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CHAM

CONCENTRATION HEAT AND MOMENTUM LTD.

Final Report on NASA

Contract NAS8-33090

By

D G Tatchell

September 1979   CHAM 1712/2

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September 1979

ABSTRACT

This is the final report on Contract NAS8-33090 between
Marshall Space Flight Center (MSFC) and CHAM Limited.

The work has involved the preparation and delivery to MSFC
of a computer code for analysing three-dimensional viscous
flows in impeller passages and other duct geometries.
The preparation of the code, named CATHY3/M, has been
successfully completed, and the code and Users' Manual
delivered to MSFC. The operation of the code has been
demonstrated by application to a sample case specified
by MSFC.

This report contains an overall review of the project, a
summary of the capabilities and main features of the code,
and a discussion of the sample-case results.   Finally,
recommendations for future use and development of the code
are provided.

TABLE OF CONTENTS   <u>Page</u>

TABLE OF CONTENTS (Cont/d..)   Page

1. INTRODUCTION

1.1 Purpose of Report

This is the final report as required by the NAS8-33090
contract, dated 27 September 1978, between Marshall Space
Flight Center (MSFC), Alabama 35812, and CHAM of North
America Inc.

The report is being submitted on completion of the work as
defined in Exhibit A to the contract. It is intended to
fulfil the requirements spelled out in Section IIB of that
Exhibit, of documenting and summarising the results of the
entire contract work, and of providing recommendations and
conclusions based on the experience and results obtained.

1.2 Objectives of the Contract

The contract objectives are defined in Exhibit A to the
contract, and are elaborated in Part B of CHAM's Proposal
1712, 15 June 1978. These are included for reference
as Appendix I to this report.

In summary the contract calls for:

● The delivery to MSFC of a computer code named
CATHY3/M for analysing viscous, steady three-
dimensional flows in passages of various geometri-
cal shape. The code was to be specifically
tailored for, but not restricted to, the analysis of
flows within the impeller passage of a centrifugal
compressor or pump. In the flows analysed, recir-
culation in the passage direction was to be presumed
absent.

● The provision of a Users' Manual giving instructions for using the code.

● The provision of two weeks sustaining engineering at MSFC, to transfer knowledge of the computer code and its proper use to MSFC personnel.

The reporting requirements are:

● Monthly progress reports, documenting work accomplished each month.

● A final report, to be submitted on completion.

The present report fulfils the latter requirement.

1.3 Outline of the Report

The remainder of the report comprises four main sections. Section 2 provides an overall review of the work achieved. Section 3 then outlines the capabilities and main features of the CATHY3/M code. Here, reference is made to the Users' Manual (Malin, Rosten and Tatchell, 1979a) for more complete information regarding the theoretical basis and workings of the code.

In Section 4, the CATHY3/M results for the sample case defined by MSFC are discussed. Then, finally, Section 5 contains conclusions and recommendations. The lists of references and notation, and the Figures and Appendices follow.

2.   OVERALL REVIEW OF THE WORK

The month-by-month progress of the work has been documented
in the monthly progress reports provided to MSFC. These
are provided, for reference, as Appendix II.

In summary:

- The effective contract date is 27 September 1978.
  Initially, completion was called for by 27 July
  1979, but this was later (amendment S/A 2FFP)
  extended to 27 October 1979.

- The majority of the work was, as authorised by
  MSFC (letter Edward M Harper to CHAM of North
  America, 20 February 1979) carried out at CHAM's
  main office at Wimbledon, England.

- Work on preparing the code started in earnest in
  January 1979.   The delayed start was, as explained
  in the first progress report, to enable separate
  developments taking place in other work at CHAM to
  be utilised in CATHY3/M from the start.   The
  delayed start was not expected to (and indeed, did
  not) substantially delay completion.

- The preparation of the code, and the setting up
  and running of the MSFC sample case was completed
  at the end of July 1979.   The code and sample runs
  as delivered to MSFC on 6th August 1979 are documented
  in the User Manual (Malin et al, 1979a) provided
  during August.

● The sustaining engineering was provided by Dr D G
Tatchell of CHAM Ltd during August 1979.   During
this period the code was loaded and checked on the
MSFC computer, and the Users' Manual and sample
run were explained.   Additional runs were also
made, in which a number of refinements were made
to the sample case.   These are discussed in Section
4 of the present report.

● The submission of the present final report represents
the completion the contract requirements as defined
in Exhibit A to the contract.

3.   THE CAPABILITIES AND MAIN FEATURES OF CATHY3/M

3.1   Preliminary Remarks

Sections 2 to 4 of the User Manual (Malin et al, 1979a)
provide an extensive description of the mathematical formu-
lation and solution method in CATHY3/M.   Here, therefore,
it is necessary only to summarise the main points relating
to the capabilities and features of the code.   For more-
complete information the reader is referred to the User
Manual.

3.2   Capabilities of CATHY3/M

These are as follows:

●   CATHY3/M calculates steady, turbulent, three-
     dimensional, subsonic flows in passages.   Heat
     transfer calculation is provided (in addition to flow-
     field calculation) but has not been used extensively
     in the calculations made so far.

●   The code is restricted to cases in which recir-
     culation in the passage direction is absent.

●   CATHY3/M provides for two separate types of passage
     geometries; namely:

     (i)   Impeller-passage geometries, in which the
            hub and shroud surfaces may be arbitrarily
            shaped, the blades may be swept back and
            inclined to the hub, and partial blades may
            be present within the passage.

(ii)   Straight ducts and passages which may have
        'irregular' (i.e. not circular or rectangular)
        cross-sectional shapes which vary with
        axial distance.

● As well as compressible, subsonic gas flows, liquid
  flows with cavitated regions can be calculated.

3.3   Main Features of CATHY3/M

(a)   Theoretical basis

● Three coordinate systems are provided. These are
  Cartesian and cylindrical-polar for straight duct
  and passage geometries, and conical for impeller-
  passage geometries.

● The differential equations solved are those repre-
  senting conservation of mass, momentum and energy
  in three dimensions in the coordinate system
  considered.

● The dependent variables are:

  o The three components of velocity;
  o Pressure, and;
  o Stagnation enthalpy.

● The density is deduced as a general function of
  pressure, and, if required, enthalpy. Cavitation
  is represented by including in the density formula
  an appropriate variation of the density of the
  mixture (i.e. gas and liquid together) with pressure.
  How this can be done, making use of property values
  for H_2 given by the GASP computer code (Hendricks
  et al, 1975) is explained in Section 2.5 of the
  User Manual.

● Turbulent transport is, as is usual, represented
  via a gradient law, involving the turbulent viscosity.
  The latter is prescribed algebraically. It may be
  prescribed uniform, or made to vary with position
  according to any chosen, physically-reasonable
  prescription.

● The boundary conditions are as follows: at inlet,
  all three components of velocity are prescribed
  (these may be uniform or non-uniform), and at exit
  the static pressures must be prescribed. For the
  latter, the pressures may be uniform, or, in
  impeller cases, may automatically be set to a more-
  realistic variation which just balances the Coriolis
  and centrifugal forces at exit.

(b)   Solution method

● The differential equations are solved by a finite-
  difference method.

● The finite-difference grid is defined so as to fit
  the passage shape. This means that, if the passage
  is irregular (i.e. does not conform to any of the
  coordinate systems used), the grid will be non-
  orthogonal.

● The finite-difference equations are derived by
  integration of the differential equations over
  micro control-volumes or cells associated with
  each grid node. In this integration special terms
  arise associated with the non-orthogonality of
  the grid.

● The equations are solved by an iterative technique,
in which, during each iteration, the solution
proceeds systematically through the grid from inlet
to outlet.   This is repeated until convergence
is obtained.

(c)   Coding features

● CATHY3/M has been prepared from CHAM's general
three-dimensional computer code PHOENICS 4/P,T/FIX*
(Rosten, 1979).

● 4/P,T/FIX (and hence CATHY3/M) is written in a
compact coding style which makes for efficient
computer usage, but is not easily understood,
particularly by newcomers. Consequently, a modular
arrangement is adapted for code organisation, in
which portions of code are clearly separated
according to the function they perform.

● In particular, in CATHY3/M, portions of code which the user is
expected to modify are clearly identified, and are
explained in the User Manual.   Almost all of the
input changes are made within a single BLOCK DATA
subroutine. Other changes requiring the user to
alter other parts of the code (mainly concerned
with changing density or viscosity prescription)
are restricted to very limited, identified
sequences, and appropriate instructions are given
in the User Manual.

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* PHOENICS stands for parabolic, hyperbolic or elliptic
numerical integration code series; 4/P,T/FIX identifies
the member of the series as that for four-dimensional
(i.e. three space and one time), parabolic, transient
flow in fixed coordinates.

- Two kinds of geometry input are provided. One (the usual procedure in CHAM codes) provides complete generality, but can involve the user in lengthy and error prone data preparation in order to set up a new geometry. Consequently, a second, automated, procedure has been provided for impeller geometries of the type of interest at MSFC. This allows the user to input the data directly in the form used at MSFC to describe the impeller.

- CATHY3/M provides two modes of operation, to be selected by the user as required. In one, all variables are stored in-core. This is efficient in computer time, but storage limitations on the computer in use may limit the grid-fineness which can be used in this mode. Consequently, as an alternative the bulk of the variables can be stored, out-of-core in secondary storage (e.g. disc), being automatically transferred to and from core as required. These core-to-secondary-store transfers increase run times (by typically 50 percent for CATHY3/M on the MSFC computer), but the use of secondary storage does allow much finer grids to be used without in-core storage problems.

- An automatic restart facility is provided, which allows results to be stored at the end of a run, to be used again to start a continuation run.

- As well as tabular output of the results, line printer generated contour plots are provided. The variables plotted are longitudinal velocity, static pressure, density, and stagnation enthalpy. Both cross-stream and longitudinal plots are provided.

4. SAMPLE-CASE SPECIFICATIONS AND RESULTS

4.1 Preliminary Results

Three runs have been made for the contract sample case,
as follows:

- Run 1: Performed at CHAM in July and delivered
  to MSFC on 6th August 1979. The specification is
  given in Section 7 of Malin et al (1979a).

- Run 2: Performed at MSFC during the sustaining
  engineering period in August, 1979. The speci-
  fication is as for Run 1, except for: an improved
  pressure-density law; a reduced (more realistic)
  outlet pressure; and, the inclusion of partial-
  blade thickness.

- Run 3: Set up and partially run at MSFC during
  sustaining engineering period. The specification
  is as for Run 2, with a finer finite-difference
  grid, and non-uniform inlet conditions for axial
  velocity.

The complete specification for these runs is given in
Section 4.2 below. Much of this is reproduced from Malin
et al (1979a). Then, in Section 4.3, the computed
results for Run 2 are discussed.

4.2 Run Specification

(Except where specifically noted, conditions are the same
for Runs 1, 2 and 3).

4.2.1 Geometry

The passage geometry is specified by Wilmer (1978). The main overall dimensions are shown in Figure 4.1.

Three partial blades are present within the passage, as follows:

	Blades 1 and 3	Blade 2
Angle from main blade	15° and 45°	30°
Location of leading edge*	In Runs 1 & 2: $\theta=40^O$ In Run 3: $\theta=40.5^O$	In Runs 1 & 2: $\theta=20^O$ In Run 3: $\theta=18^O$
Location of trailing edge	Outlet	Outlet
Thickness	In Run 1: 0. In Runs 2 and 3: 0.005m	

* θ is angle measured from inlet, as shown in Figure 4.1.

TABLE 4.1: Partial blade details

4.2.2 Flow conditions

(These are based on the specification of Wilmer, 1979).

(a) Inlet conditions

Radial and circumferential velocities at inlet are taken as uniform, as follows:

- Circumferential velocity $u_{in}=\overline{w}_{in}-\Omega R_{in}=-1.552$ m/s,

  where $\overline{w}_{in}$ is mean axial velocity at inlet;

  R_{in} is mean radius at inlet measured from axis of rotation; and,

  Ω is impeller rotation speed.

- Radial velocity $v_{in}=0$.

Axial velocity at inlet (w_{in}) was specified as follows:

- In Runs 1 and 2, $w_{in}=80,7$ m/s. (This gives a flow rate of 155.96 lbm/s, =70.73 kg/s for the whole impeller).

- In Run 3, w_{in} was specified to vary with radius, as deduced by circumferentially averaging[*] the data given by Wilmer (1979). The values used are given in Table 4.2 below. In that table, IY is the radial grid number counting from shroud to hub, and η is the distance of the grid node from the shroud, divided by the hub to shroud gap.

The density and entropy at inlet, $\rho_{in}=70.41$ kg/m^3, and $s_{in}=8618.$ J/kg$^\circ$K, are taken from GASP outputs for H$_2$ at p=12.76 atm and T=22°K; this was the closest available point to the specified inlet conditions of 10.7 atm and 23.44°K.

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[*] This is necessary to obtain inlet conditions for the rotating CATHY3/M coordinates from the inlet conditions measured at locations fixed in space.

IY	η	w_{in} (m/s)
1 (near to shroud)	.05	98.4
2	.15	94.5
3	.25	90.5
4	.35	84.5
5	.45	78.1
6	.55	75.8
7	.65	78.3
8	.75	80.9
9	.85	83.5
10 (near to hub)	.95	86.2

TABLE 4.2: Inlet conditions on w for Run 3

(b)   Exit conditions

The mean exit pressure used in the three runs is as follows:

●   Run 1, $\bar{p}_{exit}$ = 1.147. 10^7 N/m^2;

●   Run 2, $\bar{p}_{exit}$ = 9.0. 10^6 N/m^2 ;

●   Run 3, $\bar{p}_{exit}$ = 9.5. 10^6 N/m^2 .

(NB. These changes were made following discussions as MSFC, in view of doubts regarding the actual exit pressure for test-case conditions).

(c)   Rotation

The impeller rotation speed is 35,000 rpm.

4.2.3 Fluid properties

A uniform turbulent viscosity of $\mu_t = 10.0$ Ns/m^2 is used.

For density (ρ), the two- part-linear pressure density relationship described in Section 2.5 of Malin et al (1979a) is used. As explained there, this gives a good representation of the variation of density with pressure at constant entropy for both pure-liquid and cavitated, two-phase conditions.

The formula used is:

$$\text{For } p < p_A, \quad \rho = \rho_B + \frac{(p - p_B)}{(p_A - p_B)}(\rho_A - \rho_B) \;,$$

$$(4.1)$$

$$\text{and, for } p > p_A, \quad \rho = \rho_A + \frac{(p - p_A)}{(p_C - p_A)}(\rho_C - \rho_A) \;;$$

where ρ_A, ρ_B and ρ_C are prescribed densities at pressures p_A, p_B and p_C. p_A is the saturation pressure at inflow conditions; p_B is lower than p_A (i.e. in the cavitated regime) and p_C is higher than p_A (in the pure liquid regime).

The values used in the reported runs were deduced as described in Malin et al (1979) and are as follows:

	p_A N/m^2	ρ_A kg/m^3	p_B N/m^2	ρ_B kg/m^3	p_C N/m^2	ρ_C kg/m^3
Run 1	$1.39.10^5$	70.41	$1.9.10^4$	68.27	$1.01.10^7$	70.41
Runs 2 & 3	$1.39.10^5$	69.4	$1.9.10^4$	68.27	$1.01.10^7$	75.92

TABLE 4.3: Parameters in density prescription

It can be seen from Table 4.4 below that the second variant, by allowing for density variation in the pure liquid regime (i.e. $\rho_C \neq \rho_A$), provides a better overall fit to the values deduced from GASP (Hendricks et al, 1975).

p N/m^2	ρ kg/m^3		
	GASP values	Run 1	Runs 2 and 3
$1.01.10^7$	75.92	70.41	75.92
$1.29.10^6$	70.41	70.41	70.15
$1.39.10^5$	69.4	70.41	69.4
$8.14.10^4$	69.0	69.38	68.85
$1.9.10^4$	68.27	68.27	68.27

TABLE 4.4: Pressures and Densities from GASP
and the two formulae used

4.2.4 Grid distributions

The grids used are uniform in all three directions. The numbers of cells are as follows:

	Runs 1 and 2	Run 3
Hub-to-shroud	5	10
Blade-to-blade	12	12
Inlet-to-exit	9	20

TABLE 4.5: Numbers of grid cells

4.3   Discussion of the Results

4.3.1   Results presented

Only Run 2 results are presented here.   These are chosen
because Run 2 effectively supersedes Run 1 (i.e. it includes
improved density prescription, exit conditions,and partial-
blade treatment), while the finer grid run (Run 3) is
currently in progress at MSFC, and final results are not
available.

For the Run 2 results presented, the solution-controlling
parameters are as follows:

- Total number of sweeps - 50.
- Number of iterations at each slab - 5.
- Density adjusted every 2 sweeps; under-relaxed by
  0.1.

After 50 sweeps, the sum of absolute errors in longitudinal
momentum had been reduced to five percent of the rate of inflow
of momentum.   This represents an adequate level of conver-
gence; for example, the changes occuring in longitudinal
velocity between sweeps are everywhere much less than one
percent.

4.3.2   Form of presentation

The quantities plotted are:

- Static pressure, p;
- Longitudinal velocity, w; and,
- Density, ρ.

Results are shown as line-printer-generated contour plots of lateral variation of the variable in question, at a location θ = constant. The plots can be understood as follows. The range of variation of the variable is identified, as printed below each plot. This range is divided into ten equal bands. The digit '1' is printed wherever values lie within the first band (i.e. within the first ten percent of the range); '3' is printed where values lie in the third band; and so on up to '9'. Even-number bands are left blank. Thus, 9's indicate high values, 1's low values, and so on.

Figures 4.2 and 4.3 show p and w at four locations, spaced roughly equally between inlet and outlet. Because p and w are not stored at exactly the same locations in the finite-difference grid, the locations at which they are plotted are not exactly the same. The appropriate value of θ is therefore given for each plot.

Density is shown (in Figure 4.4) at only one plane, near to inlet. At other sections, density variations are very small (of the order of one percent) and are consequently not shown.

