TURBOMACHINERY

ANNUAL REPORT

J. C. Vrana

Memo 70 - 6 November 20, 1970

Memo 70-6 November 20th, 1970

TURBOMACHINERY

Annual Report

Work has been done in the following areas:

1. Linear Turbine
   a) Analysis
   b) Bucket flow model
   c) Demonstration model of a linear turbine

2. Three-dimensional compressible viscous flow in turbomachinery

3. Consultations with
   a) Brace Research Institute
   b) Canadian Transport Commission
   c) United Aircraft of Canada Ltd.
   d) Allis Chalmers

1. The Linear Turbine (See Appendix of Attachment 1)

1. a) The components of power transfer and loss have been set down and qualitatively formulated for eventual integration into a computer program. It appears that 50% reaction, and flow angles to the rail face in the range 90° to 60° at inlet and 30° to 15° at exit will be best for fully guided channels in the rail and in the re-entry assembly. For open buckets in the rail, which low cost may dictate, the reaction can only be some 10% or so, and the performance becomes strongly dependent upon the losses associated with flow in an open bucket (i.e. a bucket lacking a "suction side" boundary.) Little documentation of relevance has been found so that a test program has been initiated to study the flow and losses in open buckets for linear turbine rails.

1. b) Bucket Flow Model tests will be carried out on an array of 3 buckets made of transparent plastic and measuring about 1" by 4 1/2", opening dimensions. Angles of 50° and 35° at inlet and exit respectively, and a decreasing curvature from inlet to exit are expected to turn the flow with low mixing losses at the free boundary, low secondary losses in the stream, and good incidence range at inlet.

1. c) A 4th year Design II Group is building a demonstration linear turbine powered by vacuum-cleaner blowers and intended to run at 30 mph on a circular track.

2. Three-dimensional compressible viscous flow in turbomachinery. (See attachment #2.)

It has been clear for some time that relatively crude but realistic representations of the flow in a channel yield good engineering results, as opposed to refined analysis where significant phenomena are left out of the model as being "intractable". Thus secondary flows, Coriolis actions on sheared flows, and boundary layer mainstream stability interaction are usually ignored in turbomachinery computations.

It is proposed, and initial steps have been taken, to collaborate with Prof. J.H.G. Howard of Waterloo on the elaboration of a more complete yet tractable flow analysis program yielding outputs about as shown on Fig. I of Attachment 2.

3. Consultations.

3. a) Prof. R. E. Chilcott and one of his students have referred some aeroelastic problems on their Wind Turbine to us.

3. b) A brief note on Propulsion of High Speed Ground Vehicles was prepared for the Canadian Transport Commission.

3. c) Consultations with the Aerodynamics Department of United Aircraft of Canada Ltd. related to radial turbines.

3. d) Consultations with the Compressor Engineering group of Allis Chalmers related to the design of centrifugal compressors.

Propulsion of High Speed
Ground Transportation Vehicles

A brief technical note prepared
for the
Canadian Transport Commission
at the
request of Mr. Martin Brennan

July 18, 1970.

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July 18, 1970.

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Propulsion of High Speed Ground Transportation Vehicles.

As vehicle speed and acceleration requirements increase, so does the proportion of direct operating cost chargeable to propulsion. In addition, much of the noise and pollution generated, and some of the right-of-way costs are related to the means of propulsion. Hence the importance of a thorough understanding of the means of propelling the fast vehicles being considered for interurban and suburban public ground transportation systems. Urban tracked systems will generally be slower and have a high traffic density. Under these conditions the electrified rail, wheeled vehicle system is satisfactory and practical. Under conditions of greater distance between stops and of lower traffic density, such as would be encountered on suburban and interurban links, a number of other alternatives present themselves requiring further study. In progression of decreasing right-of-way costs, we have*

1) the linear electric motor with windings on the track

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* Tube systems of various kinds are under study, but tunneling costs are prohibitive for the next decade or two at least.

2) electrified track and on-board electric motors,

3) autonomous vehicles developing their own power.

The first is clearly not suitable for the low traffic densities outside city hubs, being more expensive than electrified track. It may however prove to be the best form of propulsion for an urban system, perhaps used in conjunction with an electromagnetic suspension and entirely passive vehicles. Table I presents the spectrum of propulsion schemes possible with the second and third alternatives above. These need to be considered in relation to the characteristics of the vehicle suspensions and powerplants. Very briefly, wheels have good load carrying ability but require fine track alignment at high speeds; whereas air cushions and electromagnetic suspensions consume power in proportion to vehicle weight. Electric motors, generators, fuel cells and internal combustion engines are heavy. Gas turbines are light, but consume more fuel than diesel engines or fuel cells.

