite elements in the discretization. Within the Galerkin formulation, for example, the algorithm statement for a two-dimensional high Reynolds number boundary layer form of Eq. (A-1) with homogeneous boundary conditions is

$$\begin{aligned} S_e\left[\int_{R_e} \{N_k\}\, L(u_1^h) d\tau\right] &= S_e\left[\{U_1\}^T \int_{R_e} \{N_k\}\{N_k\}\{N_k\}^T dx_2 \{U_1\}'\right. \\ &+ \{Nu\}_e^T \int_{R_e} \{N_k\} \frac{d}{dx_2}\{N_k\} \frac{d}{dx_2}\{N_k\}^T dx_2 \{U_1\}_e + \{U_2\}_e^T \int_{R_e} \{N_k\}\{N_k\} \frac{d}{dx_2}\{N_k\}^T dx_2 \{U_1\}_e \\ &\left. + P'_\infty \int_{R_e} \{N_k\}\, dx_2\right] \equiv \{0\}, \end{aligned} \tag{6}$$

In Eq. (6) S_e is the standard finite-element assembly operator, the "prime" denotes ordinary differentiation with respect to x_1, and the Green-Gauss theorem has been used to transform the diffusion term. Each of the integrals are analytically evaluable upon specification of the interpolation polynomials in Eq. (4). The elements of the resultant hyper-matrices are themselves column or square matrices. Following the notation developed in Ref. [4], Eq. (6) is written

$$S_e\left[\{U_1\}_e^T[A3000]\{U_1\}'_e + \left(\{Nu\}_e^T[A3011] + \{U_2\}_e^T[A3001]\right)\{U_1\}_e + P'_\infty\{A10\}\right] \equiv \{0\}. \qquad (7)$$

The meaning of the matrix notation is easily deduced with reference to Eq. (6). For instance [A3001] in the convective term denotes that it is the matrix formed by integrating over a one-dimensional element (A), the product of 3 interpolation polynomial matrices (3), the first two of which are not differentiated with the third being differentiated (001). Matrices appropriate for the PNS equations have been coded into TWAKE for linear interpolation polynomials only ($k = 1$ in Eq. (4)), for both one-dimensional $[A...]$ elements and two-dimensional triangular $[B...]$ elements.

Application of the finite-element algorithm to each of the equations in Appendix A results in a system of ordinary differential equations (and algebraic) which are compactly written as,

$$[C_i]_e\{Q_i\}'_e + [D_i]_e\{Q_i\}_e + \{S_i\}_e = \{0\}, \qquad (8)$$

where $\{S_i\}_e$ contains all of the non-homogeneous terms and $\{D_i\}$ contains the combined effects of convection and diffusion. To solve these equations the family of one-step implicit finite-difference integration algorithms is used,

$$\{F\}_{j+1} = \{Q_i\}_{j+1} - \{Q_i\}_j - \Delta x_1\left(\theta\{Q_i\}'_{j+1} + (1-\theta)\{Q_i\}'_j\right) = \{0\}, \qquad (9)$$

where j is the x_1 step index, Δx_1 is the step-size and θ is the implicitness factor, with $\theta = \frac{1}{2}$ yielding the trapezoidal rule. Combining Eqs. (9) and (8) to eliminate the derivative yields the non-linear algebraic equation set,

$$\left\{F\left(\{Q_i\}_{j+1}\right)\right\} = \{0\}. \qquad (10)$$

The Newton iteration algorithm is applied to Eq. (10)

$$\{\delta Q_i\}_{j+1}^{p+1} = \{Q_i\}_{j+1}^{p+1} - \{Q_i\}_{j+1}^p = -\frac{\left\{F\left(\{Q_i\}_{p+1}^p\right)\right\}}{\left[J\left(\{Q_i\}_{j+1}^p\right)\right]}. \qquad (11)$$

where p is the iteration index and $[J]$ is the Jacobian

$$[J(\{Q_i\})] \equiv \frac{\partial\{F\}}{\partial\{Q_i\}} \qquad (12)$$

The equations to be solved at each iteration are Eq. (11) written in the form,

$$\left[J\left(\{Q_i\}_{j+1}^p\right)\right]\{\delta Q_i\}_{j+1}^{p+1} = -\left\{F\left(\{Q_i\}_{j+1}^p\right)\right\}, \qquad (13)$$

where $\{\delta Q_i\}$, the iteration vector, is the dependent variable. The right side of the above equation is Eq. (10) evaluated at the p^{th} iteration,

$$\{F\}_{j+1}^p = [C_i]\left(\{Q_i\}_{j+1}^p - \{Q_i\}_j\right) + \Delta x_1\left(\theta\{G_i\}_{j+1}^p + (1-\theta)\{G_i\}_j\right). \qquad (14)$$

where

$$\{G_i\}^p = [D_i]\{Q_i\}^p + \{S_i\}^p. \qquad (15)$$

Iterating the solution until $\{F\}$ vanishes to within a defined tolerance implies the approximate vanishing of the iteration variable $\{\delta Q_i\}$ in Eq. (13) and hence convergence. The matrix solution technique for Eq. (13) is by L-U decomposition and back substitution.

The code has no "hard-coded" and linked control sequence until full initialization has occurred, and alternate paths exist in execution as well. The user is thus required to construct a problem-specific command sequence which will

1) generate the computational space,
2) specify the dependent variable set,
3) insure that fluid is initialized properly,
4) specify appropriate boundary conditions for each dependent variable,
5) specify certain parameters which control the flow path through the execution module and,
6) choose among several output options or otherwise provide output routines.

This has been done in Refs. [2-3] for a class of semi-bounded turbulent flows with an irregular computational domain. The next section and major portion of the remainder of this report will explain an input sequence appropriate for the simulation of surface ship wake flows. Comparing the two should efficiently educate the user in the machinations of operating the code and yield a versatility to create additional data sets. Once a command structure is developed for a class of flow geometries, the majority of the previous discussion in this section as well as other characteristics of the program can remain entirely transparent to the user. Since it is likely, however, that improved modelled equations or constitutive relations or more efficient solvers and iterative techniques will become available, an outline of the relevant sections of code which might be modified will be given in Section 4.

3. DESCRIPTION OF COMMAND DATA INPUT

The primary requirement of the user of the program is to construct an input sequence of commands which will describe the flow to be numerically simulated. Such a data sequence is included as Appendix A of Ref. [2] for the PNS computation of wing-body juncture flow. Another and quite different input sequence is included as Appendix B of this report for the turbulent wake behind a self-propelled surface ship. Following a few general remarks describing the command data structure, the next sub-section of this report will explain the functions of the fundamental commands included in Appendix B and indicate, where appropriate, how the data should be altered to compute additional flow fields of the same type. This will be followed by a short sub-section containing example modifications which either allow effects not included in the Appendix B commands or significantly alter the geometry. It will be assumed at this point that the reader is familiar with the texts of Appendices A and B.

The procedures for describing the flow-field geometry, initial fluid state and other characteristics pertinent to specific flows via the input sequence are quite flexible. At the core of the input module is subroutine BDINPT. This subroutine sequentially reads data card images from logical unit 5 (LU5). The individual card images must have the format (A8,72A1), the first eight characters (left-justified) of which contain a pre-programmed command name, while the remaining characters contain any additional parameters required by the specific command. The subroutines which read these card images translate the literal data into integer or real data as indicated. The commands can be categorized into two general groups, those which operate on and/or store numerical data, and those which cause control to transfer to other ensembles of subroutines which may themselves require additional literal or numerical data from LU5 or other logical units. The command card images are terminated by "T" if the data are numerical and by "DONE" if the data are literal. Upon completion of an operation specified by a command, control returns to BDINPT which reads the next card image. A list of available commmands and their functions can be found in Appendix C of Ref. [2].

Immediately upon execution of TWAKE, control resides in program MAIN. The principal functions of this routine are to specify the size, IZSIZE, of the primary array in the code, IZ(IZSIZE), and to call subroutine BDINPT. Currently IZSIZE = 700000 which is sufficient to compute a cross-plane containing 51x51 nodes. Additional code has been added to read file names (from LU5) and open files associated with logical units required for customized input and output subroutines. On some computer systems, these logical units may be designated by way of the job control language and in that event those particular statements in program MAIN should be deactivated. The first several card images in the data deck of Appendix B contain names for these additional LU's. It is not necessary to delete these card images if MAIN has been altered to attach these files via job control statements. This introduces an important point regarding the command data structure. If a card image contains a character string which is not recognized as a legitimate command, then control continuously passes to subsequent images until a viable command is detected. Thus the entirety of the annotated data set in Appendix B (or even this entire report) can be read into the code verbatim.

Discussion of Appendix B

The first sensible statement to BDINPT in Appendix B is the command FENAME and this command must be the first. The command calls subroutine FENAME which initializes default entries in the integer and scalar arrays, IARRAY(500) and RARRAY(500), respectively. The specifications given these entries in the current version of FENAME are appropriate for the surface ship wake calculations of Refs. [6-7] and, in principle, the several subsequent commands in Appendix B of the IARRAY and RARRAY type need not be present. They have been included to remind the user of those entries which would most likely be altered to specify a different scaling to a geometrically similar flow. As is apparent from Appendix B a command of the type

```
IARRAY     2   7   T
```

puts the value of 7 into the second location of the array IARRAY. The comments in Appendix B suffice to explain the meaning and use of the several parameters which are explicitly referenced. Descriptions of most of the other defaulted entries in these arrays can be found in Refs. [2-3]. They need to be changed only if the user needs to significantly alter the flow type and geometry. Note the specification of the coefficients of the governing equations in the form presented in Appendix A. Note also that the last several of these array specification commands, along with the ICOND and EXIT commands, are preceded by the letter "C" and consequently they have no meaning to BDINPT. Removing the extraneous letter and left-justifying, however, will cause those particular elements of IARRAY to be assigned non-zero values and thus activate debug output statements (LU6) contained in the majority of the subroutines in the code. Some entries are assigned values greater than 1 because those particular integers are decremented by 1 each time output is requested. The ICOND command causes a print to LU6 of the current status of all non-zero entries in IARRAY and RARRAY and the EXIT will terminate execution when encountered. Obviously these parameters can be activated ($I > 0$) and deactivated ($I \leq 0$) at strategic locations in the input data sequence. There does exist a NAMELIST option in FENAME whereby the several parameter specifications in Appendix B can be can be accomplished by direct reference to their Fortran variable names. The option has not been used in Appendix B since, for illustrative purposes, it is convenient to isolate the parameter specifications in groups according to function. Most of the more widely used entries in RARRAY and IARRAY are equivalenced to local Fortran variable names in FENAME. The local variable names have been assembled into two NAMELIST data strings, one for each of the arrays. The parameter specification in Appendix B can as well be accomplished by:

```
IARRAY   500  1  T NAMELIST on
FENAME   T
 &NAME01
  NTYPE=7, N2WAKE=1, NM=3, KROW=19, LCOL=19, NODE=400
 &END
 &NAME02
  UINF=6.7556, RHOINF=1.935, XMUINF=21.1E-6, REFL=1., TO=10.,
  TD=20., HSINIT=.01, HMAX=10., DELP=101.
 &END
```

The FEDIMN command must occur after the grid-size parameters (NM, LCOL, KROW, NODE in Appendix B and others defaulted in FENAME) are prescribed. This subroutine activates the linear finite-element versions of the $[A...]$ and $[B...]$ matrices (depending on NM) discussed in Section 1 and loads default entries into several arrays. The critical function of FEDIMN, however, is to partition the IZ(IZSIZE) array. The macro-structure of this array is discussed in Ref. [3] and, due to it's critical importance to creating new or altering existing code, Tables 1 and 2 are included to describe relevant further partitioning. It is sufficient at present to point out that the array always appears as equivalent to it's real counterpart, RZ(IZSIZE), and every major column matrix in the code, whether integer or real, is a subset of this array. Subroutine FEDIMN calculates addresses (entry points in IZ/RZ) for these matrices and groups of these matrices and stores these addresses in the first 200 locations of the IZ array. As an example, the following series of Fortran statements places the value of the x_2 space coordinate at computional node I into the local variable Z:

```
COMMON / ARRAYS / IZ(700000)
DIMENSION RZ(700000), L(200)
EQUIVALENCE ( IZ(1), RZ(1), L(1) )
EQUIVALENCE ( L(90), IX2COR )
Z = RZ(IX2COR + I - 1)
```

If the debug parameter, IARRAY(61), is active upon encountering FEDIMN, these addresses will be printed. The remainder of the input sequence is devoted to initializing (and sometimes further partitioning) the IZ array.

The next group of command data which deserve comments in addition to those given in the Appendix B annotation is the LINK4 sub-group. These commands, terminating with DONE, construct the finite-element domain. Commands VX2SCL and VX1SCL determine node spacing in the vertical and lateral directions, respectively, by using geometric progression. The card image immediately following VX2SCL, for example, contains 2 strings of numbers, separated by a comma for clarity (not necessary), which specify parameters for generating the vertical spacing,

```
VX2SCL      T
0.  9 -1.5 1.   , 9 -3.   1.  T
```

In this case the sets of numbers specify 2 super-elements in the vertical direction such that the first super-element begins at $x_2 = 0.0$, contains 9 finite elements (10 nodes over the span), and spans that axis until $x_2 = -1.5$, with node spacing determined by a progression ratio (Pr) of 1.0. The second super-element also contains 9 elements and continues the construction until $x_2 = -3.0$ with $Pr = 1.0$. Note that the command assumes subsequent super-elements begin where the prior super-element ended (-1.5 in this case) and the starting position is omitted. Since $Pr = 1.0$ (equi-spaced nodes) this construction could have identically been specified by

```
0.  18.  -3.  1.  T
```

and the first format has been used to remind the user of the capability. If $Pr < 1.0$ the spacing becomes increasingly denser as the interval is spanned, for example, each of the constructions

```
0.  6 -1.5 1.25 , 12 -3.   1.  T
-3.  11 -1.  1.25 , 7 0.   .8 T
```

spans the same domain (originating at different points) and will cause a relatively denser spacing near $x_2 = 0.0$. Similar comments apply to the VX1SCL command. The call to ELEM constructs the finite-element network and node-connectivity table using the beginning and ending nodes specified by the NDECRD command, nodes 1 and 19 in each direction, respectively. A schematic of the grid formed for this geometry specification is given in Fig. 1. Note that since the reference length, IARRAY(43), has been assigned the value of 1.0, the space coordinates correspond directly to ft.