4.3.3 Discussion of the Results

(a)   Pressure - Figure 4.2

It is perhaps most easy to interpret the pressure plots in reverse order, starting at $\theta=75^{o}$, near to outlet (Figure 4.2d), and moving backwards to $\theta=15^{o}$, near to inlet (Figure 4.2a).

In Figure 4.2d the domain is divided into four passages by the three partial blades, which appear as blanked-off

regions in the plot*.   Each passage has its own pressure
variation from high at the pressure side to low at the
suction side, as expected. The range of pressures (and
hence the average pressure) in each passage is roughly the
same. This also is as to be expected, as the mean exit
pressure for each passage is, of course, equal.

Further upstream, at $\theta = 55^{\circ}$ (Figure 4.2c) the four passages
are still evident. The patterns of variation in all are
very similar; the pressure varies from high at the pressure
surface to low at the suction surface, and from high at
the shroud to low at the hub. The shroud-to-hub variation
is here more marked than at $\theta = 75^{\circ}$. This variation is
caused by the centrifugal force due to rotation, which here
has a larger hub-to-shroud component than at the down-
stream plane.

At $\theta = 35^{\circ}$ (Figure 4.2b), there is only one partial blade,
dividing the domain into two passages. In each the
pressure variation is as described above.

At $\theta = 15^{\circ}$, just upstream of the central partial blade, the
pressure field is evidently influenced strongly by the
downstream pressures, and hence by the presence of the
partial blade. Thus, whereas in the absence of partial
blades the expected variation would be from high at the
pressure-shroud corner to low at the suction-hub corner,
the plot shows a second high region at the centre of the
shroud. This is caused by upstream transmission of
the high pressure at the shroud-pressure corner of the

---

* The blanked-off region does not correspond to the thickness
  of the blade, but to the region between the grid nodes on
  either side of the blade; that is, the region over which
  the interpolation performed by the plotting routine involves
  values on both sides of the blade, and is therefore
  invalid.   The blanking-out of these regions has been
  done by hand on the plots shown here, but it is proposed
  that this be automated as part of an extension to the
  present contract.

right-hand partial passage shown in Figure 4.2b.

(b)   Longitudinal velocity - Figure 4.3

Figure 4.3a shows results at $\theta=20^{\circ}$, just at the leading
edge of the first partial blade. A reverse-flow region is
evident at the centre of the passage, near to the shroud*.
This has been caused by the abrupt pressure increase as the
flow enters the pressure-side of the right-hand partial
passage.

A similar phenomenon is observed in Figure 4.3b, at the leading
edge of the second partial blades ($\theta=40^{\circ}$). Here reverse-
flow regions occur where the flow is just entering the
pressure-shroud corner of the second and fourth partial
passages (counting from the left).

At $\theta=60^{\circ}$ and $\theta=80^{\circ}$ (Figures 4.3c and 4.3d) three partial
blades are present. No obvious pattern of velocity in
each of the partial passages can be discerned. However,
it is interesting to observe that the velocities are
generally higher in the left hand partial passage (i.e.
that at the pressure side of the domain). This is due
to the higher pressures at inlet at this side of the passage
leading (wrongly), when associated with the prescribed

---

* As observed earlier, CATHY3/M is not, according to the
contract, required to handle flows with separation.
However, reverse-flow regions have been encountered in
all calculations made so far for the MSFC impeller.
Consequently, CATHY3/M has been provided with an
intermediate capability which enables it to provide
converged solutions with separation, and to ensure mass-
conservation correctly in all regions including separated
ones. However, the momentum and energy equations do
not account fully for reverse flow. Thus, results in
or near to reverse-flow regions will not be quantitatively
correct. The results are, however, likely to be quali-
tatively correct in indicating the existence of reverse-
flow regions.

uniform inlet velocities, to a higher total pressure.
Then, near to exit, where static pressures in the four
partial passages equalise, the higher total pressure in
the left hand partial passage leads to higher velocities.
This physically-unrealistic effect would therefore be
eliminated by locating the inlet plane for the calcu-
lations some distance upstream of the passage inlet, at
a location where it is reasonable to prescribe velocities
uniform. The introduction into CATHY3/M of modifications
to allow this to be done is part of a proposed extension
to the present contract.

(c) Density - Figure 4.4

Figure 4.4 shows densities at the only station plotted
for which significant variation occurs ($\theta=15^{\circ}$). A sub-
stantial cavitated region (identified by densities less
than the saturation density, $\rho_A=69.4$ kg/m^3) is predicted,
corresponding to the suction-side low pressure region
evident in Figure 4.2a. Elsewhere, the (liquid) density
is relatively uniform.

It should be observed that the predicted existence and
extent of the cavitated region will depend on the pres-
cribed exit pressure level, regarding which there is
some uncertainty. It seems likely that the value used
here ($9.0.10^6$ N/m^2) is lower than that occuring in
practice. Consequently, a higher value ($9.5.10^6$ N/m^2)
is being used for Run 3. This will almost certainly lead to
a smaller predicted cavitated region.

5.   CONCLUSIONS AND RECOMMENDATIONS

5.1   Review of Current Status

The CATHY3/M computer code, as described in the contract
(Appendix I) has been delivered to MSFC, along with a Users'
Manual providing instructions on use.

The code has been applied successfully to the MSFC specified
sample case, as described in Section 4 of this report. No
measurements are available for direct comparison, but the
results appear plausible. Separate work (Malin et al,
1979b) reports the application of the basic CATHY3 code
to a simpler centrifugal impeller geometry, and shows good
agreement with measurements, particularly for blade
pressures.

As a results of experience so far, a number of desirable
extensions and modifications to CATHY3/M have been identified
as outlined in Section 5.3 below.

In particular, attention was drawn in Section 4.3.3 to
unrealistic aspects of the results caused by starting the
solution at inlet to the impeller passage rather than
at some distance upstream.   The extension to allow CATHY3/M
to solve some distance beyond the passage inlet and outlet
is therefore needed, and is the major part of the immediate
future developments outlined in Section 5.3 below, and
under consideration at MSFC.

5.2   Use of the Code at MSFC

It is expected that use of the code at MSFC will involve
the following:

- Examining the effects on the results of uncertain physical inputs, by repeating runs with inputs varied within expected range. Probably the two most uncertain inputs at present are the exit pressure level and distribution, and the prescribed turbulent viscosity. Malin et al (1979b) describe sensitivity tests on these, which could usefully be repeated and extended for the MSFC case.

- Examining the sensitivity of the results to increasing the number or distribution of grid points. Such tests establish the quantitative accuracy of the results. Results are considered satisfactory when further refinement leads to acceptably small changes in the quantities of interest.

- Investigating other flow rates, inlet conditions, geometries etc.

- Wherever possible, making comparisons between predictions and measurements. These comparisons would ideally be for velocity or pressure distributions, but comparison of overall quantities, such as pressure rise, can also be useful.

While it is expected that MSFC personnel will, by reference to the User's Manual, be able to perform runs of the kind outlined above without reference to CHAM, it must be said that CHAM involvement in an advisory capacity would certainly be desirable, and may, on occasion, be necessary. Thus, CHAM's regular advice on planned input changes and on interpretation of results could vastly accelerate progress. Furthermore, it is likely that sooner or later failure of the program (eg lack of convergence) will occur, either due to errors in input or to extending the code outside the range of applications for which experience has been obtained. In such cases, speedy CHAM involvement is essential.

In view of the above, it is strongly advised that MSFC
should enter into a form of consultancy agreement, which
allows it to call on CHAM personnel (most conveniently,
those located at CHAM NA in Huntsville) for advice and
assistance, and enables CHAM to charge for the associated
costs.

5.3   Recommended Developments

5.3.1   Those currently under consideration by MSFC

MSFC is currently considering funding CHAM to perform the
following tasks under an extension to the present contract:

(i)   Introduction into CATHY3/M of provision to solve in
        the regions immediately upstream and downstream of the
        impeller.   This requires cyclic boundary conditions
        at the surfaces formed by extending the blades
        beyond impeller inlet and outlet. At the same time, provision
        will be made to prescribe mean pressure at inlet (where
        pressure is known) rather than outlet.

(ii)   Provision of:

        ● Options to provide input and obtain output in
          foot, pound, second units, as an alternative to
          the SI units used at present.

        ● Printout and plotting of total pressure, in
          addition to static pressure.

(iii)   Improvement of plotting sequence in CATHY3/M to
        eliminate automatically spurious contours close to
        partial blades.

5.3.2 Other recommended future developments

It is recommended that MSFC should consider increasing the immediate usefulness of CATHY3/M, and extending its potential range of applications, by the introduction of the following.

(i)   Full curvature effects in duct flows. At present, CATHY3/M provides only for straight ducts and passages. (This, of course, does not apply to the impeller-passage mode of operation, but to the alternative general duct flow capability - see Section 3.2). The addition of curvature effects would allow the code to be applied to, for example, diffuser sections between impeller stages.

(ii)   Full elliptic capability for handling separated - flow regions. As noted in Section 4.3, results from CATHY3/M indicate the existence of significant reverse-flow regions in the MSFC specified impeller. While CATHY3/M will successfully provide solutions under these circumstances, because of various simplifications in the model the results will not be quantitatively correct within or close to the reverse flow region. This limits the usefulness of the code for impeller calculations (particularly off-design cases where larger reverse-flow regions may exist) and for other flows with significant separation (such as, almost certainly, the diffuser between impeller stages). This limitation can be overcome by introduction of the full elliptic, reverse-flow capability.

(iii)   Transient effects. The introduction of transient effects into CATHY3/M would allow the code to be used to investigate, for example, cyclic instability phenomena in impeller passages.

(iv)   Improved turbulence model. It would be relatively
       straight-forward to introduce into CATHY3/M a more-
       complex turbulence model, such as the well established
       two-equation kinetic energy/dissipation model
       (Launder & Spalding, 1974). However, in view of
       the considerable uncertainty regarding the effects
       of high rotation and curvature on turbulence (see,
       for example, Majumdar and Spalding, 1977), it would
       be necessary carefully to test the results of the
       model against measurements, and possibly to refine
       the model, before the results could be viewed with
       confidence.

(v)   Slip effects in two-phase cavitated regions. At
       present, within the cavitated region, the gas and liquid
       are presumed to move with the same, local velocity
       that is, inter-phase slip is neglected.   More
       realistic predictions would result from the inclusion
       of slip effects, by use of CHAM's IPSA (inter-phase
       slip algorithm) method (Spalding, 1979).

All the above features already exist in CHAM codes of the
same type as CATHY3/M, and could relatively easily be trans-
ferred into CATHY3/M.   CHAM would be pleased to provide a
quote for performing the work if required.

6. REFERENCES

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MAJUMDAR A K & SPALDING D B (1977)[*]

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'The mathematical basis of the 4/P,T/FIX computer program'. CHAM Technical Report TR/58.

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'Numerical computation of multi-phase fluid flow and heat transfer'. Article in 'Recent Advances in Numerical Mechanics', edited by C Taylor.

[*] Copies of these references have been supplied to Mr Glenn E Wilmer of MSFC.

WILMER G E (1978)

Letter from Glenn E Wilmer of MSFC to David Tatchell of CHAM Limited, 14th June 1978, and accompanying drawings.

WILMER G E (1979)

Letter from Glenn E Wilmer of MSFC to David Tatchell of CHAM Limited, 10th April 1979, and accompanying figures.

7.   NOMENCLATURE

Symbol	Meaning
p	Pressure.
R	Radial distance from the axis of rotation.
s	Specific entropy.
T	Temperature.
u	Circumferential velocity (in rotating coordinates).
v	'Radial' velocity - i.e. velocity in shroud-to-hub direction, at constant θ.
w	Longitudinal (i.e. θ-direction) velocity.
η	Normalised coordinate in hub-to-shroud direction.
μ_t	Turbulent viscosity.
θ	Angle from inlet measured about centre of conical coordinate system (see Figure 4.1).
ρ	Density.
Ω	Angular velocity of impeller.

Subscript	Meaning
A,B,C	Reference values used to define p~ρ formula.
in	Values at inlet.

FIGURES
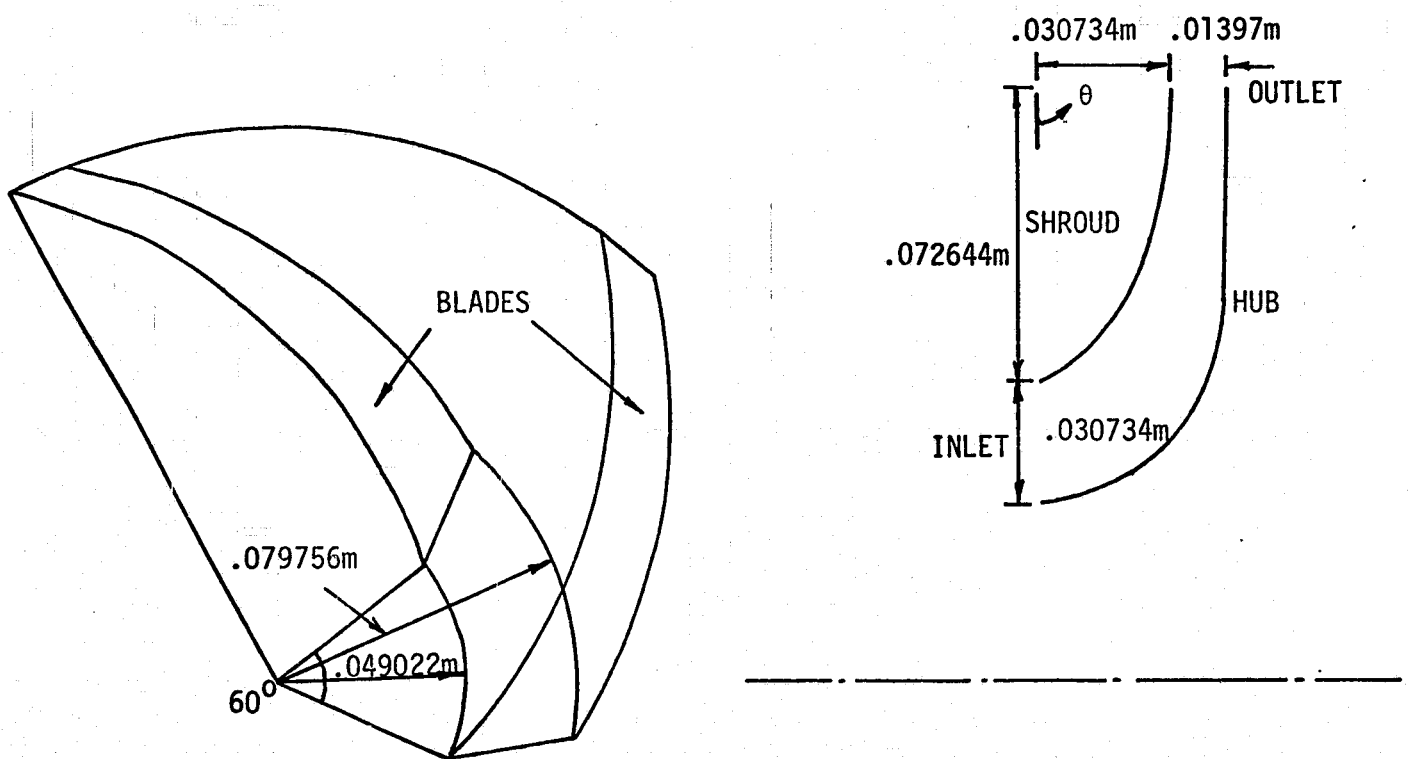
FIGURE 4.1: TEST CASE GEOMETRY

HUB

PRESSURE   SHROUD   SUCTION

a) $\theta=15^{o}$: Range of field: $2.37.10^{5}$ to $18.2.10^{5}$ N/m^2

Figure 4.2: Contours of static pressure p

HUB

PRESSURE   SHROUD   SUCTION
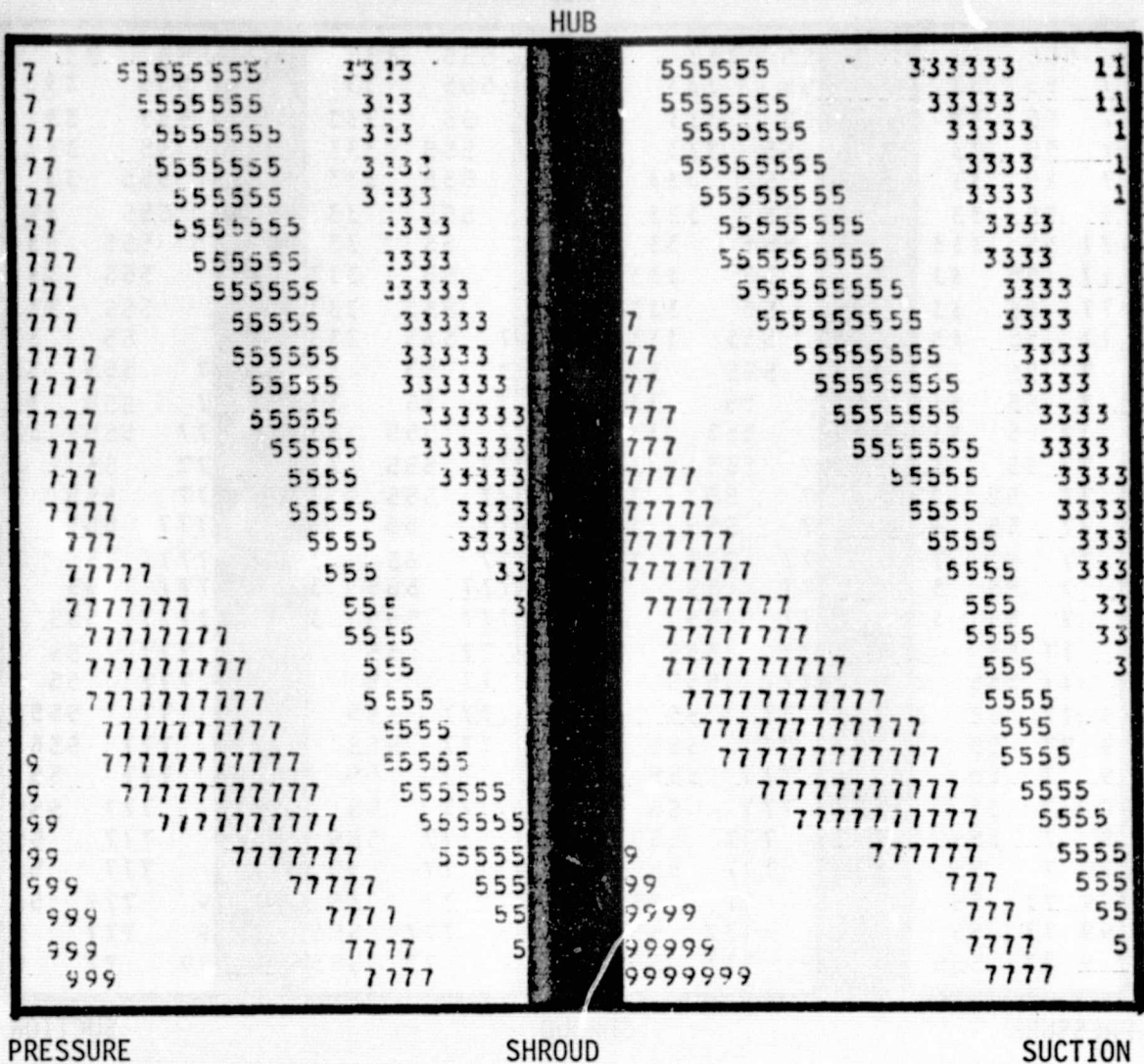
Figure 4.2b): θ=35 : Range of field: $1.48.10^6$ to $3.58.10^6$ N/m^2