One may conclude, therefore, that electrified track will serve mostly wheeled vehicles, with the possible exception of the tracked air cushion vehicle with linear electric motor propulsion. Potentially low noise, zero pollution, low power costs, but relatively expensive track are characteristic of electrified track vehicles.

Autonomous vehicles, on the other hand, may be practical over the whole range of Table I. The conventional bus, sharing the road with private automobiles, will continue to be developed, and it provides a basic standard of comparison. A gradual switch to gas turbine power will begin in the mid 1970's. For tracked (guided) vehicles, heavy powerplants will tend to be confined to wheeled suspensions, whereas the gas turbine will be preferred for air cushion suspensions. The advantage of these is that the track need not be accurately smooth, and so mechanical traction through wheels on the main track must be discarded, in spite of its high efficiency. A separate rail would allow mechanical traction, possibly combined with lateral guidance. This straightforward scheme deserves further attention.

A separate rail can also be the passive element of a linear induction motor, and this scheme is under active development in the U.S. and in France.

Fluid momentum thrust is being used on the larger demonstrator tracked air cushion vehicles, but as Table I and Figure 1 show, fans are a poor solution because of poor acceleration, noise and fuel consumption; whereas propellers require a large frontal area if they are to give a reasonable acceleration.

The linear fluid motor or linear turbine is analogous to the linear induction motor: both require a special rail, comprising aerodynamic blades or buckets in the case of the linear turbine. It will be capable of good gas HP to thrust HP propulsive efficiency, and is being developed in France and in Canada (see Appendix). The linear turbine would appear to be a good choice for gas turbine powered T.A.C.V.'s, whereas the linear induction motor would seem best on electrified rail. Indeed, the conversion of the gas HP of a gas turbine to shaft HP to KW to thrust HP in a linear induction motor incurs unjustifiably low efficiency and high weight to be seriously considered.

In conclusion, then,

a) wheel traction is the most efficient and deserves further attention for all tracked vehicles,

b) linear induction motors should be considered for electrified track only,

c) direct fluid momentum thrust has drawbacks, and

d) the linear turbine appears promising.

TABLE I

Propulsion for High Speed Ground Transportation Vehicles.

	Mechanical		Fluid			Electromagnetic
	Wheel		Momentum			
	steel	rubber	Fan	Prop	Linear Turbine	Linear Induction Motor
Propulsive efficiency, % (at 200 mph)	99.9	96 to 99	40 to 50	70	75	50 to 80
Cost (including track)	expensive	moderate	low	low	moderate	moderate
Noise	noisy	tolerable to quiet	noisy	potentially quiet	potentially quiet	quiet
Acceleration	good	excellent	poor	acceptable	acceptable to good	acceptable to good
State-of-the-art	primitive	developed	needs operational development	needs design & dev't for low noise	in the laboratory	prototypes on test
Remarks		good	noise and jet blast unavoidable	frontal area requires more clearance	good	