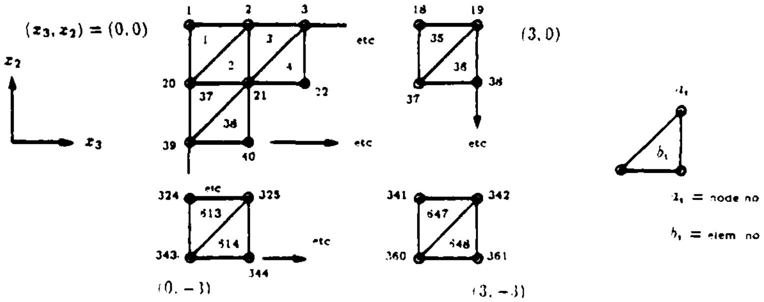

Fig. 1 – Schematic of finite-element domain

Each of the dependent variables has associated with it an integer number in accord with the table given in Appendix B. The KBNO sub-group of commands specifies boundary conditions to these variables according to their respective integer designations. The default boundary condition is vanishing gradient normal to the boundary in question. In Appendix B, for instance, there is no KBNO command for dependent variable 5 (turbulence kinetic energy) and thus either $\partial k/\partial x_1 = 0.0$ (left and right) or $\partial k/\partial x_2 = 0.0$ (bottom and top) as required. The domain created by the ELEM command above corresponds to the free surface wake experiments described in Ref. [7]. The top boundary is assumed to be the mean free surface in the "rigid-lid" approximation, the left boundary is the symmetry plane separating the port and starboard propellers, and the bottom and right boundaries are assumed to be free of viscous influence. If the initial (or boundary) conditions are asymmetric from starboard to port then a full planar solution is necessary. In this case, for instance, the KBNO 3 command and it's associated data card image would be deleted to permit the lateral velocity, u_3, to float on all boundaries. The data for ϕ (and p_p) would be replaced by,

```
KBNO     9 T   PHI BC: only free surface is impermeable
LEFT                BOTTOM      2        RIGHT       2
DONE
```

permitting entrainment at all boundary planes except the free surface. The "2's" in the above data cause the boundary node lists for the bottom and right boundaries to begin at the second node (proceeding counter-clockwise) thus preventing the bounding of the same node twice.

The next set of commands in Appendix B beginning with DESCRIPT 204 and continuing through VX3ST are concerned with specifying type of and format for printed output on LU6. The discussions in Refs. [2-3] are adequate to explain the general functions of these statements. Until the command IOSAVE is encountered the data are merely prescribing headers for scalar output and designating which scalars to write. The DESCRIPT 203 command provides header information for vector output. There is a one-to-one correspondence between the listed headers and the column vectors denoted by the code numbers listed under the IOSAVE command. The IOMULT command provides scalar multipliers for these 14 vectors and in this case the first 11 are multiplied by the scalar in RARRAY(2) (which happens to be 1.0), the next by RARRAY(171), and the last 2 again by RARRAY(2). These particular multipliers cause the output variables to be printed in their non-dimensional form as described in Appendix A. The particular pressure is multiplied by RARRAY(171) because the code operates with the variable divided by that constant. As an example to illustrate a couple of points, if the user wants to view the dimensional axial velocity and further wishes to record the effective turbulence diffusion coefficient in a form which compares it to the laminar viscosity (see Eqs. (A-1), (A-16) and (A-17)), then the last header card under DESCRIPT 203 might be altered to;

```
U3'U3'   PP        P          PHI      NUTRB/NU
```

the last statement under IOSAVE should be altered to;

```
8248 9248 1247 T
```

and the IOMULT data card should be altered to;

```
27  11*2  171  2*2  47,  15*1 T
```

These alterations, in addition to designating the header, cause the non-dimensional velocity variable defined in Appendix A to be multiplied by RARRAY(27) (u_∞ specified in a prior command in Appendix B) before printing. The multiplication of ν_t (variable number 1247) by RARRAY(47) (reference Reynolds number calculated during the input sequence) produces the ratio of the turbulent and laminar diffusion in Eq. (A-1). As to the construction of the composite numbers, the material in Ref. [2] on pages 21 and 35 is contradictory with that on page 21 correct. All arrays can be accessed using the correct procedures of Ref. [2] and appropriate addresses from the table on pages 55-58 of Ref. [3] and Tables 1 and 2 of this report. As is explained in Appendix B the axial locations where LU6 output will occur are specified by the VPVSX and VX3ST commands. Further comments regarding output options including customized output routines will be reserved for Section 4.

The LINK commands form the final sub-group which will complete initialization of the fluid. Commands of this type invoke a call to the named subroutine which in turn accesses other modules to perform operations according to the argument. The command,

```
LINK3     4  T
```

for instance, as part of the operations in subroutine LINK3 when the argument is 4, places calls to subroutines DIMEN and INDEX. Subroutine DIMEN calculates several non-dimensional parameters for later use during execution as well as initializes the turbulence model constants used in the equations of Appendix A. The call to INDEX finishes the partitioning of the IZ array begun in FEDIMN. It is here that several of the more commonly used addresses (entry points in the IZ array) are given special storage locations so that they do not have to be repeatedly calculated. For example the space between IZ(48) and IZ(49), allocated in FEDIMN, is further partitioned into segments of length NYY*NODE (NYY=IARRAY(90)) The starting address of each segment is stored in the common block JADRES which in most usages in the code has the form:

```
COMMON / JADRES / JU1 , JU2 , JU3 , JH , JK , JEPS , JPP , JP , JPHI , JEX(21)
```

In the execution module the <u>current</u> values of the dependent variables can be accessed by reference to the appropriate element of JADRES. For instance, the value of the non-dimensional u_1 velocity at node I is at RZ(JU1+I-1). Other addresses, which have a one-to-one correspondence with terms or groups of terms in Eqs. (9) through (15), are calculated and stored in the common block DERIV. It should be noted here that those users who wish to modify code in the execution module will find a knowledge of the code in subroutines FEDIMN and INDEX essential to that task. Descriptions of the primary elements of DERIV can be found in Table 2.

The next commands, calls to subroutines GEOMFL and NODELM, complete the development of element matrices and vectors that are determinable solely from geometric data. It is in GEOMFL, for example, that the derivative matrix $[A3011]$ of Eq. (7) or it's 2D-element counterparts $[B30112]$ and $[B30113]$ are calculated.

The remaining task to be completed before entering the execution module is to initialize the fluid state at the initial plane $x_1 = T_o$. Inspection of the equation set in Appendix A shows that, at the minimum, non-zero and positive starting values of u_1, k, and ϵ must be supplied on all nodes of the discretization. For swirling wake flows initial values of u_2 and u_3 should also be supplied. The user will likely find it convenient to develop his own input routines to initialize the dependent var able set. Examples of such specialized routines are the subroutines BLSIUS, BRDSHW, CRNINP, JNCINP, EDGINP, WAKPRO, VPIDATA, and DTNSRDC. These routines establish a variety of two and three-dimensional bounded and free-boundary flow fields from either empirical formulae or by accessing pre-processed data sets. The principal requirements in routines of this type are that the ARRAYS and JADRES common blocks be included and that the dependent variables ultimately be specified according to the node ordering determined during grid generation, the ELEM sub-group of commands discussed previously. While this latter point is obvious, consider that an alternate coordinate specification to that used in Appendix B, but one that yields precisely the identical geometry, is

```
VX2SCL      T
-3.  18.  0.  1.  T
VX1SCL      T
 3.  18.  0.  1.  T
```

This specification will reverse the node sequencing depicted in Fig. 1. If the user is uncertain as to how the elements and nodes are numbered, activation of the debug parameters prior to the ELEM command will generate a listing. In this application (NTYPE = 7) the LINK2 10 command accesses subroutine DTNSRDC which will read free-format data from LU19. The local file designation for LU19 is given as INPUT19 at the beginning of Appendix B and this data should be prepared in advance. In this case the first record in INPUT19 is the characteristic dissipation length scale, l_d. Each succeeding record consists of 4 entries corresponding to the starting values of the dependent variables (u_1, k, u_2, u_3) at each node of Fig. 1 in sequence. The subroutine then initializes the dissipation function, ϵ, according to the discussion of Ref. [7]. The nodal data is an interpolation to the computational plane of the experimental data of Ref. [9]. The final two commands, LINK5 6 and LINK5 4, cause the initialization of the laminar and turbulent diffusion coefficients and the Reynolds stresses according to the formulation in Appendix A. Note the presence in Appendix B of several commands preceding the transfer to execution (QKNINT) which are negated by the letter "C". Removing the extraneous letter will invoke a complete planar output of the geometry and fluid nitialization for inspection prior to execution.

At this point initialization is complete and the annotated data set of Appendix B should be viewed as the general structure necessary for computation of surface wake flows. The following is a list of the items in that data set which should be changed to simulate a different flow of the same general class:

1) change the RARRAY entries corresponding to the fluid properties (UINF, RHOINF, XMUINF),
2) change the RARRAY entries corresponding to the longitudinal boundaries of the computational domain (TO, TD),
3) if there are to be more than 19 rows or 19 columns in solution, change the IARRAY entries for KROW and LCOL to be at least as large as the number of rows and columns, and change NODE to be at least KROW*LCOL + 1,
4) change the card images following the VX2SCL, VX1SCL, and NDECRD commands to reflect the new geometry,
5) change the KBNO sub-group of commands to bound the variables consistent with the new geometry specification,
6) change the card image following the VX3ST command to designate the longitudinal stations for complete planar output, and
7) change the data on LU19 to reflect the initial fluid state consistent with the new geometry or otherwise supply a subroutine similar to DTNSRDC.

Before leaving the discussion of command data set construction it is useful to illustrate by way of examples more general modifications necessary to calculate flow fields that deviate from the type heretofore considered. The following sub-section will briefly summarize modifications appropriate for a two-dimensional flow and for a flow with non-zero $\partial p_c/\partial x_1$. Studying the contrasts between the data sets (including that in Refs. [2-3]) will result in an increased versatility in using the code to calculate dissimilar flow fields.

Additional Data Sets

The hypothetical situation to be considered is a two-dimensional version of the Appendix B data. In this case it is supposed that the flow is invariant in the lateral (x_3) direction and that the initial fluid state is described by the data on the left column of nodes in Fig. 1. If the extent of the computational domain is the same, the only necessary change to the IARRAY and RARRAY specifications (or NAMELIST) is to set NM = 2. It is more efficient to alter LCOL and NODE to better fit the problem since FEDIMN will then allocate smaller blocks when partitioning RZ.

The IPINT vector should be altered to delete the integration of u_3, e.g.,

```
IPINT      T
 1 5 6 2 7 9 8 0 0 0 , 1 -2 -2 -5 6*0 , 10*I1 1 T
```

For the same span in x_2, the only necessary changes to the ELEM sub-group of commands are to delete the VX1SCL command (and it's associated data) and alter the NDECRD command and data to the single statement,

```
NDECRD     -1 T -1 indicates 2D grid
```

The IBORD command and data should be replaced by,

```
LINK1     2 T call FINDBE: examine geometry for boundary elements
```

The boundary conditions (KBNO) should be altered to delete the condition on u_3 and to remove the references to the RIGHT boundary for p_p and ϕ.

The remaining required change concerns reading the initial fluid state. Obviously subroutine DTNSRDC could be altered to store the first column of the current INPUT19 data (u_1, k, ϵ only) into the RZ array, or a modified data file could be pre-processed to be accessed by the existing subroutine. An alternative which illustrates further capabilities of the code is to delete altogether the link to TBLINP and DTNSRDC and add:

```
DEPVAR   1 2 T load U1
 1.01225 1.01193 1.00424 1.01459 1.03879 1.02784 1.01261
 1.01261 1.00843 1.00211 1.00053 9*1.0 T
RARRAY   2 .01 T set RARRAY(2)=.01
DEPVAR   5 2 T load TKE
 .24124 .24795 .30290 .28394 .25587 .14605 .0430
 .01045 11*1.0 T
RARRAY   2 .001 T set RARRAY(2)=.001
DEPVAR   6 2 T load EPS
 .20312 .21166 .28578 .25937 .22188 .09568 .01529
 .00183 11*1.0 T
RARRAY   2 1.  T set RARRAY(2) back to 1.0
```

The DEPVAR N1 N2 command loads the RZ array beginning at entry points corresponding to the dependent variable specified by N1 (see the table in Appendix B). In this example each indicated variable will take on the 19 values specified by their respective data statements, with each datum multiplied by the value in RARRAY(N2). Note that the free format allows a short-hand notation for repeated data and the successive redesignation of RARRAY(2) disposes of the necessity to input the leading zeros.

The data set in Appendix B of Ref. [3] serves as an example of procedures required to include non-zero $\partial p_c/\partial x_1$ into a simulation. The explanation given in that reference, however, is extremely abstruse concerning the complementary (inviscid) pressure determination and only detailed deciphering of pressure-related subroutines along with subroutine DERVBL (conservation equation assembly) reveals how to and in what form to communicate the gradient information into the execution module. The fundamental requirement is to load the pressure data into the RZ array at locations IZ(105+I-1) where I ranges over the number of nodes in solution. Subroutine DERVBL expects the pressure gradient data in the form:

$$\frac{\partial P}{\partial x_1} = \left(\frac{\rho_\infty u_\infty^2}{p_\infty + \frac{1}{2}\rho_\infty u_\infty^2}\right)\frac{\partial}{\partial x_1}\cdot\left(\frac{p_c}{\rho_\infty u_\infty^2}\right), \qquad (16)$$

and the user should note that the coefficient is accessible as the inverse of RARRAY(171). Examples of routines which accomplish this formulation for specific flow geometries are subroutines PRSGRD, GETPPR and JNCPPR. The first of these calculates the pressure term for an internal (rectangular duct) flow by global mass conservation and the latter two compute the term by interpolation of prescribed axial variations of $p_c(x_1)$. With the above as background the following word description will help clarify the operations performed by the several commands on pp. 91-92 of Ref. [3]. The LINK2 23 command reads and stores into temporary storage the data which immediately follows that command. These data represent 14 groups of $[x_p, C_p(x_3)_{x_1=x_p}]$ for the geometry of Ref. [1] under the assumption of flow symmetry about the corner-bisector. During the link to subroutine NODPCP these data are used to specify pressure boundary conditions at each node under the KBNO 8 command (p. 90). A solution to Eq. (A-5) is then obtained for each of the 14 stations, the axial coordinates of which are now stored sequentially beginning at RZ(IZ(139)). The solutions are re-assembled into sub-groups of 14 values (solutions) per node and stored according to the normal node sequence beginning at RZ(IZ(140)). During execution subroutine NODPPR is called at the initiation of each marching step and the x_p interval bracketing the current x_1 determines entry points to the pressure table allowing evaluation of Eq. (16) by linear interpolation. These results are loaded sequentially, beginning at RZ(IZ(105)), for transfer to DERVBL.