HUB

PRESSURE

SHROUD

SUCTION

Figure 4.2c): $\theta=55^{o}$: Range of field: $3.98.10^6$ to $5.86.10^6$ N/m^2

HUB

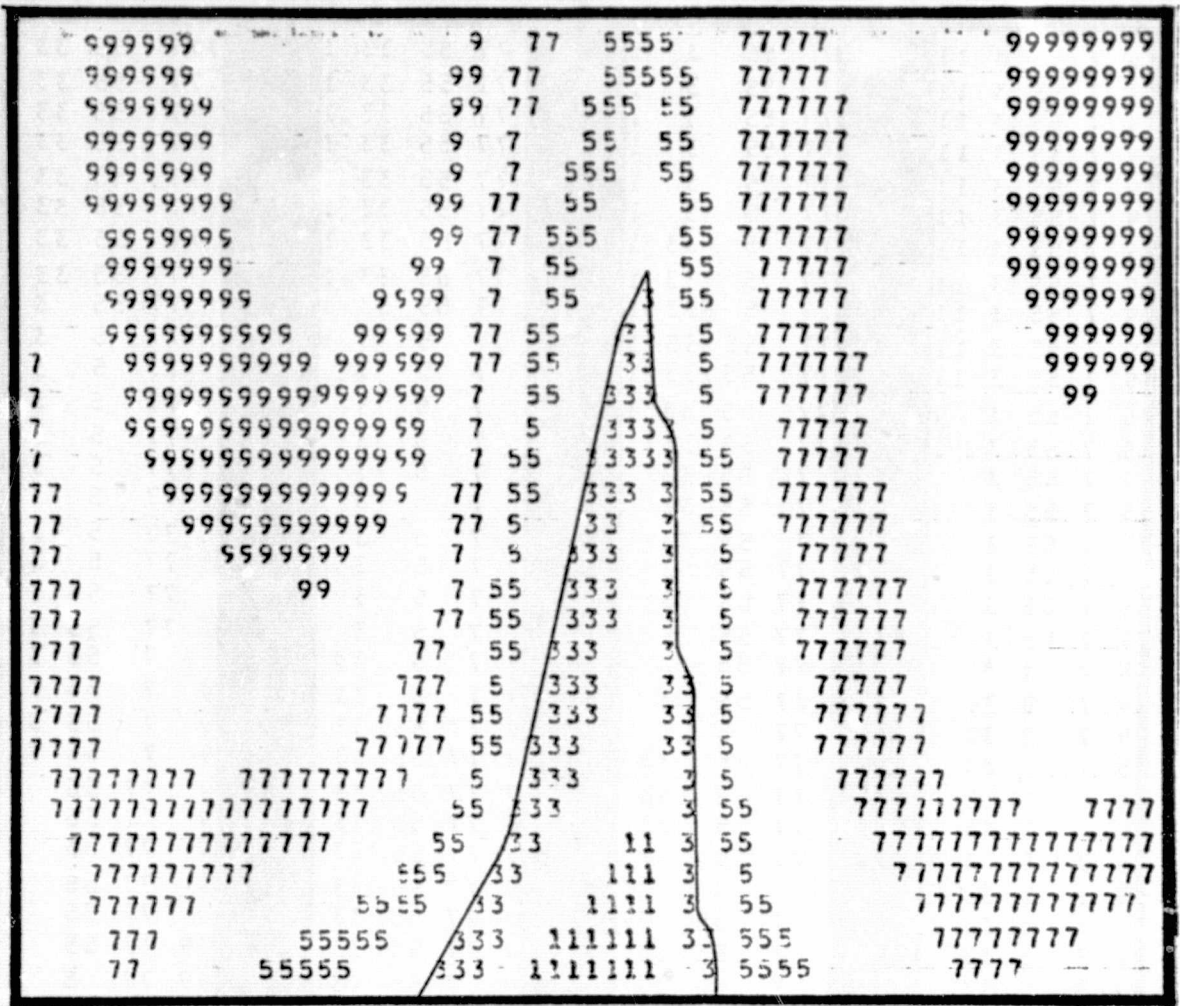PRESSURE   SHROUD   SUCTION

Figure 4.2d): $\theta=75^\circ$: Range of field: $6.43.10^6$ to $7.70.10^6$ N/m^2

HUB

PRESSURE   SHROUD   SUCTION

SEPARATED FLOW
REGION

a) θ=20°: Range of field: -52.9 to 119.6 m/s
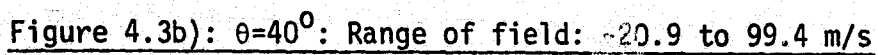
Figure 4.3: Contours of longitudinal velocity w

HUB

```
5999995999559          9999999              7777      55 5   77     99
 999    999999          999999              7777      55 5   7      999
 559    99999           999999              7777     5555   7       999
9999    99999  77       999999     99       7777     5555  77       999
999     9999   77       999999    999        777      555  77      9999
999      999   77        99999   99999      7777      555  77      9999
999      995   77        99999  999999       777      55   77     99999
99       995   777       99999  999999       777      55   77    9999
99       999  7777        9999  999999       777      55   77    99999
99      995    77777       999  999999       777     555   77     9999
59      995    7777777     999  999999       777     555   77     9999
99      999   77   777     999  999999       777     555   77     9999
99      999   77    777     99  999999       77      555   77     9999
99       99  77     777     99  999999       77     5555   7       999
99       99  77      77      99 999999       77      55 5   7      999
99      999  77 5    777     99 999999       77      55 5   7      999
99      999   7  55   777    9  999999      777      55 55  7       99
99      99  77  55    77     9  999999      777      55 55  77       9
99      99  77 5555   777    9  999999      777      55 55  77       9
99      99  7  5555   777    9  999999      777      5    5 77
9       99  7  5   55   77   9  999999      777 55      5   7
9       99 77  5    55   777 9  99999        77  55      5   77
9       9  77 55    55   777    9999         777 55       55 77
9       99  7  5      55   77                777   5   3  55  7777
99      99 77 55 33  55   777                777  55  333  5    77777
99      9  7  5  33   55   77        777    55   3 3    5    7777
99      9 77 55 3 33  55   777       777    55   33 33  5
999     5 7  5 33  3   5    777     777777     55 33   3 55
999    99 7 5  3   33 55   777      7777777   55  3  1 33 555
999     9 77 5 33  11 3   5    77   777777    55  33  1   3 555555
```

PRESSURE   SHROUD   SUCTION

SEPARATED FLOW
REGIONS

Figure 4.3b): θ=40°: Range of field: -20.9 to 99.4 m/s

HUB

PRESSURE   SHROUD   SUCTION

Figure 4.3c): $\theta=60^{o}$: Range of field: 36.6 to 111.5 m/s

HUB

PRESSURE   SHROUD   SUCTION

Figure 4.3d): θ=80°: Range of field: 45.4 to 118.0 m/s

-38-

HUB   CAVITATED REGION

```
5955555595955599999959999999999999    77              5  3    11111
9999999995999999999999599799999999999  7777           5  33  11111
999999599959999999999599999999999999    7777          5  3    1111
5999999599959999999999599999999999999     7777         5  3     111
5999995999959995999999599999999999999      777        55  33     11
9999999599959999999999599999999999999      777        55   33     1
5599999599959999999999599999999999999      717        55   333    1
9999999599959999999959999999999999999       77        555   33
9559999599959999999999559999999999999      777         55    33
99999999999999999999999599999999999999999  7777        555    333
99999999999999999999999999999999999999999  77777      5555     333
9999999999999999999999959999999999959999999 7777       5555      33
5999999595995999999999599999999999599999999  7777      5555       3
9999999999959999999999599599999999959999999   777       555
59999959999999999999959999999999595999999999   77        555
5999999555959595999999599999999999999999999     777        555
9959999555959595999999599999999999999999999     777        555
9999999599959999999959999999  99999999999999    777         555
5999999599959999999959959999    99599999999999   777         555
5999959999959999999959999      99999999999999     77          55
9999959999959999995999        99999999999999      77           5
5999599999599999995999        9999999999999       77
9999599999599999995999       99999999999999       77
99599959999999999599       99999999999999        777
999999959999999955        9999999999            7777
9999999999          9999999999              7777
599999              999999999              7777
9                   999999999             777
                    999999999              77
                   9999999999              777
                   9999999999              777
```

PRESSURE   SHROUD   SUCTION   CAVITATED REGION

$\theta=15^{O}$: Range of field: 67.5 to 70.4 kg/m^3

Figure 4.4: Contours of density, ρ

APPENDICES

APPENDIX I

Material containing contract
work specification; namely:

(i)   Exhibit A to Contract NAS8-33090,
      27 September 1978.

(ii) Part B of CHAM Contract Proposal
      H3082, 15 June 1978.

SCOPE OF WORK

I.   The contractor shall deliver a three-dimensional steady viscous
fluid flow partially-parabolic computer program, a complete sample
run to demonstrate that the program is operational, and a user manual.
Also the contractor shall provide two weeks of sustaining engineering
to ensure the proper use and understanding of the program by the
MSFC.

The program shall meet the following requirements:

1.   The program shall be programmed for and be operable
on the MSFC Univac 1108 computer system.

2.   The program shall analyze subsonic compressible
and incompressible fluid flows.

3.   The program shall have the capability of analyzing
flow in ducts of rectangular, circular, and distorted rectangular
and circular cross-sections (elliptical, rectangular with rounded
corners, parallelograms, etc.).

4.   The program shall analyze flow in rotating and stationary
ducts.

5.   The program shall analyze flow with cavitation within
the flow field.

6.   The program shall interface with MSFC fluid properties
programs (GASP, etc.).

7.   The program shall include a graphics package which
will plot pressure, velocity, temperature, and density in longitudinal
and transverse duct sections.

8.   The program shall accept arbitrary inlet boundary
conditions.

9.   The program shall accept rapid changes in duct geometry
and analyze flow turning and splitter vanes in the ducts.

10.   Input to the program shall be accomplished in a
timely and practical manner. Co-ordinate transformation of input
data shall be performed by the program.

The sample run shall be an MSFC specified pump impeller. All input data shall be identified (terminology, physical units, source, etc.). Output data shall be explicitly interpreted with respect to the sample case and expected results.

The user manual shall identify all input data required to execute the program. The format and physical units of each input parameter shall be supplied. The terminology for each input parameter and any information needed by the user to clearly define the parameter shall be included in the user manual. The user manual shall identify all output data and provide all information necessary to interpret the output data.

The two weeks of subtaining engineering shall be provided at MSFC for the express purpose of transferring knowledge of the computer program and its proper use to MSFC personnel. The following shall constitute a minimum requirement for this:

1. Provide a basic understanding of the computer program (approach, basic equations, program options, etc.).

2. Provide an in-depth review of the MSFC designated sample run (problem statement, assumptions, input data review, and output data evaluation).

3. Provide in-depth review of user manual.

4. Provide discussions of computer program's analytical limitations.

Note: Original or modified software delivered with this acquisition is subject to Part 5.3, "MSFC Computer Program Documentation Standard" of the MSFC Programmer Procedures Manual (PPM), and Part 4.4, "Restrictions & Nonstandard Features" of the MSFC PPM and the MSFC IBM 360/75 User's Guide.

II. Reports Requirements

A. Monthly Progress Reports

1. The contractor shall submit separate Monthly Progress Reports of all work accomplished during each month of contract performance. Reports shall be in narrative form, and brief and informal in content. These reports shall include:

a. A quantitative description of overall progress, pertinent details and test data.

      b. An indication of any current problems which
         may impede performance and proposed corrective
         action.

      c. A discussion of the work to be performed during
         the next reporting period.

      2. These reports shall be submitted in the number of
copies and to the address as indicated in paragraph below entitled
"Reports Distribution," within ten (10) days following the period
to be reported.

    B. <u>Final Report</u>

      The contractor shall submit a Final Report, in narrative
form which documents and summarizes the results of the entire contract
work, including recommendations and conclusions based on the experience
and results obtained. The Final Report shall include principles, pro-
cedures, and methods of application that would be generally applicable
to utilization of the results of the study. The contractor shall distri-
bute copies of the Final Report in the quantities and to the address as
indicated in paragraph below entitled "Reports Distribution."

    C. <u>Acknowledgements and Controls</u>

      Each report (progress reports, final reports, etc.) shall
be submitted under a title page showing the following information:

      1. Contractor's name and address, including segment
         generating the report.

      2. Title of report, including period covered, when
         applicable.

      3. Date of publication.

      4. Type of report and contract number.

      5. Author(s).

      6. Prepared for George C. Marshall Space Flight Center,
         Marshall Space Flight Center, Alabama 35812.

      7. Include an abstract on all technical or scientific
         reports, when applicable.

CHAM CONTRACT PROPOSAL H3082/JUNE 15 1978

PART B - Technical

6.   What CHAM offers to do

This section states what CHAM will deliver to the client, and
describes CHAM's proposed technical approach.   The contents
are intended to demonstrate that CHAM understands the requirements
of the RFP, and to describe how CHAM proposes to apply the
CATHY3 code to satisfy these requirements.

6.1   What CHAM will deliver to the client

CHAM will deliver to the client, as requested in the RFP,
the following:

1.   A three-dimensional steady viscous fluid flow partially-
      parabolic computer program as defined in Section 6.2
      below, in the form of a card deck or magnetic tape.

2.   A complete sample run to demonstrate that the program
      is operational.

3.   A user manual

CHAM will also provide two weeks of sustaining engineering
to ensure the proper use and understanding of the program
by the MSFC.

The following Section, 6.2, describes the proposed technical
approach; subsequently Section 6.3 demonstrates that this
approach satisfies the requirements of the RFP, as stated in
'Exhibit A: Scope of Work' of the RFP.

6.2 Technical approach

6.2.1   Statement of the problem

The internal flow in ducts is to be considered.   Important
features are as follows:

- The flow is three-dimensional, steady and viscous.
- The flow is partially-parabolic.   That is, it is
  essentially one-way, and there is no recirculation
  in the predominant direction of flow.
- The flow is subsonic, but may be compressible.
- Cavitation may occur within the flow field.
- The duct may be stationary or rotating.
- The duct may be of variable rectangular, circular, or
  distorted rectangular or circular cross-section.

The RFP requires the contractor to provide a computer program
to analyse the flow described above, to perform a sample run,
to provide a user manual, and to provide two weeks of sustaining
engineering to ensure the proper use and understanding of the
program by the MSFC.

CHAM's proposed approach is detailed in the following sections.
The computer program to be prepared, CATHY3/M, will handle all
the above mentioned features.

6.2.2   Equations

CATHY3/M will solve the partial-differential equations which
govern steady, three-dimensional and partially-parabolic
flow in ducts.   The dependent variables will be:

- the three components of velocity;
- pressure;

- stagnation-enthalpy.

In the flow situation considered here, sharp lateral variations in pressure may occur due to curvature and cross-sectional changes of the ducts; but, provided there is no streamwise recirculation, the flow is partially parabolic. This means that there is a predominant direction of flow, and that the diffusion of momentum, heat, etc, in that direction is negligible.

As an illustration, the equations solved in the existing version of CATHY3 are given in Appendix A. These will require modification for CATHY3/M by, for example:

- Replacing the temperature equation by that for stagnation enthalpy.
- Modifying the source terms due to rotation (Table III).
- Etc.

However, the form of the equations will remain unchanged.

6.2.3   Coordinate system

In order to account for the geometrical non-orthogonalities of the ducts, a curvilinear system of coordinates will be used. This is best explained by considering the coordinate system already embodied in the present CATHY3 program; details are provided in Appendix A.

A similar approach will be used to make the program capable of analysing distorted rectangular and circular cross-sections (see Appendix B). Indeed, it is envisaged that the main program development effort will be concerned with these distorted geometries. However, in view of the experience already obtained with the existing code, no major difficulties are anticipated.

6.2.4   Physical inputs

(a) Turbulent flow

In turbulent flows, it is assumed that the time-averaged equations are applicable, and that the shear stress, heat flux etc., obey laws similar to those in laminar flows. Thus, effective diffusion coefficients are used. They are calculated from average flow properties.

(b) Fluid properties

CATHY3/M will accept variable fluid properties (density, viscosity and specific heat). The modular construction of the program will allow these properties to be easily and quickly changed if required.