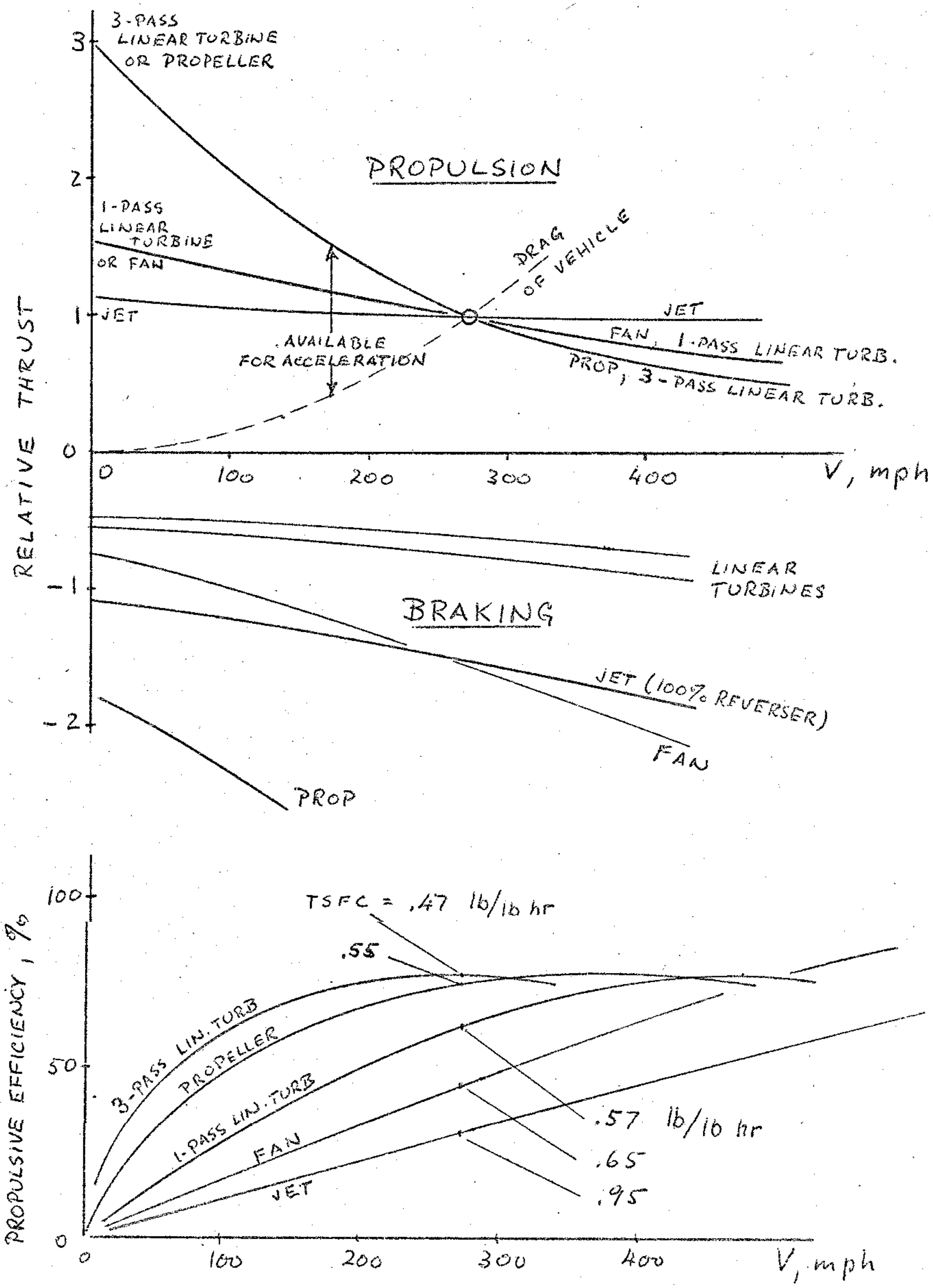
3-PASS LINEAR TURBINE OR PROPELLER
PROPULSION
1-PASS LINEAR TURBINE OR FAN
DRAG OF VEHICLE
JET
AVAILABLE FOR ACCELERATION
FAN, 1-PASS LINEAR TURB.
PROP, 3-PASS LINEAR TURB.
RELATIVE THRUST
V, mph
LINEAR TURBINES
BRAKING
JET (100% REVERSER)
FAN
PROP
TSFC = .47 lb/lb hr
.55
3-PASS LIN. TURB
PROPELLER
1-PASS LIN. TURB
FAN
JET
.57 lb/lb hr
.65
.95
PROPULSIVE EFFICIENCY, %
V, mph

FIGURE 1

APPENDIX

The Linear Turbine

Sketch VSK 3001 shows two forms of linear turbine currently under development.

The first, proposed to the U.S. Office of High Speed Ground Transportation(1) and conceived by Bertin & Cie in France, operates on the principle of recovering the excess kinetic energy of the propelling flow by means of a track-mounted cascade, which returns the flow into a vehicle-mounted exhaust unit. The latter generates an additional thrust and decreases the exhaust velocity. As proposed, no special guidance for the turbine assembly was contemplated, resulting in large gaps between components and dictating a constant static pressure from the nozzle on. Under these conditions, high noise and low peak efficiency can be expected. Furthermore, while a fan engine was contemplated as a source of flow in the reference, here all systems are

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(1) PB 183-314 F.L. Giraud, "A Preliminary Design Study of a Tracked Air Cushion Research Vehicle" Feb 1969, Aeroglide Systems Inc, 120 Broadway, New York, N.Y. 10005, for the U.S. Dept. of Transportation. Contract No. 7-35337. See pp 63 et seq.

compared on the basis of a gas generator[1] followed by at most two energy converters (turbine plus fan or propeller; linear turbine; or plain nozzle). Under these conditions the single-pass linear turbine only reaches peak efficiency at speeds well above the 250 - 300 mph range of interest.