As a final example which simply illustrates details of the above description, consider that the zero pressure gradient calculation of Appendix B has been established and one wishes to account for the resultant axial gradients of p_p in a subsequent pass through the flow field. In this subsequent iteration, the prior distribution of p_p will be identified with the current p_c. It is assumed that on the first pass the p_p distributions were saved (unformatted) on LU11 in the form specified in subroutine PLTOUT. For purposes of illustration it is further assumed that these distributions were stored only at the axial positions specified under VX3ST in Appendix B, however, it is in the near wake that the procedure has more relevance. For these conditions the following additional parameter specifications should be made before the call to FEDIMN:

```
IARRAY   405     1 T (IPRSCAL) turn on pressure table look-up procedures
IARRAY   394     4 T (NPCTAB) 4 tables of pressure coefficients
IARRAY   371   361 T (NPVSXT) 361 values in each table
IARRAY   161  1444 T (NPVSX) storage allocation 4*361 entries
```

The VPVSX command in Appendix B is removed and the following series of statements should follow the VX3ST specification:

```
RARRAY   450 2.   T temporarily set RARRAY(450)=2.
READ     11 161 74 T
SETVAL   1444 74 74 450 T
LINK2    23 T call CPSTUP to create tables
LINK1    11 T call NODPPR to initialize p grad.
RARRAY   450 0.   500 T reset RARRAY(450)=0.
```

The READ command reads from LU11 a vector of length IARRAY(161) and stores it temporarily beginning at RZ(IZ(74)). Since subroutine CPSTUP expects data in pressure coefficient form, the SETVAL statement multiplies the vector by RARRAY(450) and places the result in the same temporary storage location. The call to CPSTUP creates the tables and finally NODPPR initializes p_c and $\partial p_c/\partial x_1$.

The following section will give a brief overview of the macro-structure of the execution module as it applies to wake flows.

4. OVERVIEW OF THE EXECUTION MODULE

The QKNINT command near the end of the Appendix B data transfers control into the main drive loop. A flow chart for the routines performing the principal operations during execution is shown in Fig. 2. The flow paths branching to the sides of QKNINT pertain to output options and will be discussed at the end of this section. The following several paragraphs will summarize the major functions of the remaining subroutines. Tables 1 and 2 contain additional information regarding the RZ array entry points for those users having a need for detailed code translation.

The call to IMPLCT marks the initiation of a step in the axial direction, corresponding to the j index of Eq. (9). At this point any necessary parametric evaluations should be performed, such as those necessary for variable geometry or non-zero pressure gradient. These types of subroutines are user supplied. Examples of routines which fill the column matrix for $\partial p_c/\partial x_1$ are subroutines JNCPPR, GETPPR, and PRSGRD. The first two of these compute gradients by interpolations of either prescribed data or solutions of Eq. (A-5). Subroutine PRSGRD calculates the pressure gradient in internal flows from global mass conservation considerations.

The sequence from DERVBL through STRF in Fig. 2 is the iteration loop signified by index p in Eq. (11). Subroutine DERVBL performs the finite-element assembly indicated in Eqs. (6) and (7). The user will recognize in DERVBL the application of the various RARRAY coefficients discussed in Appendix A and the ultimate assembly of Eqs. (10) and (14) for each parabolic equation. The master loop in subroutine IMPSLV is over the dependent variable index, NP, equivalent to the index i of the equations in Section 2. As NP increments from 1 to the total number of marching equations (5 in this case), Eqs. (13) are solved in the order specified by the IPINT command. Solution is by L-U decomposition and back substitution (BANDSL). The output from BANDSL is the iteration variable, δQ_i, forming the left side of Eq. (11). If for any variable at any solution node, n

$$\frac{(\delta Q_i)_n}{(Q_{max})_i} > R_{14},$$

convergence is not considered achieved (any NPCONV(NP) greater than zero) and Q_i^{p+1} is determined by Eq. (11). Currently R_{14} (RARRAY(14)) is set to 10^{-4} in FENAME. Following IMPSLV, subroutines SETDIF and RNLDST update the diffusion coefficients and Reynolds stresses. If the convergence test was failed on any variable, two successive passes through subroutines PPRES and STRF accomplish the solutions of

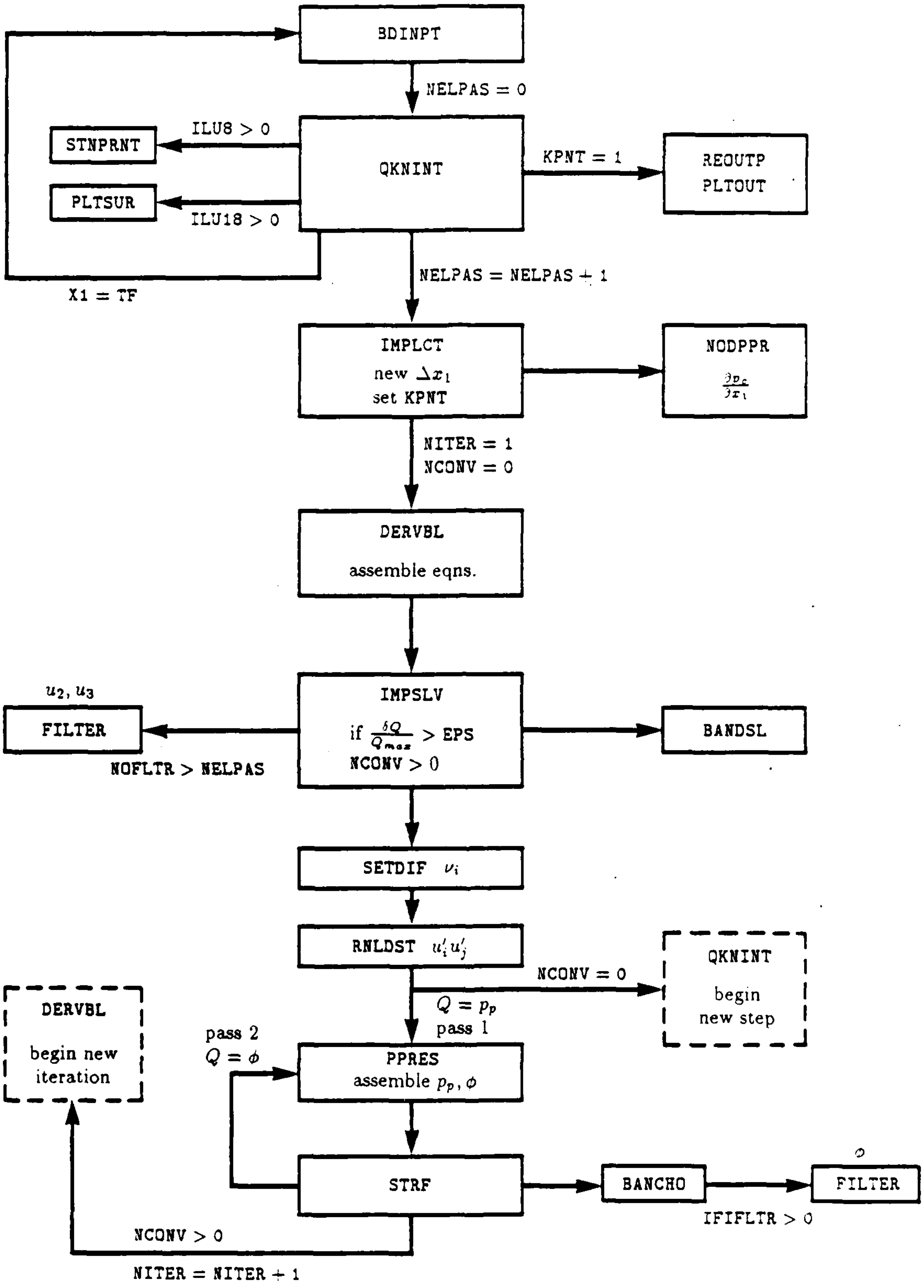

Fig. 2 – Flow chart of execution module

the Poisson equations for p_p and ϕ and control returns to DERVBL.If convergence was achieved for all variables (all NPCONV(NP) equal zero), control returns to QKNINT after the stress update. Flow charts of DERVBL and IMPSLV are given in Ref. [3].

The references to subroutine FILTER in Fig. 2 deserve special mention. Chapters 5 and 6 of Ref. [4] discuss the possibility of waves occuring in the cross-plane velocity component solutions for the linear basis algorithm ($k = 1$ in Eq. (4)). The mechanism for initiating these waves is the action of the continuity penalty function which for the linear cardinal basis enforces essentially a central difference approximation. If a calculation is exhibiting this behavior, simple grid refinement can exacerbate the problem. The original code contains options to either filter the secondary flow velocity variables directly, filter the iteration variable for the those variables, or apply no filter, with the former of these options implemented by default. This user has computed drag-wake solutions (Ref. [6]) using both "on" possibilities for the original filter, and observed only insignificant perturbations in the entrainment induced u_2,u_3 solutions. Operation with the filter off did indeed reveal the presence of small spurious waves in the ϕ solution and a resulting infection of the cross-plane velocities. It is emphasized that this observed behavior was small and sensibly not unstable at least for the initial conditions and longitudinal extent of the computations in that study. Nevertheless these observations along with the comments in Ref. [4] give reason to monitor and condition the solution if necessary. If there is a non-zero swirl component in the initial condition, however, application of the filter to the secondary flow velocities is inappropriate since the result is an immediate artificial smearing of those components. Grid refinement will alleviate the smearing effect at the expense of a corresponding increase in computer time. Consequently the current code has a filter option at subroutine STRF which will operate only on the penalty function. The default condition is an active ϕ filter set in FENAME by IARRAY(403)=1. The u_2, u_3 filters, controlled by the IARRAY entries (397), (401), (402) and (404) are currently off The use of these filter options can easily be deduced by examining the code in subroutines IMPSLV and QKNINT.

Subroutine QKNINT transfers control to the output driver whenever the parameter IARRAY(86) (KPNT) is non-zero. This parameter is set on each pass through IMPLCT and will be non-zero

1) at values of the step index NELPAS which are integer multiples of KNTPAS (IARRAY(167)),
2) at the transverse planes closest to the positions defined by

$$\frac{x_1}{R_{35}} = \frac{nR_{13}}{100}$$

where n is an integer and the RARRAY entries are described in Appendix B, and
3) at planes closest to the positions listed via the VX3ST command in Appendix B.

If KPNT is non-zero full planar output (LU6) of all arrays specified with the IOSAVE command will result. The format for this output is flexible and will automatically be determined to resemble the problem geometry constructed during the ELEM sequence. At axial stations where REOUTP is accessed, subroutine PLTOUT writes the entire dependent variable set (and Reynolds stresses) to LU15 in a column matrix form corresponding to the node sequencing from grid construction. The nodal data is preceded by a sequential listing of the x_2, x_3 coordinates of each node, which for invariant geometry are written on the first pass only. If the additional parameters ILU18 (IARRAY(408)) and/or ILU8 (IARRAY(407)) are specified non-zero during initialization,.then subroutines PLTSUR and/or STNPRNT will be called at each axial step. Subroutine PLTSUR writes to LU18 the full set of computed variables at each node in the horizontal plane $x_2 = 0$ (top row of Fig. 1), corresponding to the mean free surface. Currently a call to STNPRNT will initiate prints to each of the logical units 8, 9, 16 and 17. These are characteristic data of the calculation and are for the most part comprised of extrema of the several dependent variables in the local transverse plane. All potentially relevant IZ array entry points are included in these routines and they can quite easily be tailored to special needs. Sample data from all output units are included in Appendix C.

5. CLOSING REMARKS

The subroutines comprising TWAKE are grouped according to their primary functions and listed in Table 3. These modules, the input data files, and all output files resulting from the execution of the Appendix B data have been written to magnetic tape for delivery to OCNR (Code (12)). The data set has been executed on several NRL computers with identical results to 4 significant digits. The following is a tabulation of the execution times:

SYSTEM	CPU-min.
CRAY	2.24
VAX 11/785	35.17
VAX 11/780	41.83
HP 9000	215.95

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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TABLE 1 – Some important IZ array entry points

IZ entry	commonly used name	reference for node I	remarks
43	IC200	reference by element	standard matrices: see FEDIMN
48	IYY	RZ(IYY+NYY*(IPLOC-1)*NODE+I-1)	dependent variables[1]
71	ITEMP1	RZ(ITEMP1+(NS+1)*NODE+I-1)	Reynolds stresses[2]
74	ITEMP4	RZ(ITEMP4+I-1)	RZ(NZF+I-1) in IMPSLV[4]
89	IX1COR	RZ(IX1COR+I-1)	nodal x_3 coordinates
90	IX2COR	RZ(IX2COR+I-1)	nodal x_2 coordinates
91	IPRESS	RZ(IPRESS+I-1)	nodal values of p_c
92	IAMU	RZ(IAMU+I-1)	nodal laminar viscosity
103	IVEL	RZ(IVEL+I-1)	temporary storage, u_2
104	IW	RZ(IW+I-1)	temporary storage, u_3
105	IPRGRD	RZ(IPRGRD+I-1)	nodal $\partial p_c/\partial x_1$ term
109	IGEOM1	reference by element[3]	natural coordinate derivative (x_3)
110	IGEOM2	reference by element[3]	natural coordinate derivative (x_2)
136	IADIF	RZ(IADIF+I-1)	nodal values of ν_t

Notes

1 IPLOC is the location in the IPINT vector. In Appendix B, for example, IPLOC=2 for the turbulence kinetic energy. NYY and NODE are entries 90 and 55 in IARRAY.

2 NS={1, 2, 3, 4, 5, 6} for $\{u'_1u'_1, u'_1u'_2, u'_1u'_3, u'_2u'_2, u'_2u'_3, u'_3u'_3\}$

3 See subroutine RNLDST for examples of usage.

4 For each variable NP in turn, NZF points to the left-hand-side of Eq. (14) (including penalty term for u_2, u_3) upon entering BANDSL. At exit from BANDSL, NZF points to left-hand-side of Eq. (11).