6.2.5   Boundary conditions

(a) Inlet plane

The program will accept arbitrary inlet boundary conditions
of all dependent variables.   If experimental data at the
inlet exist , they can be supplied as a function of grid
position.   Otherwise, any reasonable estimate of the inlet
distributions can be supplied to the program.

(b) Exit plane

Information about the pressure at the exit plane needs to be
provided.   The program will accept the specification of
either the pressure distribution or the streamwise pressure
gradient at the exit plane.

(c) Lateral boundaries

The lateral boundaries can be of two types: walls and planes
of symmetry.   The program will handle both types of boundaries.

(i) Wall boundaries -   the effects of a solid boundary on the
     momentum and heat fluxes are accounted for by the use of
     wall-functions as described in Ref 1.

(ii) Symmetry planes -   This economising facility will be
     provided in the program, for many duct flows have a central
     plane of symmetry with mirror-image flow fields on either
     side.

     At the symmetry plane, the velocities normal to that plane
     and the fluxes of all variables across that plane are
     all taken as zero by the program.

6.2.6   Special features

(a) Cavitation

Cavitation will be handled as follows: Whenever predicted
pressures tend to fall below the prescribed saturation pressure,
volume sources will be provided in the continuity equation so
as just to maintain the pressure at the saturation value.
These 'volume sources' represent the vapour generation occurring
in the real flow.

(b) Splitter vanes

The effect of splitter vanes within the flow domain will be
simulated by locally modifying the finite-difference equations
so as to imply zero flow across the vanes. This accounts
fully for the flow turning effect of the vanes.

It is proposed, at this stage, to neglect the blockage effect
of the vanes (i.e. they will be treated as very thin), and
the friction at the surface of the vanes. However, these
effects could be included at a later stage if required.

6.3 Review of proposed approach

The technical requirements, laid down in "Exhibit A: Scope
of Work" of the RFP, can be subdivided into four logical
headings:

Task 1:   Computer Program
Task 2:   Sample run
Task 3:   User manual
Task 4:   Sustaining engineering.

How CHAM's proposed approach satisfies these requirements is
reviewed below.

6.3.1   Computer program

The RFP requirements (ten in all) to be met by the program
are quoted below. The quotation is followed by a summary,
using the same numbering sequence as in the RFP, of how
CHAM's proposed approach will satisfy these requirements.

"The program shall meet the following requirements:

1. The program shall be programmed for and be operable
    on the MSFC Univac 1108 computer system.

2. The program shall analyze subsonic compressible
    and incompressible fluid flows.

3. The program shall have the capability of analyzing
    flow in ducts of rectangular, circular, and
    distorted rectangular and circular cross-sections
    (elliptical, rectangular with rounded corners,
    parallelograms, etc.).

4. The program shall analyze flow in rotating and
    stationary ducts.

5. The program shall analyze flows with cavitation
    within the flow field.

6. The program shall interface with MSFC fluid
    properties programs (GASP, etc.).

7. The program shall include a graphics package which will
    plot pressure, velocity, temperature and density in
    longitudinal and transverse duct sections.

8. The program shall accept arbitrary inlet boundary conditions.

9. The program shall accept rapid changes in duct geometry
    and analyze flow turning and splitter vanes in the ducts.

10. Input to the program shall be accomplished in a timely
    and practical manner. Coordinate transformation of input
    data shall be performed by the program".
                    --- end of quote ---

CHAM's proposal will satisfy these requirements as follows:

1. CATHY3/M will be written in standard FORTRAN IV, suitable
    for most scientific computers.   It will therefore be
    operable on the MSFC Univac 1108 Computer system.

2. CATHY3/M will solve the differential equations described
    in Section 6.2.2 above, and will therefore be applicable
    to subsonic compressible and incompressible flows.

3. The present existing CATHY3 program already has the
    capability to handle circular, and rectangular ducts of
    varying cross-section. This capability will be extended
    to distorted rectangular and circular cross-section ducts
    as outlined in Section 6.2.3 above.

    Here, the "capability of" requirement will need careful and
    reasonable interpretation by the client and CHAM, lest
    excessive expectations arise. It is interpreted to mean
    that the CATHY3/M program will have provision for the
    distorted geometries (via the program modules containing
    geometrical details), that the capability will be demon-
    strated (via the sample run), and that the capability
    will be explained (via the user manual).

4. The present program already handles flow in rotating
    ducts of varying rectangular cross-section (Appendix A).
    The same approach will be used for rotating ducts of
    other cross-sections in CATHY3/M.

5. CATHY3/M will analyse flow with cavitation within the
    flow field. (Section 6.2.6 above).

6. CATHY3/M will accept variable fluid properties.   The input
    of these fluid properties will be in well defined parts of
    the program, so that the client will easily be able to
    vary these properties.   In principle, the modular con-
    struction of CATHY3/M should allow it to be readily
    interfaced with MSFC fluid properties programs.   CHAM
    will aid the client's personnel, during the sustaining
    engineering period, to effect the necessary interfacing.

7. CATHY3/M will include a graphics package (the MAPLP line
    printer contour plot routine) which will provide plots
    of pressure, velocity, temperature and density in longitudinal
    and transverse duct sections.

8. CATHY3/M will accept arbitrary inlet boundary conditions
    as explained above in Section 6.2.5.

9. CATHY3/M will be capable of handling rapid changes in the duct
    geometry and analyse flow turning and splitter vanes in the ducts,
    under the conditions described in Section 6.2 above. However,
    because the treatment is partially-parabolic, flow
    separation induced by changes in geometries or turning
    cannot be handled.

10. Data input to CATHY3/M will normally be effected through BLOCK DATA, collected together in a BLOCK DATA subroutine. CATHY3/M will also normally perform coordinate transformation of input data, from Cartesian or cylindrical-polar to the appropriate curvilinear system (Section 6.2.3 above).

Level of effort

CHAM considers that the appropriate level of effort for this task is five man-months.

This presumes that no difficulties are introduced and no extensions made to the scope of work at a later stage. For example, concerning point 10 above, it is expected that CHAM and the client will agree in the "timely and practical manner" of input to the program, within the context of the overall work schedule and costs.

It is reaffirmed here that the CATHY3/M program, as supplied, will be capable of extension by anyone who follows the sample run example and user manual, but that each new geometry may require one or more man-month for setting-up the program.

6.3.2   Sample run

What is to be done is outlined in the RFP as far as is possible at the present stage; and CHAM will do what is asked; namely:

"The sample run shall be an MSFC specified pump impeller. All input data shall be identified (terminology, physical units, sources, etc). Output data shall be explicitly interpreted with respect to the sample case and expected results".

Level of Effort

The level of effort for this task is set to be about one man-month.

However, as the sample run is not defined in the RFP, it is expected that the client and CHAM will agree on the details and objectives of the sample run, consistent with a one man-month level of effort.   It is also expected that the client will provide the specifications of the sample run within one week of the start of the work.

6.3.3   User manual

CHAM will prepare and deliver the user manual as specified in the RFP, namely:

"The user manual shall identify all input data required to execute the program.   The format and physical units of each input parameter shall be supplied.   The terminology for each input parameter and any information needed by the user to clearly define the parameter shall be included in the user manual.   The user manual shall identify all output data and provide all information necessary to interpret the output data".

Level of Effort

CHAM considers that two man-months will be required for this task.

#6.3.4   Sustaining engineering

What is required is clearly spelled out in the RFP; and CHAM will do what is asked; namely:

"The two weeks of sustaining engineering shall be provided at MSFC for the express purpose of transferring knowledge of the computer program and its proper use to MSFC personnel.   The following shall constitute a minimum requirement for this:

1.   Provide a basic understanding of the computer program (approach, basic equations, program options, etc.).

2.   Provide an in-depth review of the MSFC designated sample run (problem statement, assumptions, input data review, and output data evaluation).

3.   Provide in-depth review of user manual.

4.   Provide discussions of computer program's-analytical limitations".

7. Organisation of the work

The proposed work will involve CHAM carrying out the following
tasks.

(a) Task 1 - Computer program preparation

(i) Introduce into CATHY3 the capability to handle distorted rectangular
and circular cross-section geometries.

(ii) Introduce the curvature terms.

(iii) Introduce the rotation terms.

(iv) Introduce the cavitation feature.

(v) Introduce the capability to handle splitter vanes.

(b) Task 2 - Sample run performance

(i) Arrange input and output features of the program to be
user orientated.

(ii) Perform sample run to demonstrate that the program is
operational.

(c) Task 3 - User manual preparation

Prepare user manual as required by the RFP: Exhibit A:
Scope of work.

Deliver manual and computer program to MSFC.

(d) **Task 4 - Sustaining engineering provision**

Provide two weeks of sustaining engineering as required
by the RFP.

7.1 Manpower allocation

The estimated manpower required for the various tasks is
shown in the table below in man-hours.

Task No.	Prof Spalding	Dr D G Tatchell	Project Engineer	Typist/ Comupter aid	Total man-hours
1	15	60	600	50	725
2	5	15	150	30	200
3	5	15	150	120	290
4	-	-	75	-	75
TOTAL	25	90	975	200	1,290

7.2 Program management

CHAM will undertake the proposed work, using the most appropriate
resources within the CHAM group, both in terms of personnel
and facilities.

CHAM's Administrative Manager, Mr Micheal Spalding, will be
responsible for the overall management and successful conduct
of the proposed work.   All technical, financial and schedular
reporting, and all commitments and formal communication to
the client will be the responsbility of CHAM's Administrative
Manager.   This arrangement is not, however, intended to
preclude the reasonable flow of information between CHAM's
engineers and the client's representatives.

CHAM's Deputy Managing Director, Dr David Tatchell, will be responsible for the execution of the work. He will be assisted by a Project Engineer from CHAM's staff, who will be assigned full-time to this project. The whole project will be overviewed by CHAM's President, Professor D Brian Spalding.

APPENDIX II

Monthly progress reports, in
chronological order

.National Aeronautics and
Space Administration
George C Marshall Space
Flight Center
Marshall Space Flight Center
Alabama 35810
U.S.A.

CHAM Ref:1712/H3082

10 January 1979.

To Whom it may concern

Re: Contract NAS8-33090

This letter is intended to serve as progress reports on the
above contract for the months of October, November and
December 1978. The contents have already been reported to
Messrs Wilmer and Gross of Marshall Space Flight Center
during monthly telephone conversations.

Just after contract award (ie during October 1978) the work
content was reviewed at CHAM, and it was decided to base the
required computer code (CATHY3/M) on CHAM's latest 3-dimensional
code (TOPSI) rather than an earlier version of CATHY3 as had
been originally intended. This decision was based on the
following considerations:

(i)   The TOPSI based CATHY3/M will be superior to earlier
        versions of CATHY3 in computer time and computer
        storage requirements. This is achieved largely by
        the use of secondary storage, which reduces the amount
        of in-core storage required, and eliminates a large
        number of repetitive calculations which would other-
        wise be required.

(ii)   The special features required to turn TOPSI into
        CATHY3/M are the same as those required starting from
        the existing CATHY3: namely, provision for irregular
        duct shapes, and cavitation. Thus, the same amount

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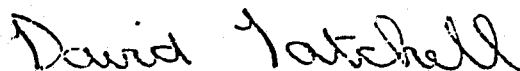
of work would be required, starting from either
starting point. However, because of parallel work
going on at CHAM on TOPSI, and because TOPSI is
an easier code to use than the existing CATHY3,
the work will be accomplished more reliably and
quickly if TOPSI is the basis.

It was recognised in October that some work was required on
TOPSI to provide a starting point for CATHY3/M, and also
for other projects. This work was planned to be completed
by early January 1979 and is indeed now complete. Work
on the CATHY3/M development is therefore just starting.
The first stage is the provision for irregular geometries
(at present the code is restricted to circular or rectangular
cross sections.) It is expected that the basic code
modifications will have been made and checked by the end
of January. Work will then commence on the introduction
of cavitation.

The work performed to date has not been contributing directly
to the present contract. The estimated completion at end
of December should be considered zero. Consequently no
invoices have been sent to date. The work now commencing
is directly concerned with the CATHY3/M development. A
full progress report and appropriate invoices will therefore
be submitted at the end of January.

Finally, I should emphasise that the late start on this
project will not cause overrun. Completion is planned within
the contract period. As noted in point (ii) above, the use
of TOPSI will enable the work now to proceed more quickly,
and with more certainty, than would otherwise have been the
case.

Yours sincerely,

David Tatchell
Deputy Managing Director

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                  EM63-13
                  EP23/Wilmer

National Aeronautics and
Space Administration
George C Marshall Space Flight Center
Marshall Space Flight Center
Alabama 35810
U.S.A.

CHAM Ref: 1712/H3082

14 February 1979

To whom it may concern

Re: Contract NAS8-33090

This letter is intended to serve as the progress report on
the above contract for the month of January 1979. The contents
have already been reported to Mr Wilmer of Marshall Space
Flight Center during the monthly telephone conversations.

As was reported in the previous progress report, work up to
early January 1979 was required to provide the starting point
for CATHY3/M. This work involved the construction of a new
basic code (TOPSI) which would provide the basic facility on
which CATHY3/M will be built. The advantages of abandoning the
earlier versions of CATHY3 have also been reported in the
previous progress report. The work on TOPSI was not contributing
directly to the present contract; therefore the estimated
completion at end of December was considered zero and no
invoice was sent then.

The above work was successfully completed early January 1979,
as planned.

Work directly relevant to the CATHY3/M development started
therefore early January 1979. The first stage of this
development was the provision for irregular geometries (since
the basic TOPSI code was restricted to circular or rectangular
cross-sections). During January the basic code modifications
were made according to what is given in the Appendix.
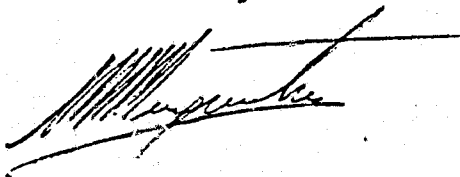
Furthermore, the above modifications were checked for FORTRAN and other errors.

The estimated completion at end of January is 4% and therefore an invoice for $2076 U.S. Dollars is enclosed.

Finally, it should be emphasised again that the slow start on this project will not cause overrun, for the reasons explained in the previous progress report.

Yours sincerely,

N C Markatos
Applications Team Manager

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APPENDIX

A coordinate system for treating flows with irregular boundaries, in which the grid cells are distorted to fit them.

Purpose: The following are the requirements for the impeller in pump of NASA Marshall's Space Shuttle:

1. Grid distortion to account for changing boundaries and for curvature.

2. Geometrically-induced body forces (grid-line curvature), and

3. Body forces resulting from rotation of the flow system about the axis.
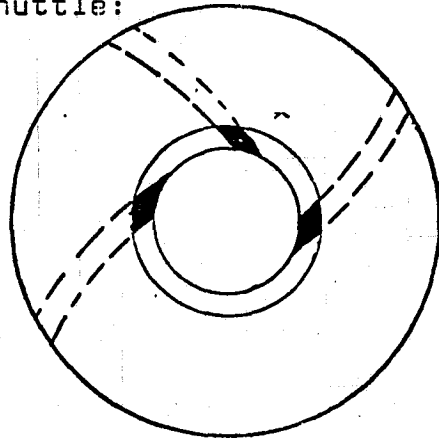
FIGURE 1:

General Principle

A non-orthogonal (i.e. distorted) set of control volumes, the boundaries of which coincide with specified edges of the domain, is superimposed on an orthogonal velocity field.

The non-orthogonal curvilinear coodinates (ξ, η, ζ) which define the edges of the control cell

The grid is specified as a set of (ξ, η) points. The actual spatial locations of a point (ξ, η) is generated by application of the following formulae:

$$r = R_S + \eta \, (R_N - R_S)$$

$$\theta = \theta_W + \xi \, (\theta_E - \theta_W) \tag{1}$$
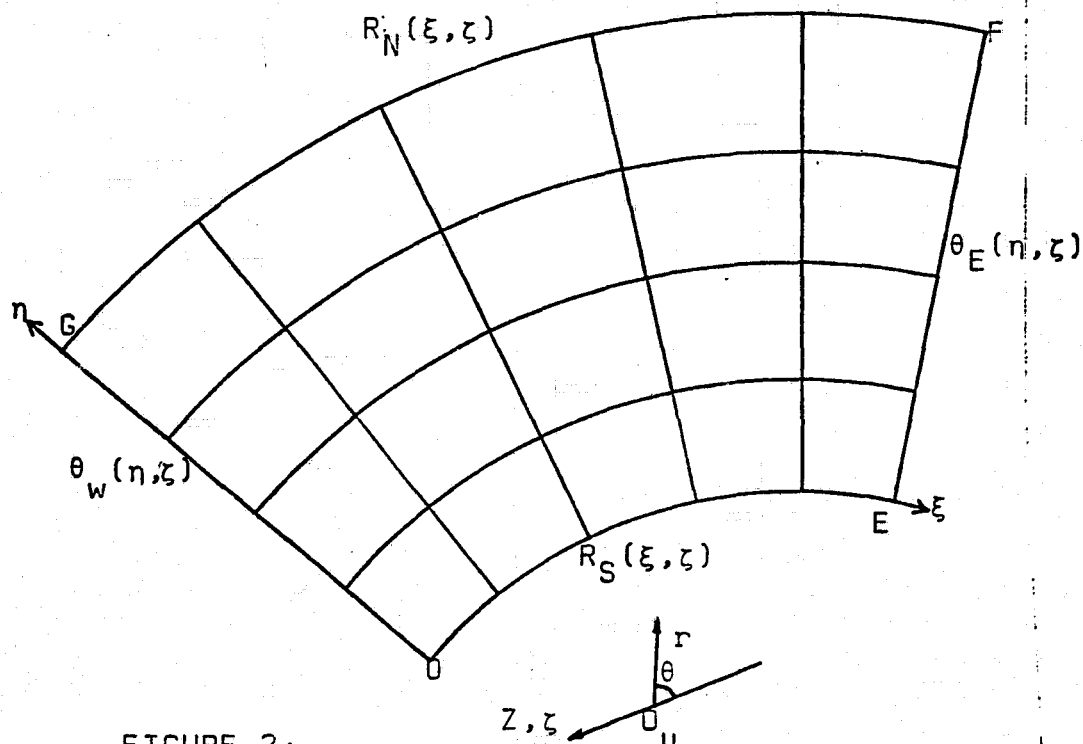
FIGURE 2:

where θ_E, θ_W, R_N, R_S, define the edges of the domain with respect to the cylindrical polar coordinates origin O_u (O_u denotes origin of velocity grid).