The second linear turbine on the sketch was conceived in an attempt to overcome the above objections. Instead of being rigidly mounted on the vehicle, it is held in close register to the reaction rail and is allowed some freedom of motion relative to the vehicle. Thus, the cascades need not form a pure velocity-staged constant-pressure Curtiss-style turbine, nor do mixing losses at the clearances have to be large. Furthermore, more than one pass becomes feasible (thus extending the peak efficiency down to speeds of interest), gas velocities can be lower throughout and muffling of the exhaust is possible for a low noise output.

A rugged, low-cost reaction rail was considered necessary as well. Precast Portland cement concrete is the basic

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(1) The gas generator considered for the fuel consumption estimates of Figure 1 would have the following performance:

Specific power	129	Gas HP/(lb/sec)	
Specific thrust	65	lb/(lb/sec)	(C_v = .98)
Fuel consumption	.48	lb/Gas HP hr	
	.95	lb/lb hr	(C_v = .98)

material envisaged for the rail, except at stations, where protracted exposure requires heat-resistant material. This linear turbine is at an early stage of development at McGill University.

Little is known of the status of the Bertin & Cie linear turbine except that full scale demonstrator trials were intended for 1970 one year ago. No major technical problems should be encountered, but noise, efficiency and reaction rail cost could be improved.

The multiple re-entry linear turbine derives from a similar type of steam turbine blading, still marketed in its original (1920's) form by the Terry Steam Turbine Co. However, little has been done to develop the high efficiency potential of the configuration, and so conservative performance estimates are tabulated. There is reason to believe this will improve by about 10 percent with further aerodynamic development.

Depending on requirements, full-scale demonstrators could be operational by 1974 to 1978.

To form an idea of the size and weight of linear turbines, consider that the nozzle feed ducts on VSK 3001 correspond to tailpipes of jet engines delivering the desired gas horsepower

(or delivering 40% of the desired thrust). On this basis, then, the Bertin linear turbine assembly should be about half as bulky as its gas generator, and weigh about 1/3 as much. The multiple re-entry turbine should be of about the same bulk and from half to equally as heavy as its gas generator, depending on construction. A muffler would increase bulk and weight. However, certain track configurations where the exhaust can discharge into a trough or gutter may require little or no further sound reduction.

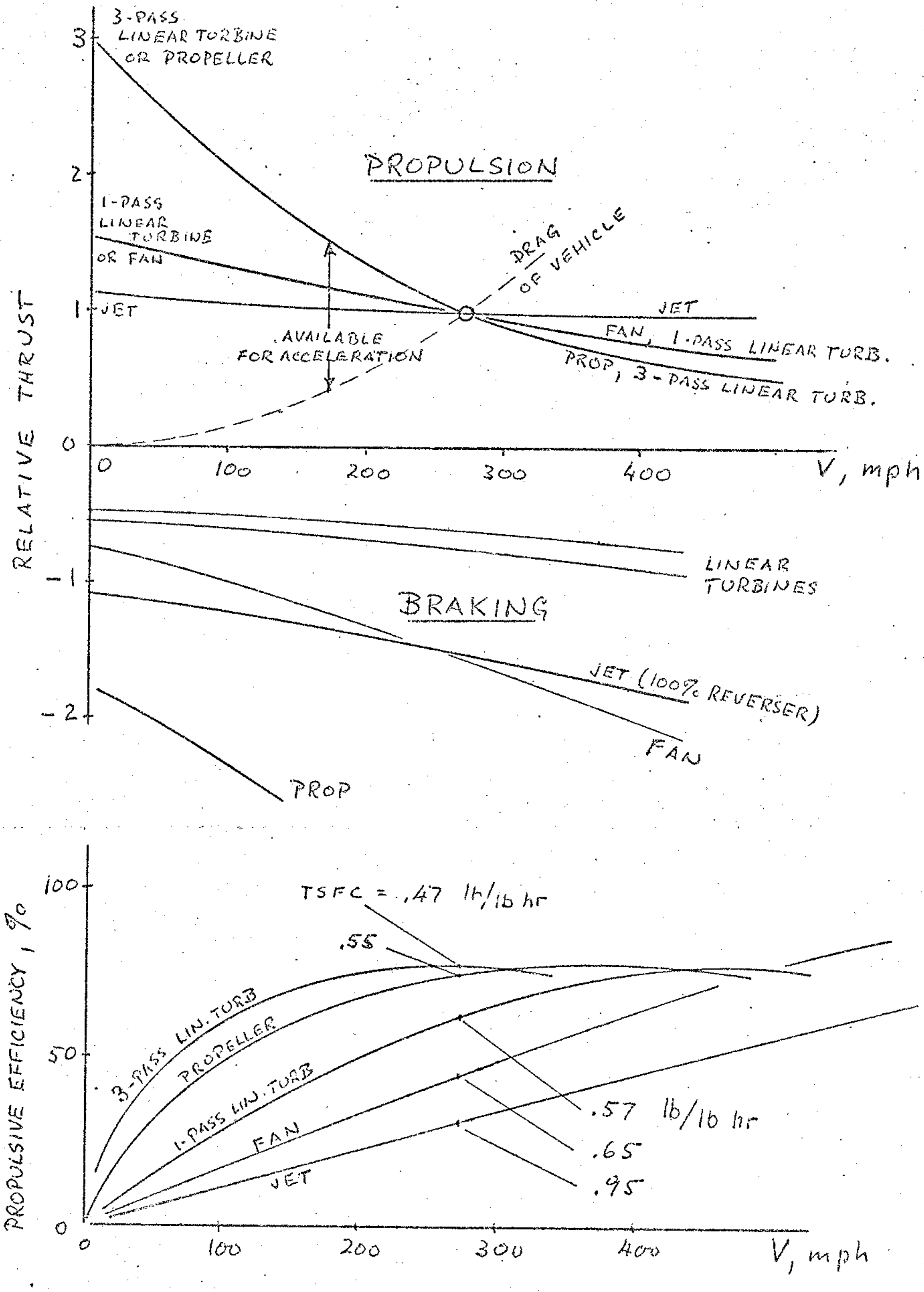
Table II presents the rough estimates that can be made about linear turbines from the available information.