TABLE 2 – Some important addresses in COMMON / DERIV /

DERIV entry	commonly used name	reference for node I	remarks
25	IIYY	RZ(IIYY+NYY*(IPLOC-1)*NODE+I-1)	IIYY ≡ IZ(48)
36	NIYB	RZ(NIYB+NP+I-1)	dep. var.[1]: $\{Q_i\}^p_{j+1}$ in Eq. (14)
37	NIZB	RZ(NIZB+NP+I-1)	$\{G_i\}^p_{j+1}$ in Eq. (14)
61	NIYY	RZ(NIYY+NP+I-1)	same as DERIV(36)
62	NIZZ	RZ(NIZZ+NP+I-1)	same as DERIV(37)[2]
63	NIRU	RZ(NIRU+I)	JADRES(1)-1[3]
64	NIRV	RZ(NIRV+I)	JADRES(2)-1
65	NIRW	RZ(NIRW+I)	JADRES(3)-1
71	NIRE	RZ(NIRE+I)	JADRES(4)-1
72	NIRF	RZ(NIRF+I)	JADRES(5)-1
74	NIYYO	RZ(NIYYO+NP+I-1)	$\{Q_i\}_j$ in Eq. (14)
75	NIZZO	RZ(NIZZO+NP+I-1)	$\{G_i\}_j$ in Eq. (14)

Notes

1 NP ≡ i in Eq. (1) for all usages in table. NP for a particular dependent variable is determined according to the variable's location in the IPINT vector.

2 RZ(NIZZ+NP+2*NODE+I-1) contains the first term on right side of Eq. (14).

3 JADRES(n) refers to nth element of COMMON / JADRES / .

TABLE 3 – TWAKE subroutines sorted according to primary function

Input	Output	Utility	Eqn. Solve
ADDDEL	CALORD	GETDAT	ASSMAT
BDATA	COMOC	LINK1	ASMSQ
BDINPT	DRVBUG	LINK2	BANCHO
BLSIUS	FEPLOT	LINK3	BANDSET
BNDSET	DPSISQ	LINK4	BANDSL
BRDSHW	ICOND	LINK5	BCONDT
COLS	OUTNOD	LOCATE	CONTES
CPINIT	OUTPG	LOOK	DERVBL
CPSTUP	OUTVEC	LOOK1	DERVDX
CRNINP	OUTVEH	LOOKAV	DFCFBL
CSFINP	PBLANK	MATSUM	DFCFNS
DELADD	PLILNK	MINMAX	DRHOBL
DELELM	PLTOUT	MNMX	DUDY
DELETE	PLTSUR	NODPPR	EDGPPR
DELNOD	PRINTA	RECIP	FILTER
DESCRP	REOUTP	RESET	GETFSL
DIMEN	RITE	RESETI	GETPPR
DSCRTZ	SCALEV	EXIT	IMPLCT
DTNSRDC	SETSCL	SETRZS	IMPSLV
EDGINP	STNPRNT	SETVAL	JNCPPR
EDGSYM	STOUT1	TBLINP	NBNDRY
ELEM		TCHECK	PPRES
FEDIMN		TIMETK	PRSGRD
FENAME		TRAPIN	QKNINT
FINDBE		VARMAX	RNLDST
GEOMDR		VECMUL	SETDIF
GEOMFL		XYSCAL	SETIMP
GETALC		ZZZZZZ	STCODE
GETBCD			STRF
GETBCM			SUMKEY
GETBND			TAUW
INDEX			TRBTHK
NDECRD			WKPRES
NODELM			WLFLXS
NODFIX			
NODPCP			
ORDER			
PRATIO			
READER			
READV1			
REDREL			
REORDR			
ROWS			
SETCNT			
TWPROT			
VPIDATA			
XYCRDM			

APPENDIX A – PROGRAMMED FORMS OF CONSERVATION EQUATIONS

The programmed conservation equations are non-dimensional, with all variables having been non-dimensionalized using reference values of length, viscosity, density and velocity as appropriate, for example,

$$x_1^* \equiv \frac{x_1}{L}\ ,\ u_1^* \equiv \frac{\overline{u}_1}{u_\infty}\ ,\ u_1'u_2'^* \equiv \frac{\overline{u_1'u_2'}}{u_\infty^2}\ ,\ p^* \equiv \frac{\overline{p}}{\rho_\infty u_\infty^2}\ ,\ k^* \equiv \frac{k}{u_\infty^2}\ .$$

The overbars indicate conventional time-averaging and the primes denote fluctuating (turbulence) components. Omitting the asterisks for convenience and assuming x_1, x_2, x_3 correspond to the streamwise, vertical, and lateral directions, respectively, the equations for an isothermal, constant property, incompressible flow are programmed in the following parameterized form:

streamwise momentum

$$u_1\frac{\partial u_1}{\partial x_1} + R_{385}\left(u_2\frac{\partial u_1}{\partial x_2} + u_3\frac{\partial u_1}{\partial x_3}\right) - \frac{\partial}{\partial x_2}\left[\left(Re_L^{-1} + (1-R_{281})\,\nu_t\right)\frac{\partial u_1}{\partial x_2}\right]$$
$$-\frac{\partial}{\partial x_3}\left[\left(Re_L^{-1} + (1-R_{281})\,\nu_t\right)\frac{\partial u_1}{\partial x_3}\right] + R_{281}\left(\frac{\partial}{\partial x_2}(u_1'u_2') + \frac{\partial}{\partial x_3}(u_1'u_3')\right) + \frac{\partial p_c}{\partial x_1} = 0, \qquad \text{(A-1)}$$

vertical momentum

$$u_1\frac{\partial}{\partial x_1}(u_2 - R_{353}\mathcal{F}(\partial\phi/\partial x_2)) + R_{348}\left(u_2\frac{\partial u_2}{\partial x_2} + u_3\frac{\partial u_2}{\partial x_3}\right)$$
$$-\frac{\partial}{\partial x_2}\left[\left(\frac{R_{346}}{Re_L} + (1-R_{282})\,\nu_t\right)\frac{\partial u_2}{\partial x_2}\right] - \frac{\partial}{\partial x_3}\left[\left(\frac{R_{346}}{Re_L} + (1-R_{282})\,\nu_t\right)\frac{\partial u_2}{\partial x_3}\right] - \frac{\partial}{\partial x_3}\left(\frac{R_{346}}{Re_L}\frac{\partial u_3}{\partial x_2}\right)$$
$$+R_{282}\left(\frac{\partial}{\partial x_2}(u_2'u_2') + \frac{\partial}{\partial x_3}(u_2'u_3') + R_{399}\frac{\partial}{\partial x1331179 81}(u_1'u_2')\right) + R_{339}\frac{\partial p_c}{\partial x_2} + R_{340}\frac{\partial p_p}{\partial x_2} = 0, \qquad \text{(A-2)}$$

lateral momentum

$$u_1\frac{\partial}{\partial x_1}(u_3 - R_{353}\mathcal{F}(\partial\phi/\partial x_3)) + R_{348}\left(u_2\frac{\partial u_3}{\partial x_2} + u_3\frac{\partial u_3}{\partial x_3}\right)$$
$$-\frac{\partial}{\partial x_2}\left[\left(\frac{R_{346}}{Re_L} + (1-R_{282})\,\nu_t\right)\frac{\partial u_3}{\partial x_2}\right] - \frac{\partial}{\partial x_3}\left[\left(\frac{R_{346}}{Re_L} + (1-R_{282})\,\nu_t\right)\frac{\partial u_3}{\partial x_3}\right] - \frac{\partial}{\partial x_2}\left(\frac{R_{346}}{Re_L}\frac{\partial u_2}{\partial x_3}\right)$$
$$+R_{282}\left(\frac{\partial}{\partial x_2}(u_2'u_3') + \frac{\partial}{\partial x_3}(u_3'u_3') + R_{399}\frac{\partial}{\partial x_1}(u_1'u_3')\right) + R_{339}\frac{\partial p_c}{\partial x_3} + R_{340}\frac{\partial p_p}{\partial x_3} = 0, \qquad \text{(A-3)}$$

continuity-penalty function

$$\frac{\partial^2\phi}{\partial x_2^2} + \frac{\partial^2\phi}{\partial x_3^2} - \frac{\partial u_1}{\partial x_1} - \frac{\partial u_2}{\partial x_2} - \frac{\partial u_3}{\partial x_3} = 0, \qquad \text{(A-4)}$$

complementary pressure

$$\frac{\partial^2 p_c}{\partial x_2^2} + \frac{\partial^2 p_c}{\partial x_3^2} = 0. \qquad \text{(A-5)}$$

particular pressure

$$\frac{\partial^2 p_p}{\partial x_2^2} + \frac{\partial^2 p_p}{\partial x_3^2} + R_{396}\left[\frac{\partial}{\partial x_2}\left(\frac{\partial}{\partial x_2}(u_2'u_2') + \frac{\partial}{\partial x_3}(u_2'u_3')\right) + \frac{\partial}{\partial x_3}\left(\frac{\partial}{\partial x_2}(u_2'u_3') + \frac{\partial}{\partial x_3}(u_3'u_3')\right)\right]$$
$$+R_{394}\left[\frac{\partial}{\partial x_2}\left(u_2\frac{\partial u_2}{\partial x_2} + u_3\frac{\partial u_2}{\partial x_3} + R_{398}u_1\frac{\partial u_2}{\partial x_1}\right) + \frac{\partial}{\partial x_3}\left(u_2\frac{\partial u_3}{\partial x_2} + u_3\frac{\partial u_3}{\partial x_3} + R_{398}u_1\frac{\partial u_3}{\partial x_1}\right)\right] = 0, \quad \text{(A-6)}$$

where, $p = p_p + p_c$,

turbulence kinetic energy

$$u_1\frac{\partial k}{\partial x_1} + R_{384}\left(u_2\frac{\partial k}{\partial x_2} + u_3\frac{\partial k}{\partial x_3}\right) - \frac{\partial}{\partial x_2}\left[\left(Re_L^{-1} + (1 - R_{283})\frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_2}\right]$$
$$-\frac{\partial}{\partial x_3}\left[\left(Re_L^{-1} + (1 - R_{283})\frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_3}\right] - \mathcal{P} + \epsilon$$
$$+R_{283}C_k\left[\frac{\partial}{\partial x_2}\left(\frac{k}{\epsilon}\left(u_2'u_2'\frac{\partial k}{\partial x_2} + u_2'u_3'\frac{\partial k}{\partial x_3}\right)\right) + \frac{\partial}{\partial x_3}\left(\frac{k}{\epsilon}\left(u_2'u_3'\frac{\partial k}{\partial x_2} + u_3'u_3'\frac{\partial k}{\partial x_3}\right)\right)\right] = 0, \quad \text{(A-7)}$$

isotropic dissipation function

$$u_1\frac{\partial \epsilon}{\partial x_1} + R_{384}\left(u_2\frac{\partial \epsilon}{\partial x_2} + u_3\frac{\partial \epsilon}{\partial x_3}\right) - (1 - R_{283})\left[\frac{\partial \epsilon}{\partial x_2}\left(\frac{\nu_t}{\sigma_\epsilon}\frac{\partial \epsilon}{\partial x_2}\right) + \frac{\partial \epsilon}{\partial x_3}\left(\frac{\nu_t}{\sigma_\epsilon}\frac{\partial \epsilon}{\partial x_3}\right)\right]$$
$$+R_{283}C_\epsilon\left[\frac{\partial}{\partial x_2}\left(\frac{k}{\epsilon}\left(u_2'u_2'\frac{\partial \epsilon}{\partial x_2} + u_2'u_3'\frac{\partial \epsilon}{\partial x_3}\right)\right) + \frac{\partial}{\partial x_3}\left(\frac{k}{\epsilon}\left(u_2'u_3'\frac{\partial \epsilon}{\partial x_2} + u_3'u_3'\frac{\partial \epsilon}{\partial x_3}\right)\right)\right]$$
$$-C_{\epsilon_1}\mathcal{P}\frac{\epsilon}{k} + C_{\epsilon_2}\frac{\epsilon^2}{k} = 0, \quad \text{(A-8)}$$

turbulence production .

$$\mathcal{P} = -u_1'u_2'\frac{\partial u_1}{\partial x_2} - u_1'u_3'\frac{\partial u_1}{\partial x_3} - u_2'u_3'\left(\frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_2}\right) - (u_2'u_2' - u_1'u_1')\frac{\partial u_2}{\partial x_2} - (u_3'u_3' - u_1'u_1')\frac{\partial u_3}{\partial x_3}, \quad \text{(A-9)}$$

kinematic turbulent stresses:

$$u_1'u_1' = C_1k - R_{400}C_2\nu_t\frac{k}{\epsilon}\left(\left(\frac{\partial u_1}{\partial x_2}\right)^2 + \left(\frac{\partial u_1}{\partial x_3}\right)^2\right) - 2R_{401}\nu_t\left(\frac{\partial u_1}{\partial x_1}\right), \quad \text{(A-10)}$$

$$u_2'u_2' = C_3k - R_{402}C_2\nu_t\frac{k}{\epsilon}\left(\frac{\partial u_1}{\partial x_2}\right)^2 - 2R_{403}\nu_t\left(\frac{\partial u_2}{\partial x_2}\right), \quad \text{(A-11)}$$

$$u_3'u_3' = C_3k - R_{404}C_2\nu_t\frac{k}{\epsilon}\left(\frac{\partial u_1}{\partial x_3}\right)^2 - 2R_{405}\nu_t\left(\frac{\partial u_3}{\partial x_3}\right), \quad \text{(A-12)}$$

$$u_1'u_2' = -\nu_t\left(\frac{\partial u_1}{\partial x_2}\right) - C_2\nu_t\frac{k}{\epsilon}\left(R_{406}\frac{\partial u_1}{\partial x_3}\left(\frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_2}\right) - 2R_{407}\frac{\partial u_1}{\partial x_2}\frac{\partial u_3}{\partial x_3}\right), \quad \text{(A-13)}$$

$$u_1'u_3' = -\nu_t\left(\frac{\partial u_1}{\partial x_3}\right) - C_2\nu_t\frac{k}{\epsilon}\left(R_{408}\frac{\partial u_1}{\partial x_2}\left(\frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_2}\right) - 2R_{409}\frac{\partial u_1}{\partial x_3}\frac{\partial u_2}{\partial x_2}\right). \quad \text{(A-14)}$$

$$u_2'u_3' = -\nu_t\left(\frac{\partial u_2}{\partial x_3} + \frac{\partial u_3}{\partial x_2}\right) - R_{411}C_2\nu_t\frac{k}{\epsilon}\left(\frac{\partial u_1}{\partial x_2}\frac{\partial u_1}{\partial x_3}\right). \quad \text{(A-15)}$$

The turbulent kinematic viscosity and the reference Reynolds number are given by,

$$\nu_t = C_4 \frac{k^2}{\epsilon}, \tag{A-16}$$

and,

$$Re_L = \frac{u_\infty L}{\nu_\infty}. \tag{A-17}$$

respectively. The function $\mathcal{F}$ in the cross-plane momentum equations is included to illustrate the action of the penalty (continuity) constraint term in the numerical algorithm (see Ref. [4], chapter 7). Aside from the "R_{nnn}" coefficients, the model contains the 10 constants $\{C_1, C_2, C_3, C_4, \sigma_k, \sigma_\epsilon, C_{\epsilon_1}, C_{\epsilon_2}, C_k, C_\epsilon\}$ which take on the commonly accepted values $\{0.94, 0.067, 0.56, 0.068, 1.0, 1.3, 1.44, 1.92, 0.12, 0.09\}$. Most of these model constants are specified in subroutine **FENAME**, however a few are computed in subroutines **DIMEN** and **DERVBL**.