- η and ξ always lie in (r, θ) plane, and ζ is parallel to Z.

- η and ξ both run from 0 to 1.

- r, and θ must be single-valued functions.

Knowledge of the actual spatial locations of the ξ-η points, allows all geometrical quantities to be determined. These, apart from areas of cell faces and volumes of control cells, include also the slopes of the cell faces which are needed for the evaluation of fluxes through all faces.

The orthogonal velocity field upon which the distorted set of
control cells is superimposed is a conical one.   The ξ-η
section analysed at each ζ station is defined by the intersection
of the walls of the duct cavity with a conical surface whose
base radius is FO (see figure below).
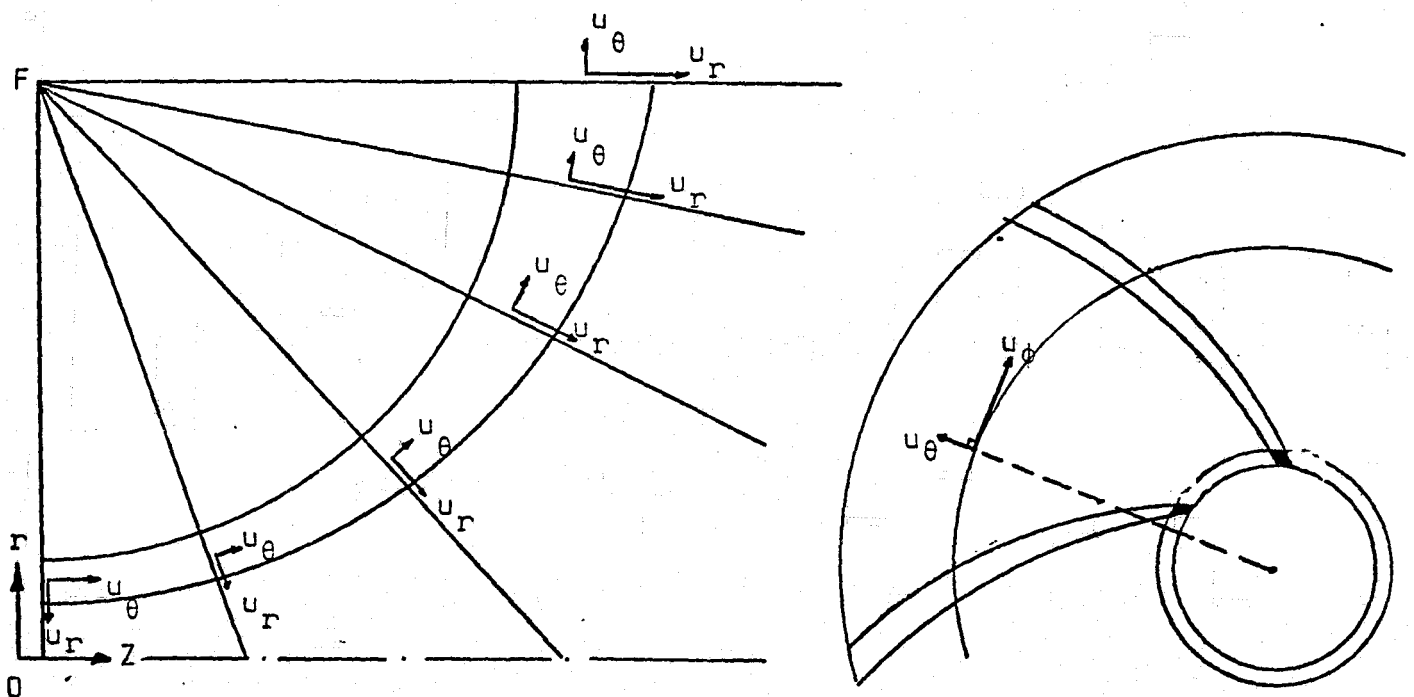
FIGURE 3 :

Note that at θ=0 and θ=π/2, the conical coordinate system
degenerates into the more familiar cylindrical polar system
of coordinates.

More details of this conical system of coordinates will be
given in the following progress report, together with a
statement of the momentum equations in this system.

CHAM   CONCENTRATION, HEAT & MOMENTUM LTD.

National Aeronautics and
Space Administration
George C Marshall Space Flight Center
Marshall Space Flight Center
Alabama 35810
U.S.A.

CHAM Ref:1712/H3082

23 April 1979

To whom it may concern

Re: Contract NAS8-33090

This letter is intended to serve as the progress report on the
above contract for the months of February and March 1979. More
details have been reported to Mr Wilmer of Marshall Space
Flight Center during the monthly telephone conversations.

1.   INTRODUCTION

Work directly relevant to the CATHY3/M development started early
January 1979. The first stage of this development was the
provision for irregular geometries.

During January the basic code modifications were made according
to what was given in the Appendix of the previous Progress
Report.

During February and March, 1979, work was concentrated on two
major items, i.e. irregular geometry, and compressibility and
cavitation. The work can be summarised as follows:-

2.   IRREGULAR GEOMETRY

(i)   Purpose of this task

Purpose of this task is the introduction into the basic computer
program of the required sequence to render this program capable
of handling any type of irregular geometry, and the extensive
testing of those sequences. This task constitutes one of the
two major tasks involved in the 1712 project, the other being
compressibility and cavitation.
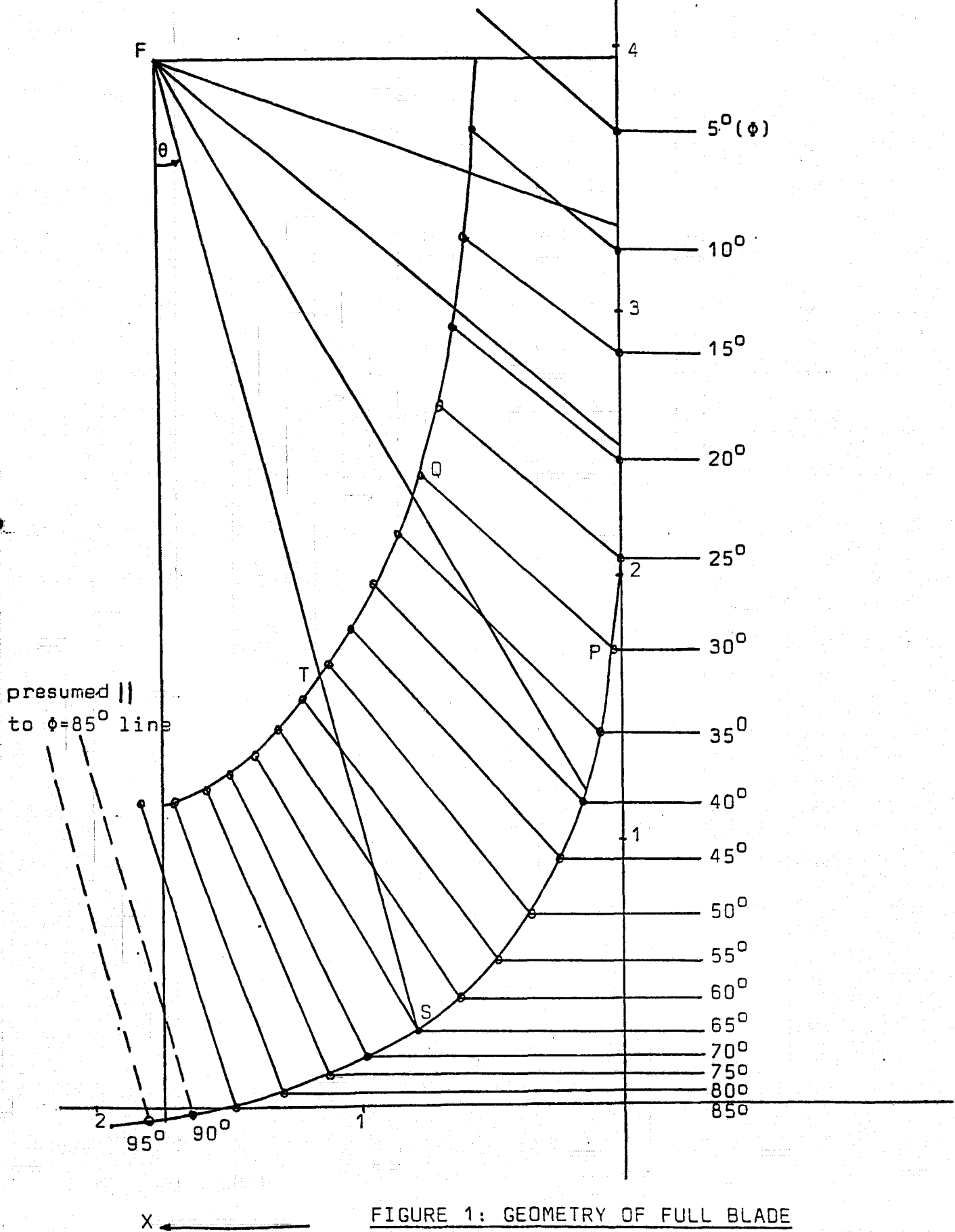
FIGURE 1: GEOMETRY OF FULL BLADE

(ii) Technical details and progress to date

The general framework for treating flows with irregular
boundaries is as given in the Appendix of the previous progress
report. It is worth restating the general principle that
"a non-orthogonal (i.e. distorted) set of control volumes, the
boundaries of which coincide with the specified edges of the
domain is superimposed on an orthogonal velocity field".

In the case of the impeller, the orthogonal velocity field in
question is a conical one.

The construction of the impeller/blade geometry from the supplied
data, in the above system, is explained below.

Figure 1 shows the impeller/blade geometry drawn to scale (5cm=1inch).
This drawing is generated from "sheet 13" provided by NASA according
to the following steps:

a) Use the "profile coordinates of the
   hub and shroud" to draw the profiles
   of the hub and shroud.

b) Draw the loci of lines of constant
   Φ using the table entitled "Full
   blade pressure surface intersect
   coordinates". The locus of the
   constant Φ line on the blade is
   the line PQ in the diagram (on fig.1,
   PQ has been marked for the line
   Φ=30°).

FIG.2
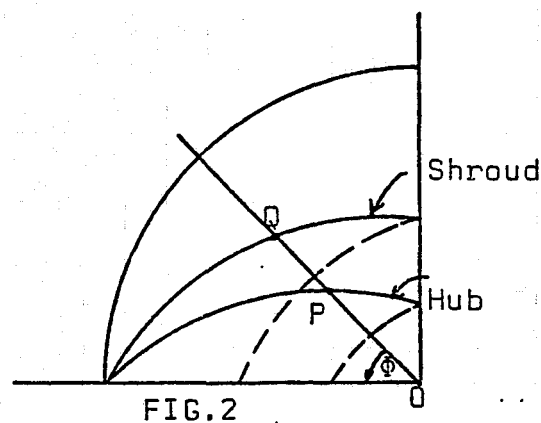
c) The location of the inlet plane was taken to pass through the
   last point given on the shroud. This agrees with measurements
   made on "sheet 10".

d) A point on the base circle of the cones, F, is simply the inter-
   section of the inlet plane with the outlet surface.

The programming concerning the irregular geometry has been
accomplished, and the program is being tested by applying it to
simple geometries, as for example square ducts. The test cases have
been devised so that each one introduces a more complicated geometry
than the previous one. In this way all the features of CHAM's
irregular geometry treatment will be checked adequately.

The last three test cases devised for this purpose are described below.

They are:

TEST CASE 1: "Simplified" impeller;

TEST CASE 2: the actual impeller geometry, but without the blades swept back; and

TEST CASE 3: the full impeller geometry, with the blades swept back.

For these tests a coarse grid 5x5x5 is considered. Of course, the code is flexible, and accepts any type of grid.

Specification of the geometry for the three remaining test cases described above

a)   Geometric quantities that need specification

The following quantities need to be specified for all cases (Fig.3)

- n and ξ, the non-dimensional coordinates of the grid on the conic surfaces. In all three cases these are to be ascribed so as to give a uniform 5x5 grid:

  {n/0,0.2,0.4,0.6,0.8,1.0}
  {ξ/0,0.2,0.4,0.6,0.8,1.0}

FIG.3

- θ (or ζ) the angle which defines the conic surfaces bounding each slab of cells. 5 slabs will be considered spaced as:

  {θ/0,15°,30°,50°,70°,90°}

- At each slab specify: $R_N(\zeta)$, $R_S(\zeta)$, $\Phi_E(n,\zeta)$ and $\Phi_W(n,\zeta)$

- Give the base radius of the cones. From sheet 10 this is C=6 inches.
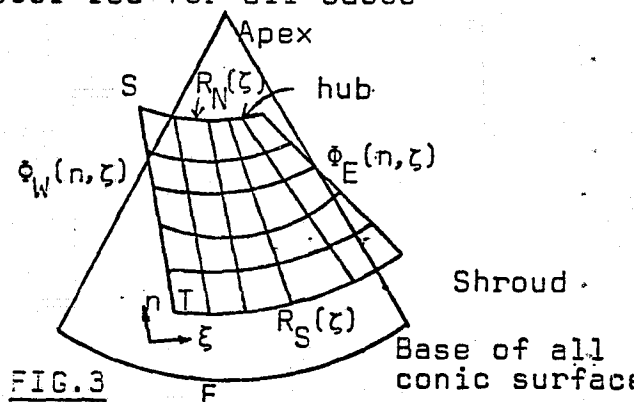
b)   Determination of R_N, R_S, Φ_E, and Φ_E at each θ surface

The lines of constant θ have been drawn on fig.1. Consider the line at $\theta=15°$. It intersects the hub at S and the shroud at T. Thus $R_N(\theta=15°)=FS$ (the local radius generating the local lampshade surface), and, $R_S(\theta=15°)=FT$.

Cont/......

Cont/......page four

The pressure surface specified in fig.' corresponds with the west edge of the n-ξ grid. Φ_W (n,θ =15°) is determined by interpolating from the lines of constant ϕ drawn on fig.1. Thus,

Φ_W (n=0, i.e. at T, θ=15°)$\simeq$ 51°,

Φ_W (n=1, i.e. at S, θ=15°)$\simeq$ 65°

At intermediate values of n the interpolation proceeds in the same way.

Note that the corresponding points on the suction surface are merely shifted through 60°. Thus,

Φ_E (n=0; θ=15°) $\simeq$ 51° + 60° = 111°

Φ_E (n=1; θ=15°) $\simeq$ 65° + 60° = 125°

c) Specification of TEST CASE 1

The following fig 4 shows the development of a conic surface for a regular Φ-r-θ grid appropriate to the "simplified" impeller.
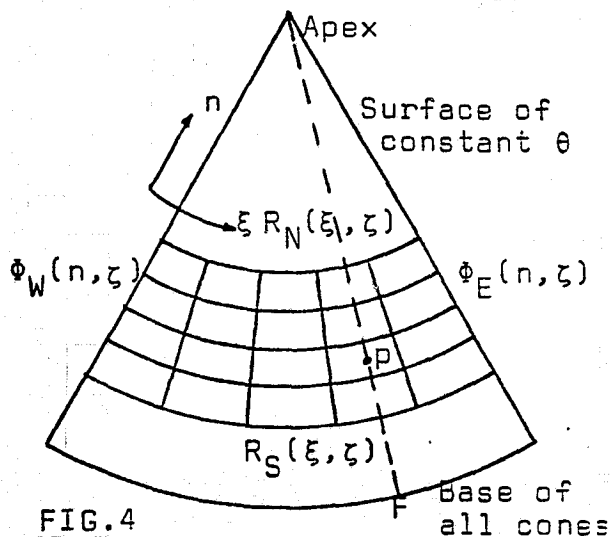
FIG.4

Note that ζ corresponds to θ. In this "simplified" impeller, lines of constant n correspond to lines of constant r (PF'=r), and lines of constant ξ correspond with lines of constant ϕ. Thus, R_N, R_S, Φ_W and Φ_E are all constants, throughout. The following values for R_N^W, and $^E R_S$ are based on those at the inlet plane:

$$R_S = 5.56 \text{ in}$$

$$R_N = 7.94 \text{ in}$$

$$\Phi_W = 0$$

$$\Phi_E = 60^\circ$$

d) Specification of TEST CASE 2

Since the blades are not swept back, it means that the blade surface runs along a line of constant Φ at each value of θ. The value of Φ taken, will be that of the midpoint of TS (see fig.1.)

θ°	$R_S(\text{in})$	$R_N(\text{in})$	Φ_W°	Φ_E°
0	5.56	7.94	88.15	148.15
15	4.75	7.5	59.0	119.0
30	3.75	6.31	35.45	95.45
50	2.91	4.50	19.25	79.25
70	2.47	3.69	10.31	70.31
90	2.37	3.44	4.56	64.56

TABLE 1

e) Specification of TEST CASE 3

The main feature of the distorted grid for the real impeller is that now the lines of constant ξ no longer correspond with the lines of constant Φ, but have been swept back so that at the edges they coincide with the blades of the impeller. Thus, at given ζ (i.e. θ), R_N and R_S are both constant, but both Φ_E and Φ_W are functions of n (i.e. Φ). Table 1 gives the values of R_S and R_N at each θ. All that remains to be done is to evaluate Φ_W and Φ_E at each n, at each θ.

Cont/......

The following table 2 gives the values of Φ_W at n=0 (i.e T in fig.1) and n=1 (i.e. S in fig.1) for each value of θ.