TABLE II

Linear Turbine Parameters

Turbine type:		Velocity staged	Multiple re-entry
TSFC (1)	)at	.57 lb/lb hr	.47 lb/lb hr
SFC (Thrust HP)	)273	.79 lb/HP hr	.65 lb/HP hr
η	)mph	.61 (.75 at 480 mph)	.74 (.75 at 250 mph)
Cost: turbine		about \$25/HP	about \$50/HP
reaction rail		?	order of \$10,000/mi
Weight		about .05 lb/HP	about .10 lb/HP
muffler		.05 lb/HP	.05 lb/HP

(1) See gas generator performance in footnote on p A-2.


3-PASS LINEAR TURBINE OR PROPELLER
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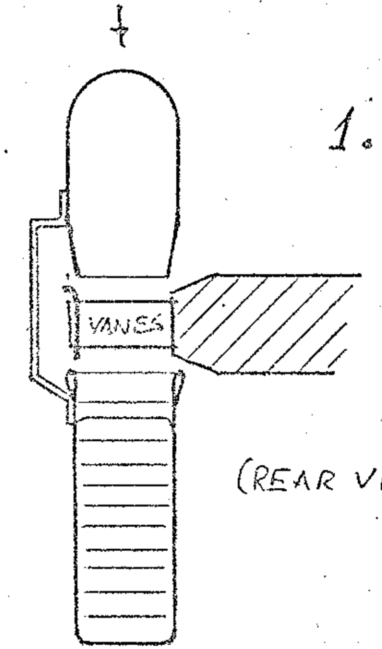
DRAG OF VEHICLE
AVAILABLE FOR ACCELERATION
JET
FAN, 1-PASS LINEAR TURB.
PROP, 3-PASS LINEAR TURB.
RELATIVE THRUST
3
2
1
0
-1
-2
0
100
200
300
400
V, mph
LINEAR TURBINES
BRAKING
JET (100% REVERSER)
FAN
PROP
PROPULSIVE EFFICIENCY, %
100
50
0
TSFC = .47 lb/lb hr
.55
3-PASS LIN. TURB
PROPELLER
1-PASS LIN. TURB
FAN
JET
.57 lb/lb hr
.65
.95
0
100
200
300
400
V, mph