The subscripts on the R_{nnn} coefficients in the above equations refer to locations in the scalar array **RARRAY(500)**. This array is initialized to default values in **FENAME** and modified to be problem specific during the input sequence. The coefficients have obvious utility in specifying a problem class from the general convp576ection-diffusion equation (Eq. (1)). Restricting attention to the PNS equations, several of the coefficients, particularly those modifying the convection and source (pressure gradient) terms, are extraneous, and have utility only for debugging or sensitivity studies. Those coefficients modifying the eddy viscosity diffusion and Reynolds stress-gradient terms have more utility since they potentiallyy provide an additional control over the degree of non-linearity and explicitness in the descretized equations by specifying more or less of the diffusion in the source terms. It should be noted, however, that in this version of the code, the Reynolds stresses are updated at every iteration, and as such any representation $0 \leq R_{nnn} \leq 1$ will give essentially identical results if only the lead order terms are retained in the Reynolds stress constitutive equations. For instance, specifying $R_{281} = 1$ or 0 in Eq. (A-1) yields the same result if only the first terms in Eqs. (A-13) and (A-14) are used and if the stresses are computed at the current iteration. In the original version of the code the following default values of coefficients in Eqs. (A-1) through (A-8) were set:

$$R_{385} = R_{348} = R_{282} = R_{339} = R_{340} = R_{396} = R_{394} = R_{384} = 1,$$
$$R_{281} = R_{346} = R_{399} = R_{398} = R_{283} = 0,$$
$$R_{353} = -1.$$

In the current version of the code the above specifications are retained with the exceptions that $R_{282} = 0$ and $R_{346} = 1$, thus all diffusion terms are determined to the same degree of approximation. Calculations were performed for a variety of permutations of the these coefficients during the studies reported in Refs. [6,7] and differences in the results due to laminar diffusion or the alternate forms of Eqs. (A-2) and (A-3) were insignificant.

The stress specification in Eqs. (A-10) through (A-15) is different from the original specification by the presence of the second terms in the equations for $u_1'u_2'$ and $u_1'u_3'$. These were added so as to include the full model specified in Ref. [4]. All of the stress coefficients have default values of unity.

APPENDIX B – COMMAND INPUT DATA FOR WAKE SIMULATIONS

```
OUTPUT8
OUTPUT9
OUTPUT15
OUTPUT16
OUTPUT17
OUTPUT18
INPUT19
              TWAKE DATA : DTNSRDC DESTROYER : INITIALIZE AT 10 FT.
              INBOARD PROPELLER ROTATION
        Call SUBROUTINE FENAME to initialize default IARRAY and RARRAY entries.
FENAME   T SUBROUTINE BDINPT calls SUBROUTINE FENAME on this command.
        Define the type of flow for simulation.
IARRAY   2 7 T sets IARRAY(2)=NTYPE=7
        NTYPE controls subsequent calls within SUBROUTINE TBLINP and SUBROUTINE
        NODPPR. This value will cause the fluid state to be initialized according to
        DTNSRDC experimental data that has been pre-processed and saved in file
        INPUT19 above.  This parameter also controls the flow path for computing
        the axial pressure gradients (zero for this case).  See SUBROUTINE NODPPR.
IARRAY   41 1 T sets IARRAY(41)=N2WAKE=1
        N2WAKE alters the flow path in the execution module such that routines
        appropriate only to flows near solid boundaries are not called.
        Define the fluid parameters.
RARRAY   27 6.7556  T sets the free-stream velocity (UINF) = 6.7556 ft/sec
RARRAY   10 1.935   T fluid density (RHOINF) = 1.935 lbf-sec-sec/(ft4)
RARRAY   38 21.1E-6 T fluid viscosity (XMUINF) in lbf-sec/ft-ft
        Define the streamwise extent of computation.
RARRAY   43 1.0  T set reference length (REFL) = 1.0 ft
RARRAY   24 10.0 T set initial X-plane (TO) = 10.0
RARRAY   35 20.  T set solution distance (TD) =20.
        The final station will be TF=TO+TD=30.
RARRAY   304 0.5 T set implicitness factor (CIMPTH)
RARRAY   196 0.5 T set implicitness factor (THETA)
RARRAY   7 .01   T set initial axial stepsize (HSINIT)
RARRAY   16 10.  T set maximum allowable stepsize (HMAX)
        HMAX is expected as a percentage to be applied to TD. In this case
        HMAX will be computed HMAX=.10*TD=2.
RARRAY   13 101.  T set the intervals for printing or storing data (DELP)
        This is also input as a percentage of TD and in this case will be computed
        to be greater than the sol'n distance.  It will print at the final station
        TF=30.  Further print controls will be implemented via the VPVSX and
        VX3ST command sequence used further along in the data set.  Note that if
        a value less that 100., e.g., 25., had been used, output would result at
        .25*TD, .50*TD etc.
        Define coefficients for conservation equations:  see Appendix A.
        Note difference in RARRAY command parameters to set entry = 0.  See BDINT.
RARRAY   385 1.    T UCMULT
RARRAY   348 1.    T VCMULT
RARRAY   339 1.    T PCFACT
RARRAY   346 1.    T VLDMLT
RARRAY   340 1.    T PPFACT
RARRAY   396 1.    T OSG
RARRAY   394 1.    T T2FIX
RARRAY   384 1.    T ECMULT
RARRAY   353 -1.   T GUMULT
RARRAY   282 0.  500 T U2STRS
RARRAY   281 0.  500 T U1STRS
RARRAY   399 0.  500 T TU1U2P
RARRAY   398 0.  500 T T2PFIX
RARRAY   283 0.  500 T EKSTRS
        Define shear stress coefficients.
RARRAY   400 1.  T C112
RARRAY   401 1.  T C113
RARRAY   402 1.  T C222
RARRAY   403 1.  T C223
RARRAY   404 1.  T C332
RARRAY   405 1.  T C333
RARRAY   406 1.  T C122
RARRAY   407 1.  T C123
RARRAY   408 1.  T C132
RARRAY   409 1.  T C133
RARRAY   410 1.  T C231
RARRAY   411 1.  T C232
        Set up finite element geometry.

        NM=3 denotes that a 3D parabolic sol'n is to be obtained.  2D triangular
        finite elements will be constructed.
IARRAY   52 19  T set no. of rows of computational nodes (KROW) = 19
IARRAY   50 19  T set no. of columns of nodes (KCOL) = 19
IARRAY   55 400 T set NODE
        NODE should be set slightly greater than KROW*KCOL to allow for sufficient
        storage allocation in dynamic dimensioning routine FEDIMN.
        Removing the "C" from 1st col. in next 3 statements turns on debug prints.
CIARRAY   61 1, 86 1 T
CIARRAY   76 300 , 7 200, 6 3 T
CIARRAY   122 1 T

        Removing the "C" in next 2 statements will print status of all non-zero
        IARRAY and RARRAY entries to this point and terminate execution.
CICOND   T
CEXIT    T
        Call SUBROUTINE FEDIMN to allocate storage for variable length vectors.
FEDIMN      T
```

Specify sequencing for solution of equation system. The following table identifies the dependent variables by integer numbers.

variable	1	streamwise velocity	(U1)
	2	vertical velocity	(U2)
	3	lateral velocity	(U3)
	4	stagnation enthalpy	(H)
	5	turbulence K. E.	(TKE)
	6	dissipation fct.	(EPS)
	7	perturbation pres.	(PP)
	8	complementary pres.	(PC)
	9	penalty fct.	(PHI)

```
IPINT   T fill the IPINT vector, read the next card image
 1 5 6 2 3 7 8 9 0 0 , 1 -3 -3 -5 -5 5*0 , 10*I1 1 T
```

The first group of 10 integers above specifies the order in which the eqns. are solved at each iteration, i.e., U1,TKE,EPS,U2,U3 etc. Note that the stag. enthalpy is not computed. Also the complementary pres. is not computed in this case but is constant. The third group of 10 integers, 10*I1 1 (this string denotes the 10 integers beginning at 1 with each successive integer incremented by 1; 1,2,3 etc) re-labels the governing equations according to the sequencing specified in the first group, i.e., eqn(1) is identified with U1, eqn(2) with TKE etc. The second group of 10 integers specifies a staggered start for the computation. Eqn(1) (U1) is solved beginning at the first axial step. The 2nd and 3rd eqns. (TKE and EPS) are turned on at step 3. The 4th and 5th eqns. are turned on at step 5. There is no delay for the remaining eqns.

Construct the finite element network

```
LINK2   14 T call SUBROUTINE DSCRTZ to set up coordinates.
VX2SCL    T compute node spacing for normal (X2) direction
 0.0 9 -1.5 1.  9 -3.  1.  T
VX1SCL   T compute node spacing for lateral (X3) direction
 0.0, 9 +1.5 1.  9 3.  1.  T
NDECRD
 1 19, 1 19 T
ELEM    T set up element connections for above geometry.
DONE    T leave DSCRTZ.
```

See Ref. 2 pp. 8-9 and Ref. 3 pp. 22-23 for explanation of the above command sequence.
This particular string will result in the construction of a 3X3 square domain with the origin of coordinates at the top left corner. The X3 (lateral) axis is spanned by 19 equi-spaced nodes (18 elements) from 0.0 to 3.0. The X2 axis is also spanned by 19 equi-spaced nodes from 0.0 to -3.0. There results 361 nodes and 648 elements.

Establish boundary conditions for dependent variables. These command data have a prescribed format. See Ref. 2 pp. 21-22, 26 and Ref. 3 pp. 18-19 for a general description of the boundary condition procedures. For any variable the default bc is zero gradient normal to boundary in question. It is only necessary to list the boundaries (for each variable in turn) where this should not be the case. For the flow situation considered, the left boundary is a plane of symmetry, the top boundary is a "rigid lid" free surface (equivalent to symmetry), and the bottom and right boundaries are in the free stream.

The next command is a list of boundary nodes. The positive direction is counter-clock-wise, e.g., -TOP creates a list of the node numbers for the top row beginning at the left most node (no. 1) and continuing to the last node in that row (no. 19).

```
IBORD
LEFT             2    BOTTOM         2    RIGHT          2    TOP            2
DONE
LINK1   2 T call NODELM to establish element-node connectivity table.
```

List variables and boundaries where value should be maintained at initial level.

```
KBNO    2 T Fix var. 2 (U2) at U2=0 on top bndry.
-TOP               DONE
KBNO    3 T Fix var. 3 (U3) at U3=0 on left bndry.
-LEFT              DONE
KBNO    9 T Fix var. 9 (PHI) at PHI=0 at freestream bndrys.
BOTTOM             RIGHT          2    DONE
KBNO    7 T Fix var. 7 (PP) at PP=0 at fresstream bndrys.
BOTTOM             RIGHT          2    DONE
```

All variables on all boundaries not specifically referenced above will be subject to homogeneous Neumann bc's. These bc's allow entrainment from the freestream. Note that PHI=0 allows non-vanishing normal gradient and mass eflux or influx. U1, TKE, and EPS could as well be prescribed as fixed at the freestream boundaries (in this instance) with no significant difference in the computed results.

Set up formats for LU6 printed output.

The next two commands store data for the first and last pages of the LU6 printed output. Anything placed after the command and before "DONE" will appear on the appropriate page.

```
COMTITLE T Read title for last page.
                3D WAKE FLOW - - - DTNSRDC: DESTROYER IB ROT.
DONE
DESCRIPT 204 T Descriptive title for first page.
                3D WAKE FLOW - - - DTNSRDC: DESTROYER
DONE
```

The next set of commands designates which scalar data is to be printed at the output stations and specifies titles and scale factors to be applied to the data. See Ref. 2 pp. 12-15.