θ^o	Φ_W at n=0	Φ_W at n=1
0	82.9	91.6
15	51.2	64.5
30	31.8	39.1
50	19.0	19.4
70	12.0	8.9
90	7.0	2.0

At the intermediate values of n (i.e. 0.2, 0.4, 0.6, 0.8), Φ_W is determined by linear interpolation.

$$\Phi_W(n) = (1-n)\Phi_W(n=0) + n\ \Phi_W(n=1)$$

Finally, the Φ_E values are determined as follows:

$$\Phi_E(n,\zeta) = \Phi_W(n,\zeta) + 60^o$$

.At the moment, the code is exercised for Test Case 1.

(iii) Future plans

The code will be tested for all 3 test cases mentioned above. It is anticipated that this task will be accomplished by mid-May 1979. Note that by the end of this exercise the major development towards the final CATHY3/M will have been completed.

Then, work will move to provide some pre-processing coding sequence to automate the data preparation.

A method of automating that preparation is the following:

Determine Φ_W(n=0) and Φ_W(n=1) as polynomial functions of θ, then Φ_W at any n will be determined by linear interpolation.

Similarly, R_S and R_N may be determined as polynomial functions of θ.

3. COMPRESSIBILITY AND CAVITATION

(i) Purpose of this task

This task constitutes the second major task of the 1712 project and involves programming and testing of the compressibility and cavitation sequences. This will enable density changes associated with compressibility and cavitation to be taken account of.

(ii) Technical details and progress to date

The two-pressure method is being introduced into CATHY3/M.

According to this method two pressures are stored, the pressure p used in the momentum equations and the "density pressure p_ρ, which is used to derive density from the gas law, or in this case, from the GASP program supplied by NASA.

The method works as follows:

- Store density pressure (p_ρ) in addition to p.

- Start calculation with p_ρ guessed say equal to the inlet pressure everywhere.

- Solve as usual, using the same solution method as for incompressible flow, obtaining densities when required from p_ρ and calculated local enthalpy, using GASP.

- After a prescribed number of sweeps adjust p_ρ according to:

$$p_{\rho,new} = p_{\rho,old} + \alpha(p_\rho - p_{\rho,old})$$

  where $\alpha \ll 1$, and update p accordingly.

- Repeat above two steps until convergence (i.e. until $p_\rho \equiv p$ to within a prescribed tolerance).

The present status of this work is as follows:

The programming of the two-pressure method is in progress. Furthermore, the NASA program GASP was mounted on CHAM's computer. Considerable modifications had to be made to the original deck to make it compatible with CHAM's Intercata computer system.

(iii)Plans

The programming of the two-pressure method will be completed
during April 1979, and testing will start early May 1979.
For this testing GASP is not to be used directly, but instead
it will be used to generate a function $p=f\{p\}$ over the required
range of p, first in tabular form, then in approximate function
form. This function will then be provided as a function state-
ment, activated instead of GASP at the appropriate point in
the code.

4   CLOSURE

It is indicated that despite the slow start of this project,
considerable work (particularly thinking) has been done already.
It is anticipated that during April and May the major technical
part of this contract (i.e. the irregular geometry and the
compressibility/cavitation) will be successfully completed.
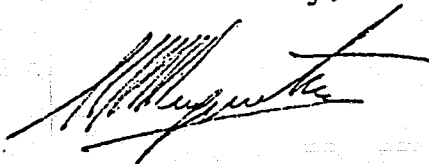
Further input is required from the client as follows:

a.   Full inlet conditions (velocities, p, h or T) for the problem
      are required as soon as possible.

b.   A full run of GASP as sent to CHAM, to provide comparison
      with the results achieved by GASP as modified to run on the
      Interdata machine.

5   ESTIMATED COMPLETION

The estimated completion at end of March is 9% (cummulative) and
therefore an invoice for $2596 (U.S.Dollars) is enclosed.

Yours sincerely,

N C Markatos
Applications Team Manager

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National Aeronautics and
Space Administration
George C Marshall Space
Flight Center
Marshall Space Flight Center
Alabama 35810
U.S.A.

CHAM Ref: 1712/H3082

6 June 1979

To whom it may concern

Re: Contract NAS8-33090

This letter is the progress report on the above contract,
for the period since the submission of the last progress
report on 23 April 1979.

1.   INTRODUCTION

The report of 23 April reported that:

a)   The coding required to enable CATHY3/M to handle
      impeller and other complex geometries was complete.

b)   Tests were being started in which the code was being
      applied to impeller geometries. Three test cases
      were described, starting with an idealised 'simplified'
      impeller, and leading up to an impeller geometry
      corresponding to that for the final contract test
      case (as specified in Reference 1), but with partial
      blades ignored .

c)   The coding required to handle density variations
      associated with cavitation and compressibility
      was being introduced.

During May, effort has concentrated on the preliminary
impeller calculations referred to in b) above. This work
is described in Section 2 below.

Progress in other tasks is covered in Section 3. This
includes work on : compressibility and cavitation,
introduction of plot routines, and documentation.

Finally, Section 4 quantifies progress to date, and
outlines plans for the future. The references are given
in Section 5.

2.   PRELIMINARY IMPELLER CALCULATIONS

2.1   Purpose of the task

This task is intended to check out the modifications made
to CATHY3/M to enable it to handle complex geometries, by
performing calculations for representative impeller geometries.
The results are to be examined for convergence and physical
plausibility.

Simplifications made at this stage include:

o   The fluid density is assumed constant, at a value
        representative of the contract test-case conditions.

o   The partial blades are not included.

o   At first relatively coarse grids are used.

In all other respects, the calculations correspond to the
full requirements of the contract. Of course, the above
simplifications will be removed in the final contract
calculations.

2.2   Specification of the calculations

(i)   Geometries

Three test case geometries were described in the April 23
progress report. These were characterised as follows:

o   TEST CASE 1: 'Simplified' impeller with surfaces
        corresponding to coordinate surfaces in the conical
        coordinates used in CATHY3. (NB This geometry is
        considered because it is 'regular' in the sense of
        the CATHY3 coordinates. Essentially, the blades are
        radial and normal to the hub, and, in a section cut
        through the axis of rotation, the hub and shroud
        surfaces are perfect circular arcs.)
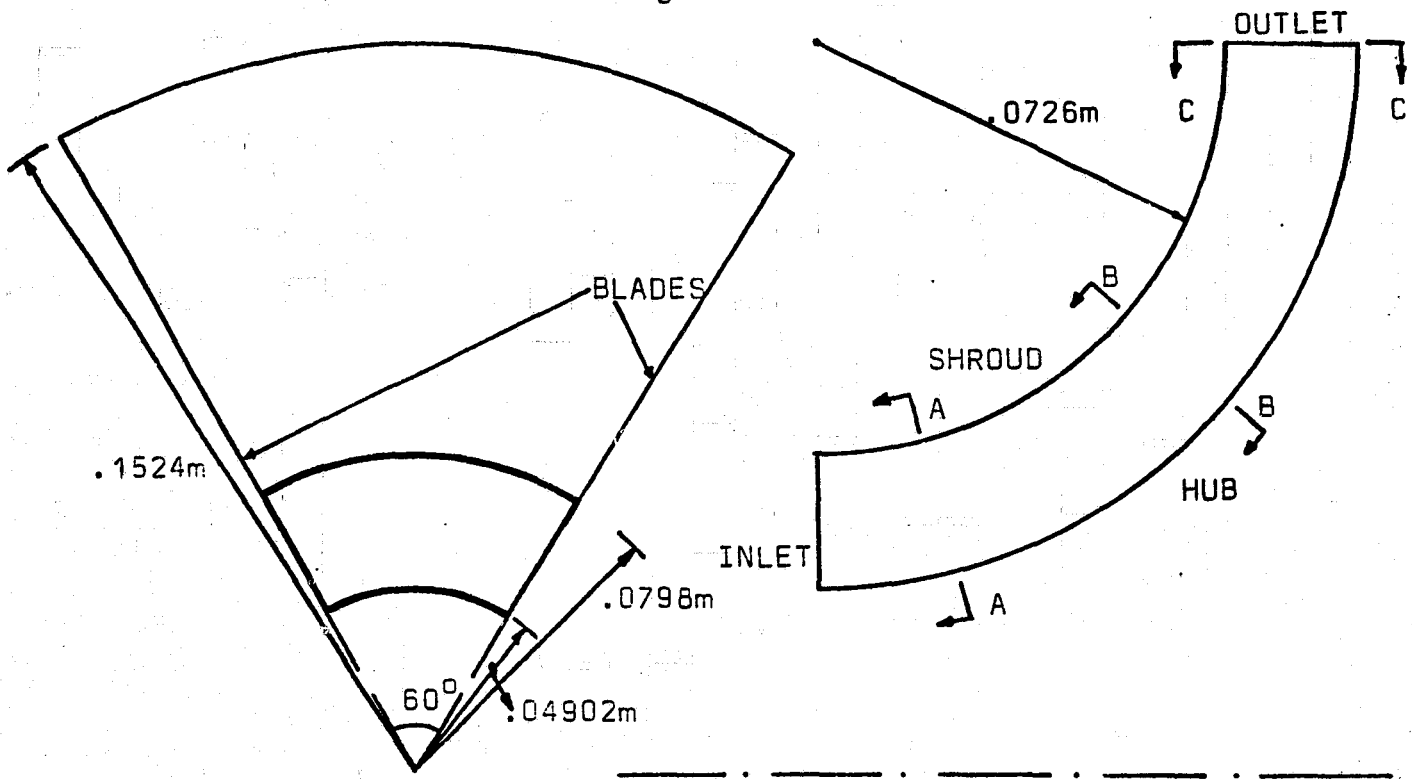
Test Case 1
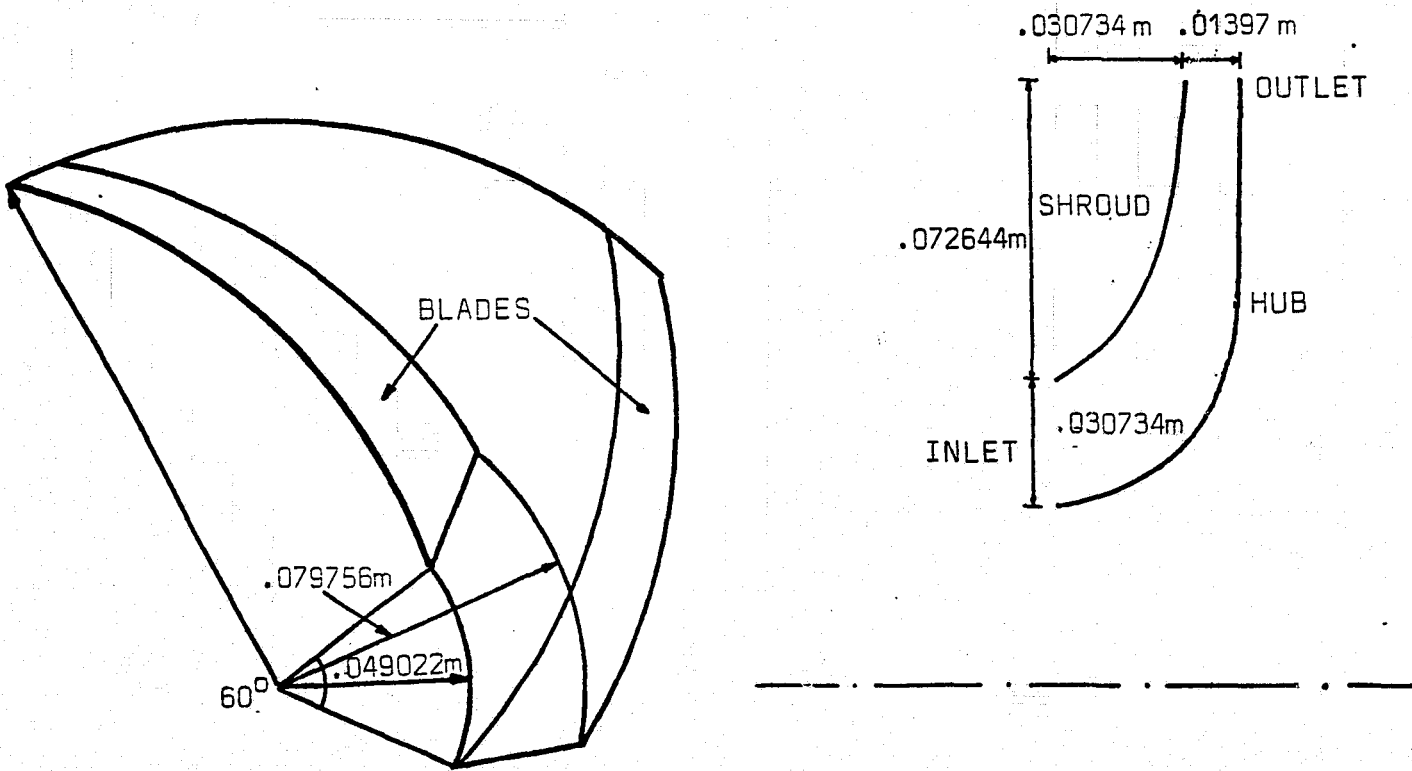
Test Case 3

Figure 1: Test Case Geometries

o   TEST CASE 2: As for final test case (Reference 1)
     but with blades normal to hub.

o   TEST CASE 3: As for final test case.

In fact, it has now been decided to omit Test Case 2,
and to proceed directly from Case 1 to Case 3. Details
of the geometries of these cases are given in the 23 April
report and are summarised in Figure 1.

(ii) Flow conditions

(These are taken as far as possible from the specification
in Reference 2).

Properties

o   Density ρ = 70.41 kg/m^3

o   Laminar viscosity μ = 1.272 10^{-5} Ns/m^2

     (Both of these are taken from GASP outputs for H_2 at
     p=12.76 atm, T=22°K; this was closest available point
     to specified inlet conditions of 10.7 atm and 23.44°K.)

o   Turbulent viscosity μ_t assumed 1000 x μ for present
     run.

Inlet conditions

o   Axial velocity w =484.82 m/s uniform. (This is
     deduced from flow rate of 155.96 lbm/sec≡70.73 kg/sec
     for each impeller passage).

o   Lateral velocities u and v = 0.

Outlet conditions

o   Static pressure p prescribed uniform.

Rotation

o   Impeller speed 35,000 rpm.

(iii) Grid distribution

The grid used has 5x5x5 internal points uniformly distributed
in each direction, as described in the 23 April report.

2.3   Results

For Test Case 1, two runs have been successfully completed.
The first was for the conditions specified above, but
without rotation; the second included full rotation. In
both cases, full convergence was obtained, and the results
appear satisfactory.

In addition, the Test Case 3 geometry has been introduced
and checked, and the first run is in progress.

The results for Test Case 1, with rotation, are shown in
Figure 2.Line-printer generated contour plots are shown
at section A-A, B-B, and C-C on Figure 1. These correspond
to lateral planes: close to inlet; about half way through
the impeller; and close to outlet.

The quantities plotted are: (w/inlet w); and (p-outlet p)/
$(\frac{1}{2}\rho w_{in}^2)$. The plots can be understood as follows. The range
of variation of the quantity to be plotted at the section
in question is identified. This is printed above each plot.
This range is then divided into 10 equal bands. The digit '1'
is printed wherever values lie within the first band (ie within
the first 10 percent of the range); '3' is printed where
values lie in the third band; and so on up to '9'. Even
number bands are left blank. Thus 9's indicate high values,
1's low values and so on.

The plots can therefore be interpreted as follows:

o   Near to inlet (ie at Section A-A) high pressures
       occur near to the hub (due to the curvature of the
       passage in the plane through the axis of rotation)
       and at the blade pressure surface (due to rotation).
       The velocities show high values in the hub/suction-
       surface corner, and low values in the shroud/pressure-
       surface corner. (Note that in this particular run
       wall friction effects are neglected, so low-velocity
       boundary-layer regions near to the wall are not seen).

o   By the mid-section (Section B-B) the main pressure
       variation is from pressure to suction blade surfaces.
       The hub to shroud variation is relatively smaller,
       and still in the same direction as at inlet . The
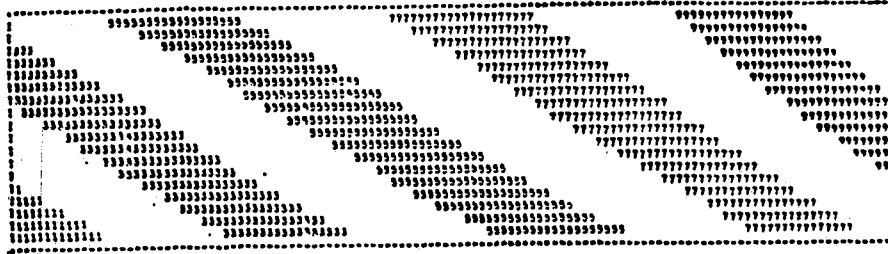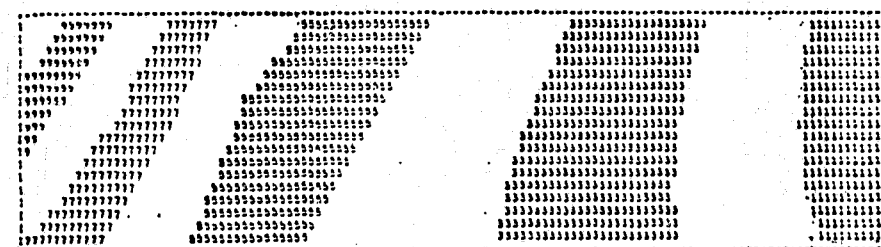   velocity variation is similar to that at inlet.
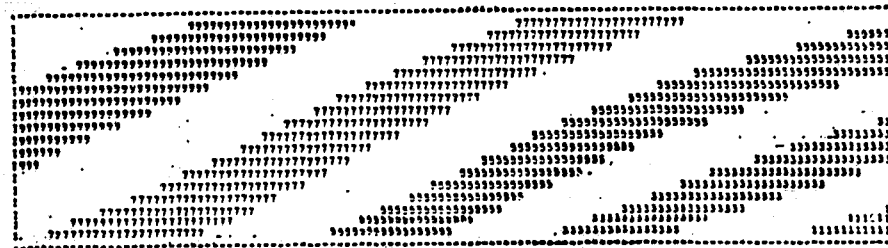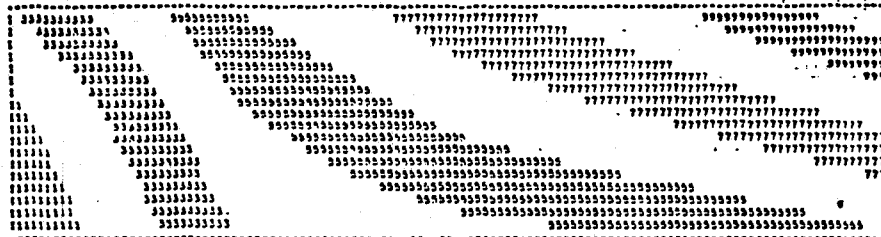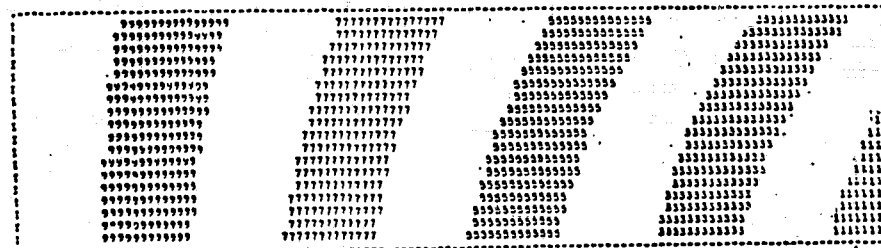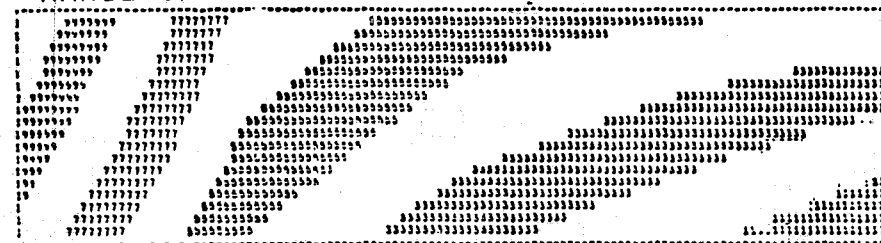
Figure 2: Results for Test Case 1, with rotation.
(Explanation of plots is provided in
Section 2.3 of text).