FIGURE 1

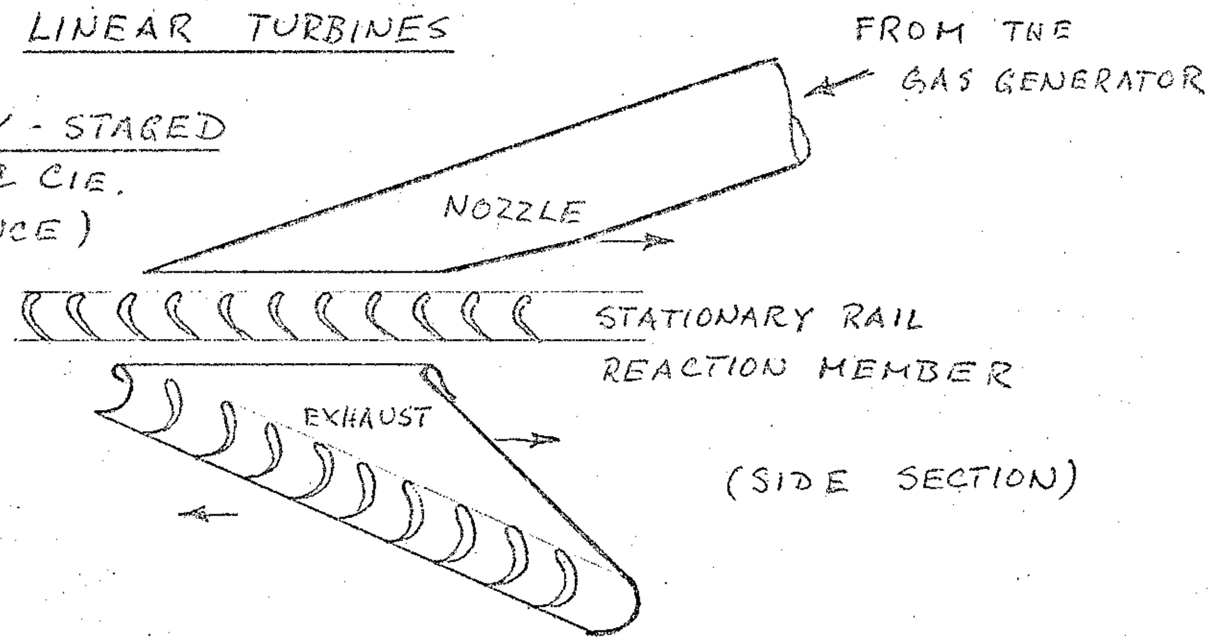
LINEAR TURBINES

1. VELOCITY - STAGED

BERTIN & CIE.
(REFERENCE)



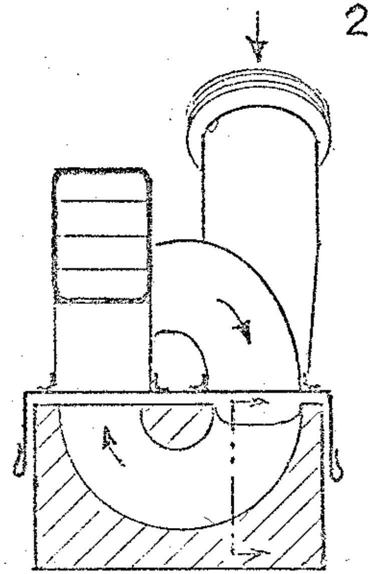
(REAR VIEW)

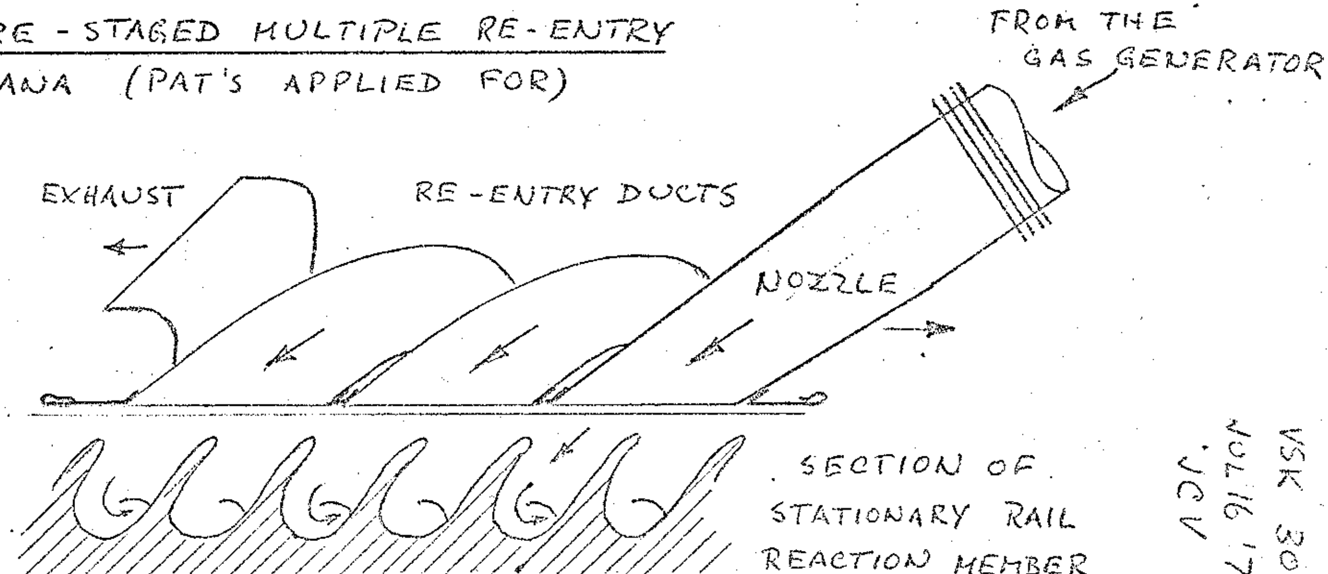


(SIDE SECTION)