Fill the header title vector until "DONE".

```
DESCRIPT 332 T IOPAR vector
 REFERENCE         ENGLISH-FT         ENGLISH-IN       M-K-S          C-G-S
 LENGTH.........   .FT.........     .IN.........     .M..........    .CM.
 VELOCITY.......   .FT/SEC...       .N.A........     .M/S.......     .CM/SEC.
 DENSITY........   .LBM/FT3....     .N.A........     .KG/M3......    .G/CC...
 TEMPERATURE....   .RANKINE....     .N.A........     .KELVIN.....    .N.A
 ENTHALPY.......   .BTU/LBM....     .N.A........     .KJ/KG......    .N.A
 FROZ.SPEC.HEAT.   .BTU/LBM-R..     .N.A........     .KJ/KG-K....    .N.A
 VISCOSITY......   .LBM/FT-S...     .N.A........     .NT-S/M2....    .POISE...
 LOCAL PRESSURE.   .PSF........     .PSI........     ..UEDGE.....    .CPU TIME..
..DPDX1...         ..ENERGY..       .INT. VAR..      NWGEOM H'S       ..H21...
..G23.....         .X1/LREF..       .DX1/LREF.       .EPSILON..      .DX1M/LREF
```

```
REFL REY. NO.
DONE
        Define location in RARRAY of scalars in accord with above titles.
IONUMB   T
 999, 5*200, 999, 200 4*43, 200 27 200 27 27, 200
 10 200 10 10, 200 58 200 58 200, 200 97 200 97
 200, 200 30 200 30 200,
 200 38 200 2*38, 999, 36 2*36 63 300, 100 135 120 200 186 188,
 11 12 14 85 47 T
        Define location in RARRAY of scale factors applied to above scalar data.
        Positive values are multipliers and negative values are divisors.
MPARA   T
 5*2, 2 2 162 164 163, 2 2 2 164 163, 2 2 2 170 174,
 2 2 2 165 2, 2 -175 2 2 2, 2 2 2 176 2, 2 2 2 177 178,
 -351 2 169 2 2, 3*2 108 2, 5*2, 5*2 T
        Designate titles for profiles of output dependent variables until
        "DONE".  See Ref. 2, page 15.
DESCRIPT 203 T
U1 / UREF       U2 / UREF       U3 / UREF        TKE/TKEREF       EPS/DISSREF
U1'U1'          U1'U2'          U1'U3'           U2'U2'           U2'U3'
U3'U3'          PP              P                PHI
DONE
        Define variables to be output under above titles.  Each entry is a composite
        number which is decoded by the program.  See Ref. 2, pp. 17-21 and 35.
IOSAVE   T output vectors
 1248 2248 3248 5248 6248 3271
 4271 5271 6271 7271 8271 7248
 8248 9248 T
        Define scalar multipliers to be applied to each vector in turn.  In this
        case all vectors are multiplied by RARRAY(2) (which = 1.0) except the
        12th entry (PP) which is multiplied by RARRAY(171).
IOMULT   T scalar multipliers for IOSAVE vectors.
 11*2 171 2*2 14*1 T
        Specify axial locations for printed and stored output.  The program in
        SUBROUTINE DPSISQ designates a print at axial locations where the
        external pressure is specified.  Even though the freestream pressure
        is constant in this flow, the print mechanism will be activated by
        creating a pressure table.
        The next command specifies a pressure table with 4 entries, pressure
        equals ambient level at each location.
VPVSX
 4*2116.8 T
        The next command specifies the axial locations where the pressure is at
        the above levels.  A print on LU6 will always occur at the initial and
        final stations.
VX3ST
 10.  16.  22.  30.  T
        Call SUBROUTINE DIMEN to compute non-dimensional parameters.
LINK3   4 T DIMEN and INDEX
```

```
        Call SUBROUTINE GEOMFL to generate the element matrices and vectors
        for the natural coordinate system.  See Ref. 4, Chapt. 3.
LINK1   3 T GEOMFL
        Call SUBROUTINE NODELM again to compute element thickness and area from
        data calculated in GEOMFL.
LINK1   2 T NODELM
        Call SUBROUTINE TBLINP (NTYPE=7) to link with SUBROUTINE DTNSRDC and
        initialize U1,U2,U3,TKE,EPS on each node in finite-element domain.
        Data will be required from LU19 (file INPUT19) specified above and
        prepared in advance by the user.
LINK2   10 T Distribute 3D wake vel. vector and TKE,EPS
        Call subroutines SETDIF and DFCFBL to initialize diffusion coefficients.
LINK5   6 T SETDIF-DFCFBL
        Call SUBROUTINE RNLDST to initialize Reynolds stresses.
LINK5   4 T RNLDST
        Initialization is complete.  Transfer control to main drive loop.
        Removing "C" from 1st col.  in next 4 commands will cause a print of
        all non-zero IARRAY and RARRAY parameters, a node table print, and a
        listing of the initial fluid state.  The program will terminate at
        "EXIT" before entering execution sequence.
CICOND
CLINK2   5 T NODES
CLINK2   6 T OUTPUT
CEXIT
        Turn off any debug switches which may have been turned on.  Note:  they
        may be left on during execution at the expense of a great amount of
        output on LU6.
IARRAY   61 0, 86 0 T
IARRAY   76 0 , 7 0, 6 0 T
IARRAY   122 0 T
QKNINT   T Begin integration procedures.
EXIT     T Terminate run at end of QKNINT call.
CASE END
```

APPENDIX C   SAMPLE DATA FROM OUTPUT UNITS

1 LU8

```
     Xt          time      iPpmn     Ppmn      iPpmx     Ppmx       iPmn      Pmn       iPmx      Pmx
0.1000E+02 0.1001E+02     1   0.0000E+00     1   0.0000E+00     1   0.0000E+00     1   0.0000E+00
0.1001E+02 0.1002E+02    79  -0.1485E-03    65   0.2562E-05     1   0.0000E+00     1   0.0000E+00
0.1002E+02 0.1003E+02    79  -0.1485E 03    65   0.2563E-05     1   0.0000E+00     1   0.0000E+00
0.1003E+02 0.1005E+02    79  -0.1484E-03    65   0.2577E 05     1   0.0000E+00     1   0.0000E+00

etc

0.3000E+02 0.3000E+02    41   0.3929E 04   154   0.7480E 06     1   0.0000E+00     1   0.0000E+00
```

2 LU9

```
     Xt          time          dx      idPpmn   dPpdxmn   idPpmx   dPpdxmx   idPmn    dPdxmn    idPmx    dPdxmx      dPpdx        dPdx
0.1000E+02 0.1001E+02 0.1000E-01   361   0.0000E+00   361   0.0000E+00     0   0.0000E+00     0   0.0000E+00 0.0000E+00 0.0000E+00
0.1001E+02 0.1002E+02 0.1000E-01    79   0.3634E+00    65   0.6269E-02     0   0.0000E+00     0   0.0000E+00 0.8265E+01 0.0000E+00
0.1002E+02 0.1003E+02 0.1100E-01    42   0.1551E 03     3   0.8651E-04     0   0.0000E+00     0   0.0000E+00 0.1008E 02 0.0000E+00
0.1003E+02 0.1005E+02 0.1210E-01    43   0.5364E 03     3   0.4089E-03     0   0.0000E+00     0   0.0000E+00 0.1118E 02 0.0000E+00

etc

0.3000E+02 0.3000E+02 0.1658E+01    66  -0.1220E 04    61   0.5167E-04     0   0.0000E+00     0   0.0000E+00 0.1463E 02 0.0000E+00
```

3 LU16

```
 nel     Xt            time            V21            V22             V11           V12         nvmax     Vthmx         theta       iemx     EPSmax
  1 0.10000E+02 0.10010E+02-0.13475E+00 0.36589E-02 0.38800E-01 0.12250E 01      60 0.48605E 01 0.21157E+03      42 0.66264E 03
  2 0.10010E+02 0.10021E+02-0.13471E+00 0.36589E 02 0.38800E-01 0.12114E 01      60 0.48605E 01 0.21157E+03      42 0.66264E 03
  3 0.10021E+02 0.10033E+02-0.13467E+00 0.36589E 02 0.38800E-01 0.11966E 01      60 0.48605E 01 0.21157E+03      42 0.66264E 03
  4 0.10033E+02 0.10046E+02-0.13463E+00 0.36510E-02 0.38800E-01 0.11805E-01      60 0.48605E 01 0.21157E+03      42 0.66170E 03
  5 0.10046E+02 0.10061E+02 0.13458E+00 0.36423E 02 0.38800E-01 0.11630E 01      60 0.48605E 01 0.21157E+03      42 0.66066E 03

  etc

 39 0.30000E+02 0.30000E+02 0.39278E-01 0.15688E-02 0.51472E-02 0.10097E-03     100 0.13156E 01 0.60506E+02      42 0.83351E 04
```

4 LU17

```
 nel     Xt       itmx    TKmx     iumx    U1mx      iumn     U1mn    iU2mx     U2mx     iU2mn    U2mn     iU3mx    U3mx     iU3mn     U3mn
  1 0.10000E+02   42   0.5306E 02   81   0.1047E+00    5   0.1348E+00   81   0.4568E 01   79   0.3464E 01     2   0.3880E 01   61   0.4643E 01
  2 0.10010E+02   42   0.5306E 02   81   0.1047E+00    5   0.1347E+00   81   0.4568E 01   79   0.3464E 01     2   0.3880E 01   61   0.4643E 01
  3 0.10021E+02   42   0.5306E 02   81   0.1046E+00    5   0.1347E+00   81   0.4568E 01   79   0.3464E 01     2   0.3880E 01   61   0.4643E 01
  4 0.10033E+02   42   0.5301E 02   81   0.1045E+00    5  -0.1346E+00   81   0.4568E 01   79   0.3464E 01     2   0.3880E 01   61   0.4643E 01
  5 0.10046E+02   42   0.5295E 02   81   0.1045E+00    5   0.1346E+00   81   0.4568E 01   79   0.3464E 01     2   0.3880E 01   61   0.4643E 01

  etc

 39 0.30000E+02   42   0.1783E 02  101   0.3814E 01    6   0.3928E 01  100   0.1145E 01   96   0.1004E 01   118   0.1154E 01   61   0.9911E 02
```

NOTES: All of the above files are written from subroutine STNPRNT. One record is written to each file during each axial step. Each write for each file is 1 record and LU's 8 9 are written only if ILU8 1.

APPENDIX C   continued

```
5  LU15

 361      19      19 0.10000E+01 0.21100E 04 0.19350E+01 0.67556E+01 <---- dimensionalizing scalars
   1 0 00000E+00 0.00000E+00
   2 0 00000E+00 0.16667E+00
   3 0 00000E+00 0.33333E+00 ------ (X2,X3) for each node
   4 0 00000E+00 0.50000E+00
   5 0 00000E+00 0 66667E+00        scalar data and nodal coordinates written
                                    on the first pass only
   etc

 360 0 30000E+01 0 28333E+01
 361 0 30000E+01 0.30000E+01
   X STATION     0 10000E+02
0 12250E 01 0 00000E+00 0.00000E+00 0.24123E 02 0 20312E 03 0 24955E 02 0 23256E 05 0.54799E 03 0 19265E 02 0 13153E 05 0 40254E 03
0 27100E 01 0 00000E+00 0.38800E-01 0.28269E 02 0 25766E-03 0.27964E 02 0 46704E 04 0 61419E 03 0.19164E 02 0.34905E 04 0 91131E 03
0 74600E 01 0 00000E+00 0.35300E-01 0.36449E 02 0.37723E-03 0.32922E 02 0.10769E 03 0.65539E 03 0.19063E 02 0 12852E 04 0 20751E 02
0 11495E+00 0 00000E+00 0.29750E-01 0.34432E-02 0.34637E-03 0.33613E 02 0.62570E 04 0 38980E-03 0.15524E 02 0 11676E 03 0 20813E 02
0 13475E+00 0 00000E+00 0.21850E-01 0.32051E 02 0.31106E-03 0.30888E 02 0 61750E 04 0 44456E 05 0.14601E 02 0 13052E 03 0 20315E 02
0 10865E+00 0.00000E+00 0.54625E-02 0.36589E 02 0.37941E-Q3 0.31655E 02 0.25583E 03 0.5992.)E 03 0 18659E 02 0.92187E 05 0 22507E 02
0 48200E 01 0 00000E+00 0.13658E 02 0.22399E 02 0.18173E-03 0.19521E 02 0.19412E 03 0 45965E 03 0 12173E 02 0 60009E 04 0 12130E 02

 etc

0 00000E+00 0.00000E+00 0.00000E+00 0.25000E-04 0.21429E-06 0.23445E 04 0.00000E+00 0.00000E+00 0.14115E 04 0 00000E+00 0 14115E 04
0 00000E+00 0 00000E+00 0.00000E+00 0.25000E 04 0 21429E-06 0.23445E 04 0.00000E+00 0.00000E+00 0.14115E 04 0.00000E+00 0 14115E 04
   X STATION -   0.16029E+02
0 19746E 01 0 00000E+00 0 00000E+00 0.21380E 02 0.13088E-03 0.20231E 02 0 28424E 04 0.11435E 03 0 15878E 02 0.31235E 05 0 79859E 03
0 26745E 01 0 00000E+00 0 14537E-01 0.22394E 02 0 14144E 03 0.20773E 02 0 46825E 04 0 20752E 03 0 15648E 02 0 22848E 04 0 94489E 03
0 49922E 01 0 00000E+00 0.22899E 01 0.25059E 02 0 16867E 03 0.22829E 02 0 42575E 04 0 37820E 03 0 14674E 02 0 90453E 04 0 13155E 02

 etc

0 00000E+00 0 23558E 06 0 19331E 06 0.25000E 04 0 21429E-06 0.23445E 04 0.00000E+00 0.00000E+00 0 14115E 04 0 65742E 09 0 14114E 04
0 00000E+00 0 59262E 06 0.61608E 06 0.25000E-04 0.21429E-06 0.23442E 04 0.00000E+00 0.00000E+00 0.14116E 04 0 17759E 08 0 14117E 04
   X STATION     0 22342E+02
0 29276E 01 0 00000E+00 0.00000E+00 0.17598E 02 0 82790E 04 0.16617E 02 0.31926E 04 0.81084E 04 0 11967E 02 0 22266E 05 0 77427E 03
0 32915E 01 0 00000E+00 0 72209E 02 0.18009E 02 0 85639E 04 0.16711E 02 0.34247E 04 0.97059E 04 0 11847E 02 0 28734E 04 0 85443E 03

 etc

0 00000E 00 0 50141E 06 0 52051E 06 0.25000E 04 0 21429E 06 0 23443E 04 0.00000E+00 0.00000E+00 0 14115E 04 0 29649E 08 0 14116E 04
   X STATION     0 30000E+02
0 28595E 01 0 00000E+00 0 00000E+00 0.14161E 02 0.51471E 04 0.13286E 02 0 45579E 04 0.27229E 04 0 87757E 03 0 17317E 05 0 71672E 03
0 30234E 01 0 00000E+00 0.26166E 02 0 14357E 02 0 52595E 04 0 13387E 02 0 51739E 04 0.34754E 04 0 87771E 03 0 16946E 04 0 74540E 03
```

NOTES. These data are written from subroutine PLTOUT at axial stations where KPNT-1. On each call the X1 station is written followed by KROW'LCOL number of records. Each record consists of the values of 11 fluid variables at that node.