o   Near to outlet (Section C-C) the range of pressure
variation is much less. This is a consequence of
the prescribed uniform outlet pressure. The velocity
variation is virtually reversed. This can be under-
stood as follows: at inlet the velocities are
prescribed uniform, and the pressures are calculated
non-uniform as shown at Section A-A; this implies
a non-uniform total pressure distribution, with
high values at the hub/pressure-surface corner (as
for pressure) and low values at the shroud/suction-
surface corner. At outlet the pressure is prescribed
uniform; therefore, if stagnation pressure is
conserved along streamlines (as will approximately
be the case) high velocities will result in the hub/
pressure-surface corner (where stagnation pressure
is high) and velocities will be low in the opposite
corner. The predicted results are therefore consistent
with the inlet and outlet conditions as prescribed.

2.4   Planned further work

The planned next steps are:

(i)   Complete run currently in progress for Test Case 3
       (ie realistic geometry). This includes rotation,
       but (like the run reported above) neglects wall
       friction.

(ii)   Introduce finer grid.

(iii) Introduce wall friction.

(iv)   Introduce better inlet conditions (NB Reference 2
       includes specification of flow angle (and hence u
       velocity)at inlet, and variation of w and flow
       angle between hub and shroud. These would be
       included at this stage).

       At each of stages (ii), (iii) and (iv) the code will
       be run to convergence, and the results checked for
       plausibility. Following stage (iv) the code will
       be ready for the introduction of cavitation and
       partial blades (which will have been checked out
       separately) for the final test-case run.

It is planned that stages (i) to (iv) above will
be completed by the end of June. The final test
case will therefore be ready to run early in
July.

3.   OTHER WORK

3.1   Compressibility and cavitation

The two-pressure method as described in the 23 April
report has been completely coded into CATHY3/M. This
is now ready for testing, first for compressible gas flow,
then using properties for liquid H_2 including cavitation,
obtained from GASP or an alternative. These tests will
first be made on simple two-dimensional curved passages, then
on the representative impeller geometries described in
Section 2. It is planned that these tests should be
completed by the end of June.

The question of whether the GASP program should be used
directly to provide properties (ie density and viscosity)
input to CATHY3/M is being considered. At present GASP
is working satisfactorily on CHAM's Interdata computer,
but has not yet been interfaced directly with CATHY3/M.
On the basis of observed computer times for both programs,
GASP requires about twice the solution time of CATHY3/M
per grid node per sweep, to provide property values for
one set of flow conditions. Thus, if GASP were to be used
to update density once per grid node per sweep (as would
be the normal practice if it were interfaced directly with
CATHY3/M), the CATHY3/M computer time would increase by
roughly a factor of three.

Thus, while direct interfacing of GASP with CATHY3/M presents
no coding difficulties, from the point of view of computer
efficiency the alternative use of algebraic property formulae
should be considered. This would apply both for present
use at CHAM, and for future use at MSFC. Of course, if it
were later found necessary to make use of GASP directly, this
would be accomplished simply by replacing reference to the
property formula by an appropriate call to GASP.

The property formulae required would be of the form:

o   density = function (pressure, enthalpy),

o   viscosity= function (pressure, enthalpy),

over the ranges of pressure and enthalpy required. The
'formulae' could be either algebraic expressions deduced
by curve fitting, or tabulations with interpolation. In
either case the formulae would be provided in CATHY3/M,
as function statements or subroutines, and would be
accessible for easy modification by a user.

It is understood that formulae of this kind deduced from
GASP are available from NASA, and that these are being
provided to CHAM. These will then immediately be introduced
into CATHY3/M as described above.

3.2   Graphics package

The MAPLP line-printer plot routine has been introduced into
CATHY3/M as required by the contract. Typical MAPLP plots
are shown in Figure 2, referred to in Section 2.

3.3   Documentation

The basic documentation of the mathematics and solution
method of CATHY3/M has been completed. This will be
supplemented during June and July by the User's Guide
providing extensive instructions on using the code.

4.   CLOSURE

The current estimate of contract completion is 38%, that is,
18% up to the end of April (already invoiced), and 20% for
May. An invoice is therefore being submitted for $10,381.20,
to give a cumulative total of $19,727.70 (ie 38% of $51,915.00).

The immediate plans for the individual tasks have been
discussed above. In summary, the current plans call for:

o   Completion of code and manual by end July.

o   Delivery of deck and manual to MSFC at end July.

o   Provision of 'sustaining engineering' at MSFC by
      Dr D G Tatchell during August. (The plan is to
      provide the first week at the beginning of August
      and the second towards the end after MSFC personnel
      have had time to acquire experience of using the
      code).

It should be observed that delaying the sustaining engineering into August (as already agreed with Mr Glenn E Wilmer of MSFC during discussions) requires a short no-cost extension to the present contract. It is understood that this is already being arranged.

6.   REFERENCES

1.   Letter from Glenn E Wilmer of MSFC to David Tatchell of CHAM Limited, 14 June 1978, and accompanying drawings.

2.   Letter from Glenn E Wilmer of MSFC to David Tatchell of CHAM Limited, 10 April 1979, and accompanying figures.

Yours sincerely,

David Tatchell

David G Tatchell
Deputy Managing Director

Distribution: AP 29F
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                 EM63-13
                 EP23/Wilmer

11th July 1979

CHAM Ref: 1712/H3082

National Aeronautics and Space Administration
George C Marshall Space Flight Center
Marshall Space Flight Center
Alabama 35812
U S A

To whom it may concern

Re: Contract NAS8-33090

This letter is the progress report on the above contract for
the month of June 1979.

1.   INTRODUCTION

The last report, dated 6 June 1979, reported that:

(a)   CATHY3/M had been applied to a simplified impeller,
      (referred to as Test Case 1) with blades radial and
      normal to the hub, and hub and shroud surfaces forming
      circular arcs in a plane cut through the axis of
      rotation.   Converged, plausible results had been
      obtained for a coarse grid (5 x 5 x 5) both with
      and without rotation.

(b)   Work was just beginning on Test Case 3, the final
      test-case geometry, but without partial blades.

(c)   The two-pressure method for handling compressibility
      and cavitation had been completely coded.   Tests
      were planned to begin in June.

(d)   The MAPLP line-printer plot routine had been intro-
      duced.

(e)   The basic documentation of the mathematics and
      solution method had been completed.

During June, the main activity has been performing runs for
the test-case impeller, as in (b) above.   This work is des-
cribed in Section 2 below.

Work is only just starting on the testing of compressibility and cavitation (item (c) above). The start on this was delayed by the additional effort made to improve convergence rate for the test-case-impeller runs (as reported in Section 2). There is therefore nothing new to report on this.

Other related work is reported in Section 3. This is the application of CATHY3 to an impeller geometry for which measurements are available. First results, given in Section 3, show good agreement with data for velocity and pressure distributions.

Finally, Section 4 quantifies progress to date, and outlines plans for completion. The references are given in Section 5.

2.   CALCULATIONS FOR TEST-CASE IMPELLER

This work continues that reported in Section 2 of the 6 June report.

2.1 Modifications to the test-case specification in the 6 June report

Since the last report, the Test Case 3 specification has been reconsidered, and modified as follows:

(a)   The inlet axial velocity has been reduced from 484 m/s to 80.7 m/s. This is because the higher value used earlier was based on the wrong understanding that the specified flowrate (Reference 1) applied to a single impeller passage, not to the whole impeller, as intended.

(b)   The outlet pressure distribution is now allowed to vary in the circumferential direction, to correspond to a balance of pressure and Coriolis forces. (This is effectively assuming that the flow exits perfectly radially). The formula used is:

$$\left(\frac{1}{R}\frac{\partial p}{\partial \phi}\right)_{exit} = -2\Omega\rho\overline{w}_{exit} \qquad (2\text{-}1)$$

where p is pressure, ϕ is angle in circumferential direction, R is radius from rotation axis, Ω is rotational speed of impeller, ρ is density, and $\overline{w}_{exit}$ is mean outlet velocity.

The following observations can be made on the above practice:

(i)   The new practice was introduced because earlier results (eg. those shown in the 6 June report) showed large changes in flow near exit, associated with the outlet boundary condition then used of uniform pressure. Results with the new boundary condition appear much more realistic.

    (ii)   In reality, the actual exit pressure variation is likely to be neither uniform, nor that given in eqn (2-1), but somewhere between. Consequently, provision is made in CATHY3/M for multiplication of the right-hand side of eqn (2-1) by a user-specified factor, which can be chosen to have any value between zero and unity. This allows the complete range of possible outlet conditions to be investigated.

(c)   The angle between the blades is now reduced from 60° to 20°. The latter corresponds to the angle between the first and second partial blades in the MSFC specified impeller. Thus, the calculation is being performed in an imaginary passage, formed by extending the partial blades back to inlet. This, it is thought, is more reasonable than solving for the full passage with partial blades removed, because the absence of the partial blades will lead to substantial flow separation, not present in the real case.

(d)   For Test Case 3 runs, the circumferential velocity* at inlet (u_{in}) is set equal to:

$$u_{in} = \Omega \overline{R}_{in} - w_{in} \qquad\qquad (2-1)$$

where Ω is rotational speed of impeller, R_{in} is mean radius at inlet measured from rotation axis, and w_{in} is axial velocity at inlet.

This corresponds to a flow angle upstream of the impeller of about 45°, as deduced from Reference 1, and ensures that the flow enters smoothly, parallel to the blades.

Finally, as well as Test Case 3, a simpler geometry (Test Case 3a) has been considered. This differs from Case 3 only in that the blades are radial and normal to the hub. In this case, the inlet circumferential velocity, u_{in} is set to zero to give inflow parallel to the blades.

2.2 Improvements to the rate of convergence

Two detailed changes have been made to the CATHY3/M solution procedure to improve the rate of convergence; namely:

●   When pressure-corrections are solved for at a slab, the line-by-line procedure now uses most recent values for off-line quantities, rather than results from the previous pressure-correction iteration as is usual in an alternating-direction implicit (ADI) procedure. This substantially speeds up convergence of the iterations on pressure correction at each slab.

---

* In the rotating coordinates used in CATHY3/M.

- Velocities are now updated using a Jacobi point-by-point procedure, rather than ADI as previously. This virtually eliminates the need for the heavy under-relaxation used previously, and accelerates overall convergence.

Without these modifications, Case 3a (with full rotation) required about 120 sweeps for full convergence (i.e. sum of absolute momentum errors less than one percent of inflow momentum; field values settled to less than one percent). With the modifications, only 30 sweeps are required for convergence to the same level.

2.3 Results obtained

In addition to the results for Case 3a (radial, normal blades) reported above, converged results have been obtained for Case 3 (full test-case geometry, with inclined, swept-back blades), with full rotation, both with and without wall friction. An annotated output (one copy only) showing the final results is being provided to MSFC with this report.

Convergence for this case requires about 30 sweeps. Five iterations are performed at each slab. These are required because of the non-linearities arising from the high degree of grid non-orthogonality associated with the swept back blades. In contrast, for Case 3a, with radial blades, only one iteration at each slab is required.

The Case 3 solution requires about 45 minutes on the CHAM Interdata 7/32, which is equivalent to about 30 seconds on a CDC 7600.

3. OTHER RELATED WORK

In connection with a forthcoming publication, preliminary results have been obtained for comparison with the data of Mizuki, Ariga and Watanobe (Reference 2). These are summarised below:

Geometry: Hub and shroud surfaces as in Figure 1. Blades radial and normal to hub; blade-to-blade angle 30°.

Flow conditions:
- Rotational speed 6000 rpm.
- Inlet velocities: $w_{in}=34m/s$

$$u_{in}= -\Omega \overline{R}_{in}$$

$$v_{in}=0.$$
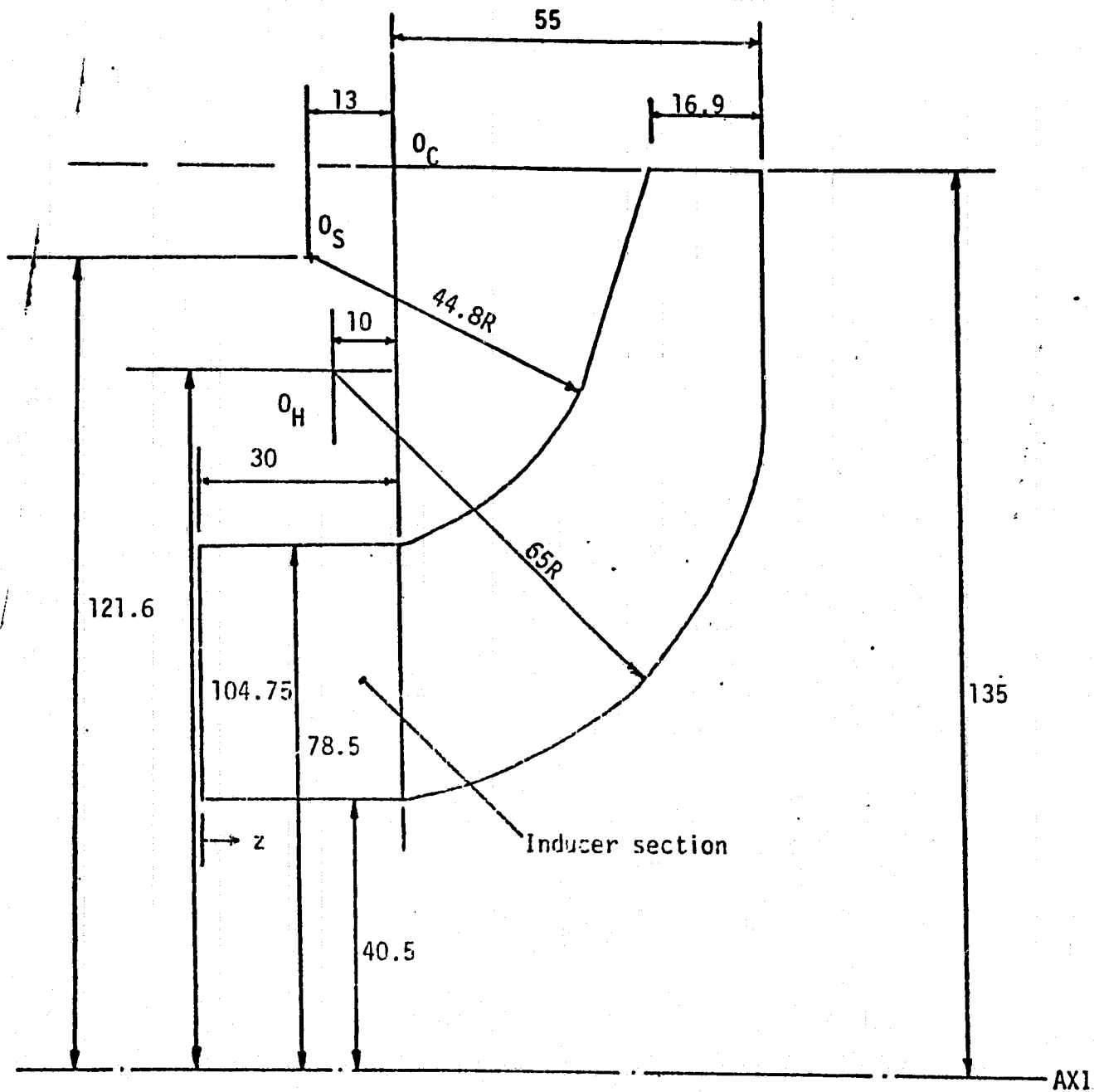
- Outlet pressure variation from equation (2-1).