2. PRESSURE - STAGED MULTIPLE RE-ENTRY

J.C. VRANA (PAT'S APPLIED FOR)





VSK 3001
JUL 16 '70
JCV

Some Outstanding Problems of the
Internal Aerodynamics of Turbomachinery

A brief note to the Subcommittee on
Internal Aerodynamics of ACOP,
September 25th, 1970.

J. C. Vrana

The airplane is today within 20% of the limiting performance predictable from aerodynamic theory. By contrast, turbomachinery exhibits inefficiency levels two or three times as high as can be accounted for theoretically. [1]

Whether improvements in the description and understanding of turbomachine flows will result mostly in an increased loss estimation rather than improved efficiencies is hard to decide at present, since the available flow analyses are all based on the neglect of evidently significant phenomena. Not only have we negelected so far to describe quantitatively such phenomena as streamtube rotation and its progress downstream of the blades, induced drag, unsteady interaction of blade rows, skew unsteady and corner boundary layers, rotating boundary layers, steady and periodic two- and three-dimensional separations, vortex roll-up at L.E.-annulus intersections, and tip clearance flows; [2] but in several areas even qualitative, descriptive material on which to build a theory is lacking. Nevertheless, we can today confidently envisage the task of providing the turbomachine designer with computer programs and graphic display terminals, giving him much the same interactive design capability as has been developed recently for aircraft designers. Consider for a moment the potential of a turbine stage design program for instance, displaying the information of Figure 1, and updating it rapidly in response to geometry changes as input with a light pen by the designer. Most but not all of the components needed to formulate such a program are available today. The purpose of this note is to draw attention to those areas most urgently requiring further effort.

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1. Appendix A to "Comments on Current Aerodynamic Design Problems of Gas Turbine Rotating Components," to the Turbine---Group of A.C.O.P., by J. C. Vrana, April 30th, 1969.
2. Rotor-stator casing boundary layers, development of secondary flow, curved and rotating boundary layers, rotor-stator wake transport, and 3-dimensional transonic (wave) solutions are now being successfully attacked.

Starting with items where even qualitative, "behavioral" data is meagre, we should investigate:

1) Tip leakage flow patterns and their interactions with casing and blade boundary layers. Flow visualization at reasonable Reynolds numbers should be carried out for several representative parameter combinations for each of

a) axial compressor rotor tip, clean inlet,
b) axial compressor rotor tip 2nd stage,
c) axial compressor stator hub,
d) axial turbine rotor tip,
e) centrifugal compressor, along the shroud,
f) radial turbine, hub and shroud, over a range of incidences.

2) Leading edge horseshoe vortex formation and development. The effects of inlet boundary layer skewness, of round fillets, of ridge-shaped L.E. fillets, and of incidence curvature and loading in the blading on the vortices should be studied visually.

3) The interactions of wakes and passage eddies from one blade row, with the flow field, shock waves and boundaries of the next blade row (in relative motion). These have not been observed except through measuring instruments. Some of the sketches in the literature purporting to explain unsteady lift noise and vibrations, and temperature field nonuniformity, are highly improbable. Photographic records of these unsteady processes would be invaluable. If possible, the effects on casing and blade boundary layers should be qualitatively described.

Further work of a quantitative nature would be useful on:

4) The effects of streamwise and normal Coriolis fields on blading and casing boundary layers and separations.

5) The behaviour of the wall shear coefficient C_f under unsteady conditions (tip leakage, blade row interactions).

6) The diffusion of vortex cores under varying boundary layer or other turbulence, and streamwise and cross-flow pressure gradients.

7) Decay of wakes containing shed circulation.

8) The behaviour of turbulent and transitional boundary layers under conditions of:

a) convergence on gently curved surfaces,
b) convergence in corners (similar and dissimilar layers),
c) crossing corners due to secondary flows.

9) The behaviour of transition under varying conditions of
   a) rotation, stagger and pressure gradient,
   b) spanwise flow and external flow disturbances,
   c) heat transfer.