APPENDIX C continued

```
6  LU18

361      19      19 0.10000E+01 0.21100E-04 0.19350E+01 0.67556E+01 0.10000E+01 <—— dimensionalizing scalars
    1 0.00000E+00
    2 0 16667E+00
    3 0 33333E+00
    4 0 50000E+00
    5 0 66667E+00
    6 0 83333E+00 —X3 nodal coordinate for top row of nodes (X2=0) written
    7 0 10000E+01     on 1st pass only
    8 0 11667E+01
    9 0 13333E+01
   10 0 15000E+01
   11 0 16667E+01
   12 0 18333E+01
   13 0 20000E+01
   14 0 21667E+01
   15 0 23333E+01
   16 0 25000E+01
   17 0 26667E+01                                 dX1
   18 0 28333E+01                                /
   19 0.30000E+01                               /
    X STATION    0.10000E+02        0.10000E 01 0.10000E-01      1
0 12250E 01 0 00000E+00 0.00000E+00 0.24123E 02 0.20312E-03 0.24955E-02-0.23256E 05 0.54799E 03 0.19265E 02 0 13153E 05 0 40254E 03
0 27100E 01 0.00000E+00 0.38800E-01 0.28269E-02 0.25766E-03 0.27994E-02-0.46704E 04 0 61419E 03 0 19164E 02 0 34905E 04 0.91131E 03
0.74600E 01 0.00000E+00 0.35300E-01 0.36449E 02 0.37723E-03 0.32922E 02-0.10769E 03 0.65539E 03 0.19063E 02 0 12852E 04 0.20751E 02
0 11495E+00 0.00000E+00 0 29750E-01 0.34432E-02 0.34637E-03 0.33613E-02-0.62570E 04 0 38980E 03 0.15524E 02 0 11676E 03 0 20813E 02
0 13475E+00 0.00000E+00 0.21850E-01 0.32051E 02 0.31106E-03 0.30888E-02 0.61750E 04 0.44456E 05 0.14601E 02 0 13052E 03 0.20315E 02
0 10865E+00 0 00000E+00 0 54625E-02 0.36589E 02 0.37941E-03 0.31655E-02 0.25583E 03 0 59929E 03 0 18659E 02 0 92187E 05 0 22507E 02
0 48200E 01 0.00000E+00 0.13656E-02 0.22399E 02 0.18173E-03 0.19521E-02 0.19412E 03 0.45965E 03 0 12173E 02 0 60009E 04 0.12130E 02
0 28800E 01 0 00000E+00 0.00000E+00 0.12039E-02 0.71611E-04 0.11022E-02 0.77916E 04 0.13549E 04 0 67093E 03 0 16866E 05 0 67612E 03
0 49050E 01 0 00000E+00 0.00000E+00 0.12913E 02 0.79544E-04 0.11878E-02 0.90482E 04 0 74563E 04 0.72260E 03 0 84212E 05 0 71232E 03
0 37250E 01 0.00000E+00 0.00000E+00 0.11049E-02 0.62958E-04 0.10097E-02 0 95147E 04-0.13295E 03 0.61571E 03 ) 23075E 04 0 60543E 03
0 13350E 01 0 00000E+00 0.00000E+00 0.62678E-03 0.26900E-04 0.56513E-03 0.51481E 04-0.10779E 03 0 34967E 03 ) 17432E 04 0.33542E 03
0 00000E+00 0.00000E+00 0.00000E+00 0.30356E 03 0.90668E-05 0.28136E-03 0.84043E 05-0.22139E 04 0.17070E 03 ) 23917E 05 0.16876E 03
0 00000E+00 0.00000E+00 0.00000E+00 0.21995E-03 0.55919E-05 0.20627E-03 0.00000E+00 0.00000E+00 0 12418E 03 0 00000E+00 0.12418E 03
0 00000E+00 0 00000E+00 0.00000E+00 0.14572E-03 0.30156E-05 0.13666E-03 0.00000E+00 0.00000E+00 0.82273E 04 0 00000E+00 0 82273E 04
0 00000E+00 0 00000E+00 0.00000E+00 0.25000E-04 0.21429E-06 0.23445E 04 0.00000E+00 0 00000E+00 0 14115E 04 0 00000E+00 0.14115E 04
0 00000E+00 0 00000E+00 0.00000E+00 0.25000E-04 0.21429E-06 0.23445E-04 0.00000E+00 0.00000E+00 0.14115E 04 0 00000E+00 0 14115E 04
0 00000E+00 0.00000E+00 0.00000E+00 0.25000E-04 0.21429E-06 0.23445E-04 0.00000E+00 0 00000E+00 0 14115E 04 0 00000E+00 0.14115E 04
0 00000E+00 0 00000E+00 0.00000E+00 0.25000E 04 0.21429E-06 0.23445E 04 0.00000E+00 0.00000E+00 0 14115E 04 0 00000E+00 0 14115E 04
0 00000E+00 0 00000E+00 0.00000E+00 0.25000E-04 0.21429E-06 0.23445E-04 0.00000E+00 0 00000E+00 0 14115E 04 0 00000E+00 0 14115E 04
    X STATION    0.10010E+02        0.11000E-01 0.10000E-01      2
0 12114E 01 0 00000E+00 0.00000E+00 0.24123E 02 0.20312E 03 0.24966E 02 0.21546E 05 0.54423E 03 0.19265E 02 0 12102E 05 0.40365E 03
0 26966E 01 0.00000E+00 0.38800E-01 0.28269E 02 0 25766E 03 0.28001E 02 0.47094E 04 0.61210E 03 0 19164E 02 0.35058E 04 0.91198E 03
0 74505E 01 0.00000E+00 0.35300E-01 0.36449E-02 0.37723E 03 0.32921E 02-0.10838E 03 0.65570E 03 0.19063E 02 0 12579E 04 0 20750E 02
0 11488E+00 0 00000E+00 0.29750E 01 0.34432E 02 0.34637E 03 0.33613E 02 0.62480E 04 0.38991E 03 0.15524E 02 0.11675E 03 0 20813E 02
```

etc.

NOTES: These data are written from subroutine *PLTSUR* at each axial step if *ILU18=1*. Each call writes the values of 11 fluid variables for each node in the plane of the mean free surface.

APPENDIX C   continued

7 LU6

These data are written from subroutine REOUTP at axial locations specified under the VX3ST command.

```
 STEP FOR INT. STARTUP.                      1      -3      -3      -5       5
 DEP. VAR. VECTOR. IPINT + 2*NDP.            1       2       3       4       5       6       7       8       9      10

 LOCATION OF DEPENDENT VAR.

   1     1     2     4    3-     5    4-     0    5-     2    6-     3    7-     6    8-     7     9     8    10     0
 11-     0   12-     0   13-     0   14-     0   15-     0   16-     0   17-     0   18-     0    19     0    20     0
 21-     0

 ADDRESSES OF DEP. VARIABLES.            25223   30023   31623       0   26823   28423   33223   34823   36423       0


          5 VARIABLES BEING INTEGRATED.
  1    5    6    2    3

          8 VARIABLES IN SOLUTION.
  1    5    6    2    3    7    8    9

ORDER OF CALLS AT END OF QKNUIN

 LINK5(10)

 PRINTOUT VARIABLES

 1248   2248   3248   5248   6248   3271   4271   5271   6271   7271
 8271   7248   8248   9248

PRINTOUT VARIABLE MULTIPLIERS.

 2      2      2      2      2      2      2      3      2      2
 2    171      2      2

PRINTOUT VARIABLE FACTORS. (N)

    N  EQ  1; STRAIGHT PRINT.
    N  EQ  2; MULT. LAST VEC. BY THIS ONE   STORE IN LAST.    Note the other output options available using
    N  EQ  3; ADD TO LAST VEC.   STORE IN LAST VEC. LOC.      the 2nd string of numbers under the IOMULT
    N  GE  4; RAISE ENTRIES TO (N-2) POWER                    command.
    N  LT  0; TAKE NTH ROOT OF ENTRIES IF  GT. 0.0

 1      1      1      1      1      1      1      1      1      1
 1      1      1      1


This page is written on the 1st pass only
```

7 LU6 continued

STATUS OF 409 IARRAY VALUES.

```
  1     ND  =      1     2  NTYPE  =      7     3         =    0     4 ISPLIT  =    0     5 NOMEGB  =      0
  6   KODG  =      0     7   KOD5  =      0     8 KPRINT  =    0     9 NRSTRT  =    0    10 NUCHLT  =      0
 11 NPTDOF  =      1    12    NCC  =      0    13 NCOORD  =    0    14  NELEM  =  648    15     NN  =      0
 16  NNODE  =    361    17    NNS  =      0    18  NPART  =    2    19    NOE  =    0    20  NPRNT        132
 21 NRESET  =      0    22     NC  =      8    23     NB  =    4    24  NPTEL  =    3    25   KIND          4
 26  KOUNT  =      1    27  NSKIP  =    400    28  IPASS  =    0    29   IRUN  =    0    30     NP  =      9
 31    NEQ  =      8    32 IWLSEP  =      2    33   NBUG  =    0    34 LPRINT  =  100    35 NISICC  =      0
 36 NPRSCC  =      0    37 NEWPRT  =      8    38 NOUTVC  =    8    39 NBASSM  =    0    40  NOUTS  =      1
 41 N2WAKE  =      1    42  INPUT  =      5    43         =    0    44 NSTORE  =    0    45   NEXP          0
 46     NF  =      4    47     LG  =      2    48   NDOF  =    0    49   NQEL  =    3    50   LCOL  =     19
 51  IROUT  =      0    52   KROW  =     19    53    NDB  =    0    54 NHHALF  =    0    55   NODE        400
 56 NADDVP  =      0    57 NEQXXX  =      0    58 NEQKNN  =    5    59 NCPTAB  =    1    60 NMBOUT  =     14
 61  KDUMP  =      0    62  NTITL  =      6    63         =    0    64    NSM  =   10    65 NMBSAV  =      0
 66 IFILTR  =      2    67     NS  =      4    68     NI  =    0    69  NBSET  =    0    70 NDTSET  =      0
 71 ISTAIN  =      0    72 IVALUE  =      0    73  ISTAD  =    0    74  IRRAY  =    0    75         =      0
 76 KREDBG  =      3    77 NGRPHI  =      0    78  NGRPP  =    0    79    NQQ  =    0    80 NPRDCT  =      1
 81 IVWVAL  =      0    82  IVSTA  =      0    83  IFSLT  =    0    84  NVARD  =    0    85  NVAR1  =      0
 86   KPNT  =      0    87 NRTAPE  =      0    88  NLINE  =   60    89 NUPUDT  =    0    90    NYY  =      4
 91    NZZ  =      4    92 IZSIZE  = 700000    93    NTK  =    2    94   NIZS  =  200    95 NVELTB  =      0
 96  IBASE  =    200    97   ITKE  =      1    98   IMAT  =    1    99    IBL  =    1   100  IREND  = 131616

101  NJETS  =      0   102   KOUT  =      0   103    MTM  =    0   104  NFLIP  =    1   105 IPTSPL  =      1
106     KK  =      0   107  NE1E2  =      3   108 NCNADD  =    0   109 NTAPER  =    0   110 NPRESH  =      0
111   IMAX  =      1   112 NWALLS  =      1   113 KPLVAR  =    0   114         =    0   115 IFORCE  =      0
116         =      0   117  IBUG1  =      0   118  IBUG2  =    0   119  NGBUG  =    0   120    IFR  =      0
121  NSPEC  =     10   122  IWRIT  =      0   123   IGAS  =    0   124 NDERIV  =    2   125 NCALLS  =      2
126 ISPEED  =      0   127 IDIFRT  =      0   128 ICNTND  =    0   129 IMATAB  =    2   130  NGETH  =      1
131  NBORD  =      0   132 IPWRIT  =      0   133   ITOP  =   79   134 NPSIBD  =    0   135 NPSBDL         0
136   KSAV  =      0   137         =      0   138         =    0   139  INGAS  =    0   140 NTCNTS  =      0
141   KFSL  =      0   142 NOUTPR  =     59   143 ICALL5  =    0   144  ITRAN  =    0   145 NICOND         1
146 NSFDBE  =      1   147  NPAST  =      0   148   NONC  =    0   149     IT  =    0   150  NODNO  =      0
151 KWFLXS  =      0   152 INITKE  =      1   153 NPUNCH  =    0   154 NSDFCF       0   155 NS2DFC  =      0
156 ITWOCL  =      0   157  NPASS  =      0   158 INITCN  =    0   159     IL  =    0   160     IH  =      0
161  NPVSX  =      4   162 IEPSET  =      0   163 NPSIST  =    0   164 NPSIND  =    0   165 NCCALL  =      0
166 N3DFNS  =      1   167 KNTPAS  =     99   168 NDPRES  =    0   169   KCDC  =    0   170    NBC  =      0
171  NBCND  =    401   172   LOWD  =      2   173 NCOMOC  =    0   174 NCOMTD  =    3   175   IFSL         0
176   NTKS  =     10   177 NU2POS  =      0   178 NU3POS  =    0   179    LOC       1   180  NSTRT  =     11
181  NVELP  =      0   182   LOGS  =      0   183         =    0   164              0   185         =      0
186   ITDA  =      0   187   ITDB  =      0   188  KTFIN  =    0   189   NSTD  =    9   190  NMOUT          3
191     NM  =      3   192    N2M  =      6   193    NM2  =    9   194    NDP      10   195 KFXBND         0
196 ITWALL  =      0   197 NTPRNT  =      0   198 NPGRDT  =    4   199 NPGRDV       4   200 INTPSI         0

etc

401 ISFLTR  =    200   402 IEFLTR  =    200   403 IFIFLTR =    1   404  IFINC  =    1   405 IPRSCAL =      0
406 ITSFRN  =      1   407   ILU8  =      1   408  ILU18  =    1   409         =    0
```

The status of IARRAY is written on each call to REOUTP.