Figure 1: Geometry for B-type impeller of
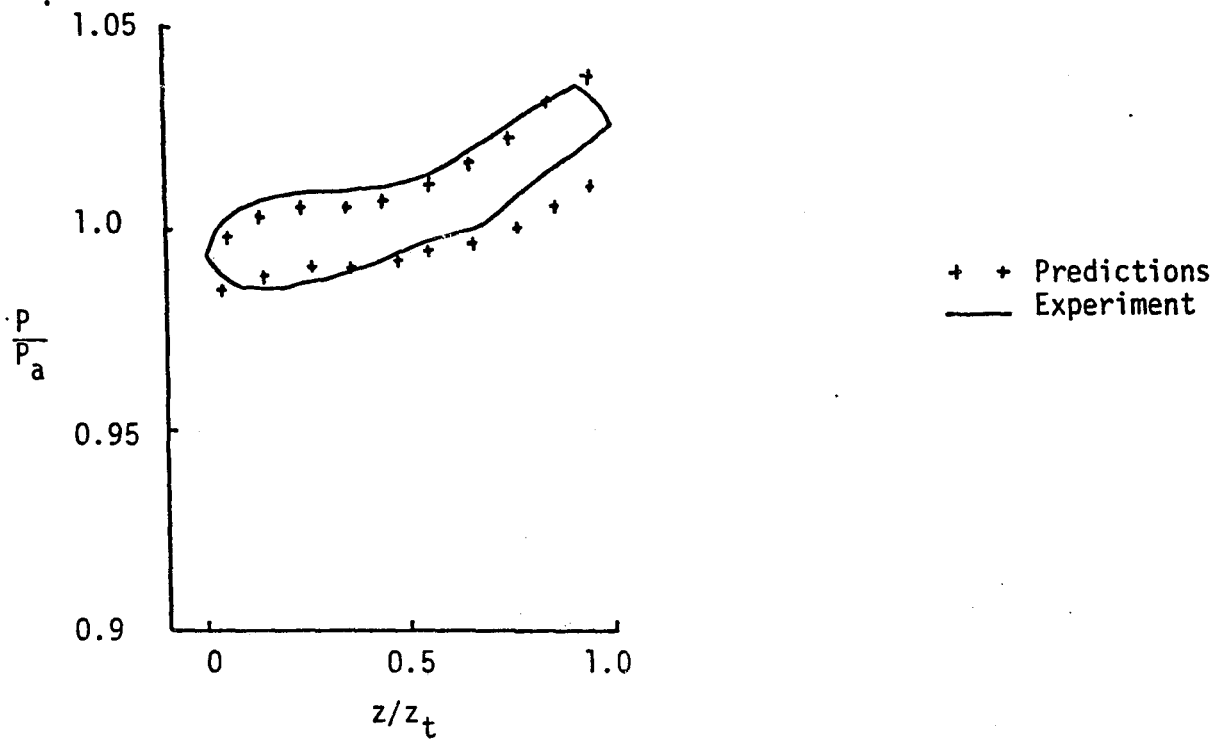Mizuki et al (1974) - dimensions
in mm

Figure 2: Pressure and suction surface pressure distributions on the shroud
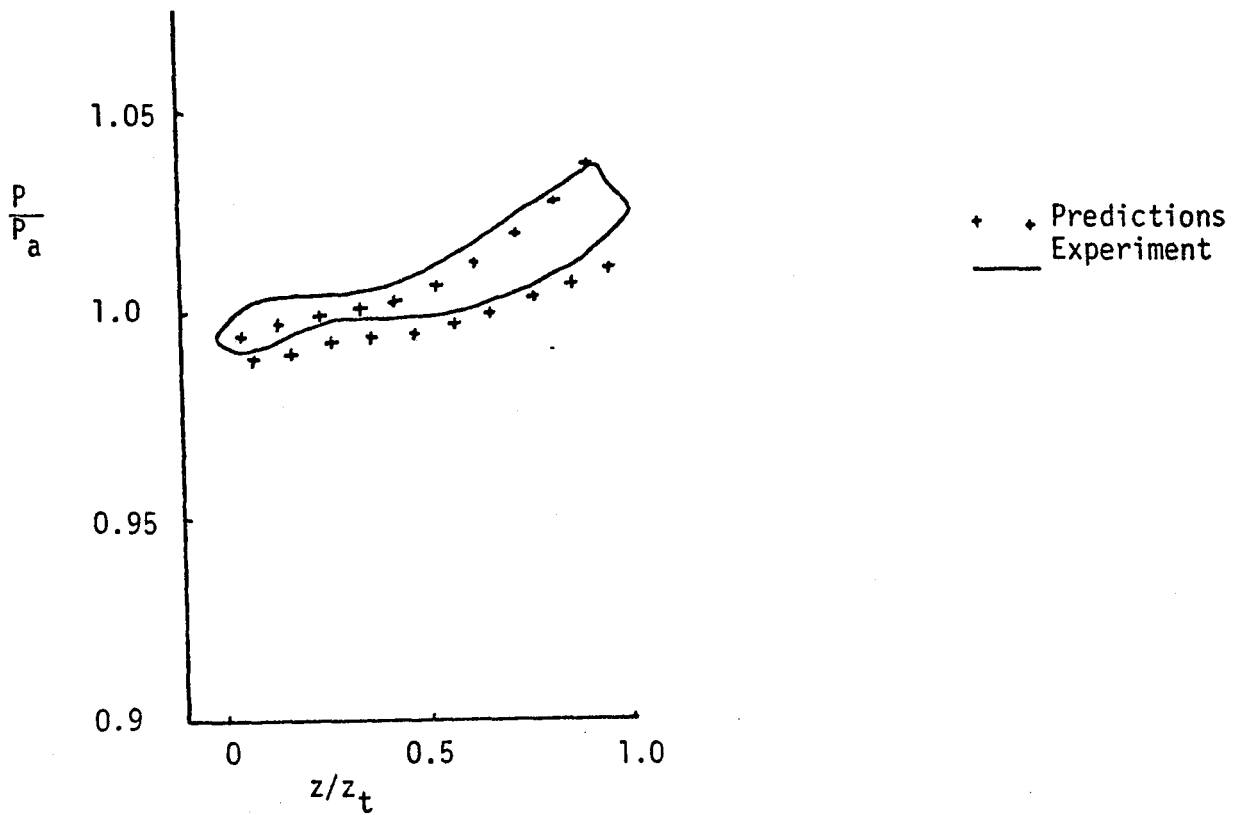

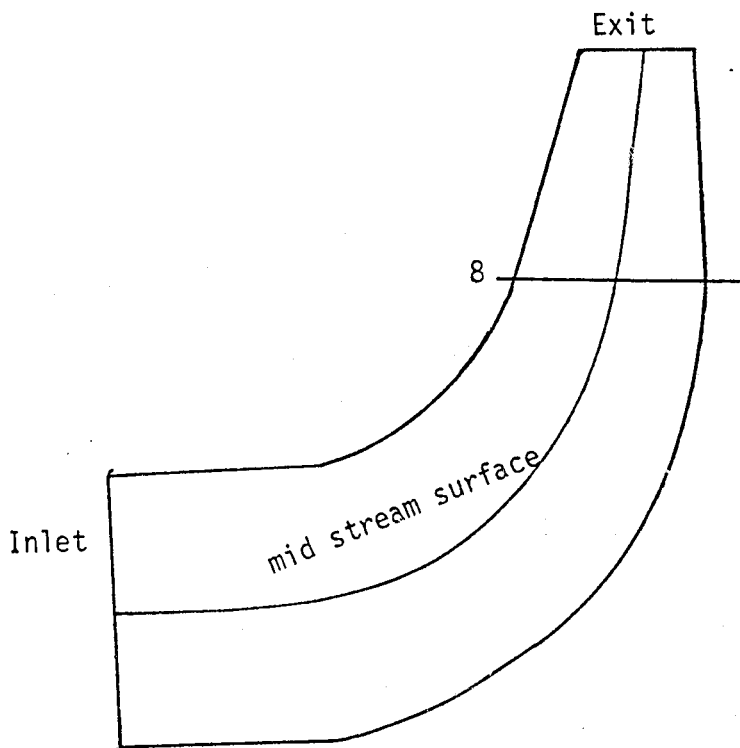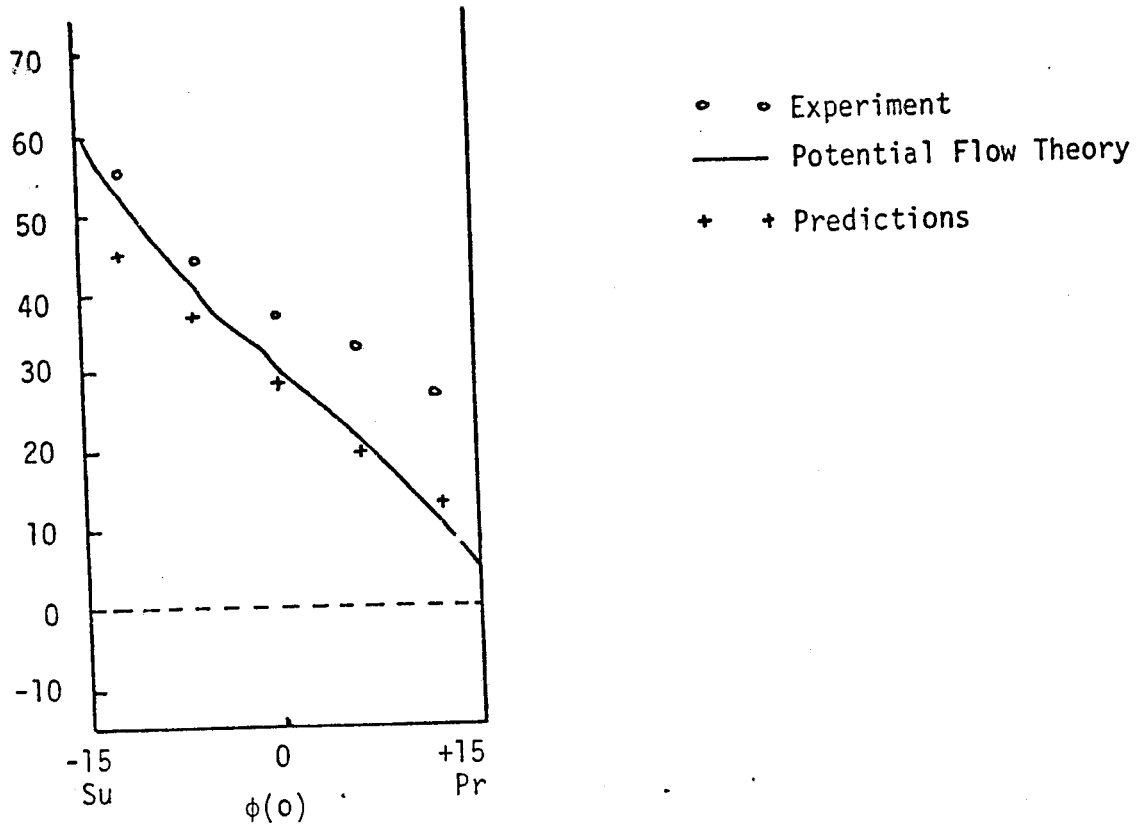Figure 3: Pressure and suction surface pressure distributions at the hub

Figure 4: Meridional velocity at flow station No. 8 at mid-section
(i.e. mid way between hub and shroud)

-8-

Properties:
- Density ρ = 1.241 kg/m^2
- Laminar viscosity μ = 1.773.10^{-5} Ns/m^2
  (Above as for air at NTP).
- Turbulent viscosity μ_t taken uniform, =0.027 Ns/m^2

Grid: 5 x 5 x 10 (radial x circumferential x longitudinal), uniformly spaced.

Convergence: 30 sweeps, one iteration at each slab.

Results:
- Figures 2 and 3 show predicted pressures (normalised with p_a, atmospheric pressure) at the pressure and suction surfaces, on the hub and shroud. The figures show the variation from inlet (z/z_t=0) to outlet (z/z_t=1.0).

- Generally, agreement with the data is good. The overprediction of the pressure-to-suction pressure difference near to outlet is probably associated with the use of the full pressure variation given by eqn (2-1) as the exit condition. As was remarked earlier, this will tend to overestimate the outlet pressure difference, and ought probably to be reduced by some fraction.

- Figure 4 shows the variation of meridional velocity (w) between suction and pressure surfaces, at a location more than half way through the passage. The results compare fairly well with the potential flow results (indicating that viscous effects are not dominant for this particular set of conditions), and show roughly the same profile shape as the measurements, but at a lower velocity level.

- In general, the agreement between the preliminary, coarse-grid, predictions of CATHY3 and the data is encouraging.

4. CLOSURE

The current estimate of contract completion is 58%; that is, 20% completed during June. An invoice is therefore being submitted for $10,383.00, to bring the total up to $30,110.70 (i.e. 58% of $51,915.00).

It is planned that code and manual will be completed by the end of July. The tasks involved are:

- Running Test Case 3 for finer grid.
- Introduction of partial blades, and running full impeller.
- Testing of compressibility and cavitation.
- Running full test case, with compressibility and cavitation.
- Completing documentation.

The code and manual will then be delivered to MSFC at the end of July, and the sustaining engineering provided during August as outlined in the 6 June report.

5. REFERENCES

1. Letter from Glenn E Wilmer of MSFC to David Tatchell of CHAM Limited, 10 April 1979, and accompanying figures.

2. S Mizuki, I Ariga and I Watanobe. 'Investigation concerning the Blade Loading of Centrifugal Impellers'. ASME Paper Number 74-GT-143, 1974.

Yours faithfully,

David G Tatchell
Deputy Managing Director

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CHAM REF: 1712/H3082

August 12 1979

National Aeronautics and Space Administration
George C Marshall Space Flight Center
Marshall Space Flight Center
Alabama   35810
U S A

To whom it may concern

Re: Contract NAS8-33090

This letter is the progress report on the above contract for the month of
July 1979.

1.   INTRODUCTION

The last report, dated July 11 1979 reported that:

a)   The CATHY3/M code was running successfully for a coarse (5 x 5 x 5)
      grid for Test Case 3, (based on the final test case geometry, but
      without partial blades).

b)   Work was just starting on the testing of compressibility and
      cavitation.

c)   It was planned to complete the code testing and the users' manual
      by the end of July, and to provide the sustaining engineering
      during August.

The current situation is as follows. The code assembly and testing was
completed during July. The code was delivered to MSFC in card deck
form on August 6, and has now been successfully acitvated on the MSFC
UNIVAC 1108. The users' manual has been completed, and was delivered
in draft form on August 6. The final typed version will be supplied
during the week 14 to 18 August. The sustaining engineering is
currently being provided by Dr D G Tatchell of CHAM Ltd at MSFC.

Continued.....

Section 2 below summarizes the work performed during July, and Section 3 quantifies progress to date and outlines plans for completion. The references are given in Section 4.

2.   PROGRESS DURING JULY

During July, the following tasks were performed with the CATHY3/M code.

(i)   The cavitation treatment was activated and checked. This was done for Case 3a, as defined in the July 11 report. (Case 3a is Case 3, with radial blades). The details of the density calculation sequence are given in the users' manual (Malin et al, 1979). To test the treatment, an artificial density~pressure relationship was provided with (in the notation of Malin et al):

p_A = 2.5 10^5 N/m², ρ_A = 70.41 kg/m³, p_B = 2.3 10^5 N/m²,

ρ_B = 0.7041 kg/m³, and ρ_C = ρ_A.

These values were chosen: to arrange that liquid density ρ_A (= ρ_C) corresponded to inlet density already in use; to ensure that cavitation occurred for the conditions considered (ie that pressures of less than p_A occurred); and to provide a severe test of convergence, by imposing a very abrupt density variation between p_A and p_B.

The two pressure method by which compressibility and cavitation are handled has been described in the April 23 progress report and is also described by Malin et al. In the tests performed during July, the density was adjusted every two sweeps, and was underrelaxed by a factor of 0.1. Convergence was obtained in about forty sweeps. The results were plausible. A small cavitated region was located near to inlet (ie at slab IZ=1) at the suction-hub corner.

(ii)   Partial blades were introduced and tested. How partial blades are input and treated is described by Malin et al. The case considered was as for Case 3 (ie with inclined,swept-back blades as in the final test case), with a total blade-to-blade angle of 35°, with one partial blade located at ϕ=20°, extending from outlet, to θ=18° (ie 18°, or about 20% of passage length downstream of inlet). Convergence was obtained within about forty sweeps, as usual.

(iii)   The final test case was set up and run. The geometry is that defined by Wilmer (1978), and includes three partial blades. The grid used was 5 x 12 x 9 (radial x circumferential x longitudinal). The full conditions are given in Section 7 of Malin et al. 52 sweeps were run, at which stage good convergence had been achieved. The predicted pressures showed no cavitation (ie all pressures above saturation pressure at inlet entrapy), but this may be due to the outlet pressure prescribed by Wilmer/ (1979) being too high.

The results for this case have been delivered to MSFC, and have been reproduced on the MSFC computer. Additional runs are now in progress, including ones with lower, more realistic prescription of outlet pressure.

In addition to the above, during July the users' manual (Malin et al, 1979) was written, and typing was started. The final version will be delivered to MSFC by August 18.

3.   CLOSURE

The current estimate of contract completion is 88%; that is, 30% completed during July. An invoice is therefore being submitted for $15,574.50 to bring the total up to $45,685.20 (ie 88% of $51,915.00).
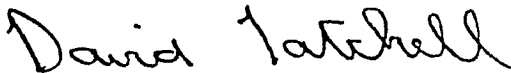
It is planned that the bulk of the sustaining engineering will be provided during August. The project final report will then be provided.

All contract requirements will then have been satisfied, except that one or two man days of sustaining engineering will remain. These are to be held back, at MSFC's request, to allow advice to be obtained as required during the first few months of use of the program.

4.   REFERENCES

1.   Malin M R, Rosten H I, and Tatchell D G (1979)
       "The Users' Manual for the CATHY3/M Program"
       CHAM Report 1712/1.

2.   Wilmer G E (1978)
       Letter to D G Tatchell of CHAM Ltd, and accompanying drawings.

3.   Wilmer G E (1979)
       Letter of D G Tatchell of CHAM Ltd, and accompanying figures.

Yours sincerely

David G Tatchell
Deputy Managing Director

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