The above list is not exhaustive, for all its length. Conversely, the importance or even the relevance of the subjects mentioned for further research may be questioned. It is nevertheless hoped that this input from a student of Turbomachinery may help the Subcommittee in steering research on Internal Aerodynamics towards the many unresolved and fascinating questions posed by flows in rotating machinery.

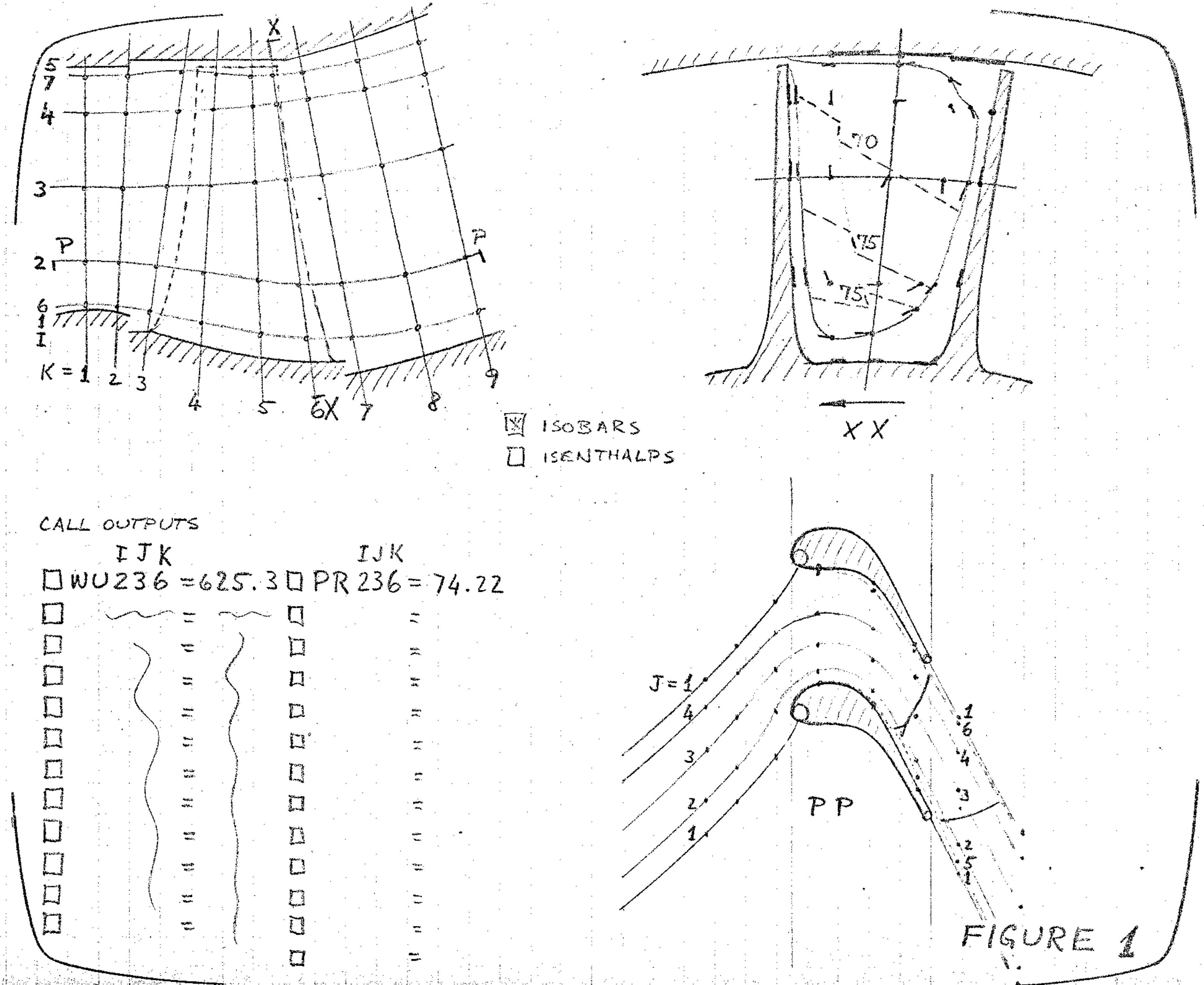
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FIGURE 1

We regret to inform you that Professor John C. Vrana died on January 4th, 1971.

Any correspondence or information may be requested from the secretary, Miss R. Curley or the Chairman, Professor B. G. Newman in the Department of Mechanical Engineering of McGill University, Montreal 110, Quebec.