7. LU6 continued

STATUS OF 414 RARRAY VALUES.

```
  1   FACT  = 1.0000E+00   2    ONE  = 1.0000E+00   3    ALC  = 1.0000E+00   4    THK  = 1.0000E+00   5     AJ  = 7.7828E+02
  6  SOUND  = 0.0000E+00   7 HSINIT  = 1.0000E-02   8 RMINS1  =-1.0000E+00   9   PINF  = 2.1168E+03  10 RHOINF  = 1.9350E+00
 11     XT  = 0.0000E+00  12     HT  = 0.0000E+00  13   DELP  = 2.0200E+01  14    EPS  = 1.0000E 02  15      H  = 1.0000E 02
 16   HMAX  = 2.0000E+00  17   HMIN  = 0.0000E+00  18  U2INF  = 0.0000E+00  19  U3INF  = 0.0000E+00  20   PTIM  = 3.0200E+01
 21     RE  = 6.1953E+05  22     TF  = 3.0000E+01  23   TIME  = 1.0000E+01  24     TO  = 1.0000E+01  25         = 0.0000E+00
 26  TWOPI  = 6.2832E+00  27   UINF  = 6.7556E+00  28  RUNIV  = 4.9719E+04  29         = 0.0000E+00  30 CPOINF  = 7.7218E+00
 31      G  = 1.0000E+00  32 RTCON1  = 1.5566E+03  33         = 0.0000E+00  34         = 0.0000E+00  35     TD  = 2.0000E+01
 36 PEDDIM  = 2.1168E+03  37    XLE  = 1.0000E+00  38 XMUINF  = 2.1100E 05  39  PEDGE  = 9.7957E-01  40 TRATIO  = 1.0000E+00
 41         = 0.0000E+00  42 TKEDGE  = 1.0000E+00  43   REFL  = 1.0000E+00  44    SQ2  = 1.4142E+00  45     HS  = 0.0000E+00
 46  XMDXR  = 0.0000E+00  47 REFLRE  = 6.1953E+05  48 TIMESV  = 0.0000E+00  49  RTEST  = 1.0000E 02  50 SSINIT  = 1.0000E 02
 51  AMNUT  = 0.0000E+00  52 XSCALE  = 1.0000E+00  53 YSCALE  = 1.0000E+00  54         = 0.0000E+00  55 RTCON4  = 0.0000E+00
 56 RTCON5  = 0.0000E+00  57 RTCON6  = 0.0000E+00  58 TOFINF  = 5.3300E+02  59 FACTMU  = 1.3072E+01  60 GAMMAF  = 1.4000E+00
 61 XMACHO  = 5.9696E-03  62   CONV  = 1.0000E+00  63  UEDGE  = 1.0000E+00  64         = 0.0000E+00  65         = 0.0000E+00
 66    XMF  = 2.9400E+01  67     PR  = 1.0000E+00  68  EP4MD  = 1.0000E+00  69 DIAGNL  = 1.0000E+00  70 CONRHO  = 1.0000E+00
 71 STLDVR  = 3.8478E-07  72 STLDTR  = 4.9200E+02  73 STLDCR  = 2.0400E+02  74 STLDEX  = 1.5000E+00  75 STLCON  = 2.1100E 05
 76    ZTT  = 0.0000E+00  77   CON1  = 9.9069E-03  78   CON2  = 1.8587E-05  79  FACTP  = 7.6499E-02  80  FACTH  = 2.4297E-04
 81   UTAU  = 0.0000E+00  82  PIBAR  = 1.0000E+00  83  COMPX  = 0.0000E+00  84  COMPY  = 0.0000E+00  85  HMIND  = 0.0000E+00
 86    AVD  = 2.5300E+01  87  U2REF  = 0.0000E+00  88  U3REF  = 0.0000E+00  89 EPSINF  = 3.0831E+02  90 TKEINF  = 4.5638E+01
 91         = 0.0000E+00  92  PFSLL  = 1.0000E-01  93  PFSLH  = 9.0000E-01  94  RATO2  = 0.0000E+00  95 EPTEST  = 1.5000E 10
 96 PSISTR  = 0.0000E+00  97   HINF  = 4.1157E+03  98 XPRIME  = 0.0000E+00  99 PPRCON  = 8.8310E+01 100 PPRIME  = 0.0000E+00

101         = 0.0000E+00 102         = 0.0000E+00 103  DEPLT  = 2.0200E+01 104 VELCST  = 7.1642E 06 105  ROCST  = 1.3370E+01
106   PTPL  = 3.0200E+01 107   VELD  = 0.0000E+00 108 ENMULT  = 5.9659E+02 109    XMA  = 2.8970E+01 110    XMH  = 2.0160E+00
111 TWELVE  = 1.2000E+01 112         = 0.0000E+00 113         = 0.0000E+00 114         = 0.0000E+00 115 ARSCAL  = 0.0000E+00
116     RR  = 1.4354E+01 117 RTOHM1  = 1.3083E+01 118  XMSDF  = 0.0000E+00 119 ROUALC  = 1.3072E+01 120   VARB  = 0.0000E+00
121   HDOT  = 0.0000E+00 122 HRSDOT  = 0.0000E+00 123     QR  = 1.0000E+00 124    CON  = 4.3500E 01 125   XLAM  = 1.1000E 01
126         = 0.0000E+00 127         = 0.0000E+00 128         = 0.0000E+00 129    SCT  = 1.0000E+00 130         = 0.0000E+00
131  SPLIT  = 2.8350E 02 132  HRCON  = 2.9126E 02 133   PCNT  = 1.0000E+00 134  Q3MAX  = 0.0000E+00 135 ENERGY  = 0.0000E+00
136  OSMAX  = 3.0000E+00 137   AVDP  = 0.0000E+00 138  RUESQ  = 0.0000E+00 139    H31  = 1.0000E+00 140    G32  = 0.0000E+00
141    G33  = 0.0000E+00 142     G1  = 0.0000E+00 143         = 0.0000E+00 144         = 0.0000E+00 145 E1E2SW  = 3.0000E+04
146    TOA  = 5.3000E+02 147    TOH  = 5.2000E+02 148    CVH  = 1.0000E+00 149    CVU  = 3.0480E 01 150    CVT  = 1.0000E+00
151    CVP  = 4.7250E-04 152  CVRHO  = 1.6020E+01 153   CVCP  = 4.1860E+03 154 XMACHS  = 5.9696E 03 155  TSINF  = 5.3300E+02
156   AINF  = 1.1317E+03 157 RHOUIN  = 1.3072E+01 158    CPA  = 7.7218E+00 159    CPH  = 1.1084E+02 160  CPINF  = 7.7218E+00
161 PRFACT  = 0.0000E+00 162 FTTOIN  = 1.2000E+01 163 FTTOCM  = 3.0480E+01 164 FTTOMT  = 3.0480E 01 165 DRTODK  = 5.5556E 01
166 PSFTOA  = 4.7250E-04 167 PSFTOT  = 3.5910E 01 168 PSFTON  = 4.7880E+01 169 PSFTOI  = 6.9440E 03 170 PDFTOK  = 1.6020E+01
171  EULER  = 2.4470E+01 172 XMFACT  = 6.0138E 03 173         = 0.0000E+00 174 PDFTOC  = 1.6020E 02 175 EBTOKJ  = 2.3244E+00
176 CBTOKJ  = 4.1840E+00 177 VLBTON  = 1.4880E+00 178 VLBTOP  = 1.4880E+01 179 RADCON  = 1.7453E 02 180 PMSKGS  = 4.5455E 01
181 C1KORE  = 1.0000E+00 182 C1DORF  = 1.4400E+00 183 C2DORF  = 1.9200E+00 184 C2KORE  = 1.0000E+00 185  PRDIS  = 1.3000E+00
186    H21  = 1.0000E+00 187    G22  = 0.0000E+00 188    G23  = 0.0000E+00 189     F1  = 3.0000E+00 190  SLOPE  = 0.0000E+00
191  ADUCT  = 1.0000E+00 192         = 0.0000E+00 193 XNWGEO  = 1.0000E+00 194   XTTT  = 0.0000E+00 195    YTT  = 0.0000E+00
196 THETAP  = 5.0000E 01 197         = 0.0000E+00 198  YPLUS  = 0.0000E+00 199 RNULOC  = 0.0000E+00 200         = 0.0000E+00

etc

401   c113  = 1.0000E+00 402   c222  = 1.0000E+00 403   c223  = 1.0000E+00 404   c332  = 1.0000E+00 405   c333  = 1.0000E+00
406   c122  = 1.0000E+00 407   c123  = 1.0000E+00 408   c132  = 1.0000E+00 409   c133  = 1.0000E+00 410   c231  = 1.0000E+00
411   c232  = 1.0000E+00 412         = 1.0000E+00 413         = 1.0000E+00 414           0.0000E+00
```

The status of RARRAY is written on each call to REOUTP.

```
7. LU6   continued

           NODE AND COORDINATE MAP OF DISCRETIZATION

X2COR
SCALE
FACTOR
......
X2COR        NODE NUMBERS...
......

X1COR
SCALE      .. X1COR ...
FACTOR
           X2 scale and coordinate                      Node nos.
   E  1
 0          001     002     003     004     005     006     007     008     009     010     011     012     013     014
 0166667    020     021     022     023     024     025     026     027     028     029     030     031     032     033
 0333333    039     040     041     042     043     044     045     046     047     048     049     050     051     052
 0500000    058     059     060     061     062     063     064     065     066     067     068     069     070     071
 0666667    077     078     079     080     081     082     083     084     085     086     087     088     089     090
 0833333    096     097     098     099     100     101     102     103     104     105     106     107     108     109
 1000000    115     116     117     118     119     120     121     122     123     124     125     126     127     128
 1166667    134     135     136     137     138     139     140     141     142     143     144     145     146     147
 1333333    153     154     155     156     157     158     159     160     161     162     163     164     165     166
 1500000    172     173     174     175     176     177     178     179     180     181     182     183     184     185
 1666667    191     192     193     194     195     196     197     198     199     200     201     202     203     204
 1833333    210     211     212     213     214     215     216     217     218     219     220     221     222     223
 2000000    229     230     231     232     233     234     235     236     237     238     239     240     241     242
 2166666    248     249     250     251     252     253     254     255     256     257     258     259     260     261
 2333333    267     268     269     270     271     272     273     274     275     276     277     278     279     280
 2500000    286     287     288     289     290     291     292     293     294     295     296     297     298     299
 2666667    305     306     307     308     309     310     311     312     313     314     315     316     317     318
 2833334    324     325     326     327     328     329     330     331     332     333     334     335     336     337
 3000000    343     344     345     346     347     348     349     350     351     352     353     354     355     356

 E 1          0       0166667 0333333 0500000 0666667 0833333 1000000 1166667 1333333 1500000 1666667 1833333 2000000 2166666

 0          015     016     017     018     019       X3 scale and coordinate
 0166667    034     035     036     037     038
 0333333    053     054     055     056     057
 0500000    072     073     074     075     076     NOTE:  Real data are written in "E" format with the leading decimal and
 0666667    091     092     093     094     095            and exponent designation omitted.  The correct scaling is printed
 0833333    110     111     112     113     114            by the associated column or row.
 1000000    129     130     131     132     133
 1166667    148     149     150     151     152

etc

 2833334    338     339     340     341     342
 3000000    357     358     359     360     361

 E 1        2333333 2500000 2666667 2833334 3000000 <-- X3 coordinate

        X3 scale
```

7 LU6   continued

```
                                          3-DIMENSIONAL PARABOLIC NAVIER STOKES OPTION

                                   3D WAKE FLOW - - - DTNSRDC: DESTROYER

 REFERENCE      ENGLISH FT      ENGLISH IN      M-K-S          C-G-S

X  X  X  X  X  X  X  X - X - X - X  X  X - X - X  X - X - X  X -
 LENGTH           .FT.........   .IN.........   .M.........   .CM
                  1000000E+01    1200000E+02    3048000E+00   3048000E+02
 VELOCITY         .FT/SEC...     .N.A........   .M/S.......   .CM/SEC.
                  6755600E+01                   2059107E+01   2059107E+03
 DENSITY          .LBM/FT3....   .N.A........   .KG/M3.....   .G/CC...
                  1935000E+01                   3099870E+02   3099870E-01
 TEMPERATURE      .RANKINE....   .N.A........   .KELVIN....   N.A
                  5330000E+03                   2961111E+03
 ENTHALPY         .BTU/LBM....   .N.A........   .KJ/KG.....   N.A
                  1770649E+04                   4115698E+04
 FROZ.SPEC HEAT   .BTU/LBM-R..   .N.A........   .KJ/KG-K....  .N.A
                  7721760E+01                   3230784E+02
 VISCOSITY......  .LBM/FT-S...   .N.A........   .NT-S/M2....  .POISE...
                  2110000E-04                   3139680E 04   3139680E 03
X  X  X - X - X - X - X - X - X - X - X - X - X - X  X  X  X  X  X -
 LOCAL PRESSURE.  .PSF.........  .PSI.........  ..UEDGE ....  .CPU TIME..
    9795670E+00   2116800E+04    1469906E+02    1000000E+01   0       E+00
 .DPDX1 ..        ..ENERGY..     .INT. VAR..    NWGEOM H'S    ..H21...
    0       E+00  0       E+00   0       E+00                 1000000E+01
  G23.            .X1/LREF..     .DX1/LREF.     .EPSILON ..   .DX1M LREF
    0       E+00  1000000E+02    1000000E-01    1000000F 01   0       E+00
REFL REY  NO
    6195301E+06
  X  X  X  X  X - X - X - X - X - X  X - X - X - X  X  X  X - X - X - X - X  X - X - X  X  X  X  X
                                                                 MAX ITER. STEP  STEP  PASSES   PRINT    OF
```

Each call to REOUTP results in print of above header data and full planar output for each vector listed under IOSAVE command. See the next page for an example of a typical vector output for this geometry

7. LU6   continued

```
                                    U1 scale
            U1 / UREF        E  1                       U1 at each node
   E  1
 0           1012250 0972900 0925400 0885050 086[illegible]350 0891350 0951800 0971200 0950950 0962750 0986650 1000000 1000000 1000000
-0166667     1011930 0966940 0917020 0881050 0873610 0912430 0968320 0978660 0962330 0974490 0994310 1000000 1000000 1000000
.0333333     1004240 0944910 0914600 0931085 0960770 0985280 0999365 0998180 0994765 0999800 1000000 1000000 1000000 1000000
 0500000     1014590 0963205 0987725 1060200 1077030 1044810 1011430 1005880 1000000 1000000 1000000 1000000 1000000 1000000
 0666667     1038790 1014640 1038690 1090100 1104710 1076400 1023500 1005510 1000000 1000000 1000000 1000000 1000000 1000000
 0833333     1027840 1035340 1054100 1071590 1091130 1070140 1022160 1009500 1000000 1000000 1000000 1000000 1000000 1000000
 1000000     1012610 1019220 1029070 1041290 1056570 1038210 1010370 1006030 1000000 1000000 1000000 1000000 1000000 1000000
-1166667     1008430 1009060 1013040 1018250 1022110 1015510 1009250 1007180 1000000 1000000 1000000 1000000 1000000 1000000
-1333333     1002110 1002260 1003260 1004560 1005530 1003880 1002310 1001800 1000000 1000000 1000000 1000000 1000000 1000000
-1500000     1000530 1000570 1000810 1001140 1001380 1000970 1000580 1000450 1000000 1000000 1000000 1000000 1000000 1000000
-1666667     1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000
 1833333     1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000
-2000000     1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000
 2166666     1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000
 2333333     1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000
 2500000     1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000
 2666667     1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000
 2833334     1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000
 3000000     1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000 1000000

 E 1         0       0166667 0333333 0500000 0666667 0833333 1000000 1166667 1333333 1500000 1666667 1833333 2000000 2166666


 0           1000000 1000000 1000000 1000000 1000000
 0166667     1000000 1000000 1000000 1000000 1000000
 0333333     1000000 1000000 1000000 1000000 1000000
 0500000     1000000 1000000 1000000 1000000 1000000
 0666667     1000000 1000000 1000000 1000000 1000000
 0833333     1000000 1000000 1000000 1000000 1000000
 1000000     1000000 1000000 1000000 1000000 1000000
 1166667     1000000 1000000 1000000 1000000 1000000
 1333333     1000000 1000000 1000000 1000000 1000000
 1500000     1000000 1000000 1000000 1000000 1000000
 1666667     1000000 1000000 1000000 1000000 1000000
 1833333     1000000 1000000 1000000 1000000 1000000
 2000000     1000000 1000000 1000000 1000000 1000000
 2166666     1000000 1000000 1000000 1000000 1000000
 2333333     1000000 1000000 1000000 1000000 1000000
 2500000     1000000 1000000 1000000 1000000 1000000
 2666667     1000000 1000000 1000000 1000000 1000000
 2833334     1000000 1000000 1000000 1000000 1000000
 3000000     1000000 1000000 1000000 1000000 1000000

 E 1         2333333 2500000 2666667 2833334 3000000
```