PROJECT TUBEFLIGHT

SUMMARY OF RESEARCH AT RPI ON TUBEFLIGHT
TR PT 6801

SUMMARY OF RESEARCH AT RPI on TUBEFLIGHT

9 September 1966 - 9 November 1967

Prepared for the Office of High-Speed Ground Transportation United States Department of Transportation under Contract C-117-66 (Neg)

RENSSELAER POLYTECHNIC INSTITUTE Troy, N.Y. 12181

January 1968
PREFACE

This report is a summary of the researches performed at Rensselaer Polytechnic Institute during the period 9 September 1966 - 9 November 1967 under contract with the Office of High-Speed Ground Transportation of the United States Department of Transportation.

Studies under this program during the past year have focussed on the areas of Propulsion (Chapter I), inherent stability (Chapter II), stability augmentation (Chapter III), electrical power supply (Chapter IV), and small-scale experimentation (Chapter V).

Specific problems within each of these areas are discussed in detail in the technical reports which are listed in the Appendix. These reports are -- or will soon be -- available through the Clearinghouse for Federal, Scientific and Technical Information, 5285 Port Royal Road, Springfield, Virginia 22151.
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INTRODUCTION

Project Tubeflight deals with an intercity high-speed ground-transportation scheme that has been under study at Rensselaer Polytechnic Institute for several years. The scheme is one in which air-cushion-supported vehicles propel themselves in a novel way in nonevacuated tubes. The study was supported in part by the Army Research Office (Durham) during the period 1964-1964 and has been conducted, more recently, under a grant from the National Science Foundation and a contract with the Office of High-Speed Ground Transportation of the United States Department of Transportation.

Work on this project under the latter contract was started in December 1965. Its initial phase was a feasibility study, the results of which are presented in our first summary report [1].

During our second year under this contract, our effort has been aimed primarily at the determination of more precise quantitative information on the expected performance of various components of the system. The results of this effort are summarized in the following chapters and are presented in greater detail in the reports listed in the Appendix.

* Numbers in brackets refer to R.P.I. reports listed in the Appendix.
CHAPTER I

PROPULSION

I-1. Gasdynamics of internal propulsion. Power required.

In estimating the power requirements of tubeflight vehicles in the condition of matched internal propulsion, it seems reasonable to use the analytical model of a vehicle in steady level motion in a tube of infinite length and to treat the flow within the tube as steady in a coordinate system fixed to the vehicle. The validity of this approach has, however, been held in question until recently because of the unexplained results of two independent studies made in 1964 -- Ref. I-1, in which the problem was studied as an initial-value problem both ahead of the vehicle and behind it and the flow was treated as one-dimensional and viscous with an arbitrary schedule of heat transfer, and Ref. I-2, in which the same problem was treated in a two-dimensional linearized analysis.

Ref. I-1 revealed that over most of the subsonic range of travel speeds the only steady-flow solution of the nonlinear differential equations governing the flow downstream of the vehicle is one whereby the pressure behind the vehicle is everywhere equal to that of the undisturbed medium at infinity. Ref. I-2 produced the same result for all subsonic conditions, with an equivalent criterion for steadiness of the flow -- namely, that the nondimensional enthalpy and velocity perturbations behind the vehicle must be equal.

The same result has recently been obtained by J. Schmid in a linearized analysis (soon to be published) in which, following a suggestion of T. R. Goodman of Oceanics, Inc., the problem is treated in the subsonic case as a boundary-value rather than as an initial-value problem. In this approach the vehicle is represented by an actuator disc which introduces specified jumps of enthalpy and velocity, and the differential equations for the flow upstream and downstream of the vehicle are coupled through these jumps. The physical meaning of this result is that, within the approximation of the linearized theory, the flow relative to the subsonic actuator (or vehicle) cannot be steady unless the flow upstream of the actuator so adjusts itself to the specified jump that enthalpy and velocity perturbations on the downstream side of the actuator are equal. The unique condition for steadiness is likely to be modified by nonlinearities, but the essential fact remains that unless this unique condition is satisfied -- and there is no obvious reason for believing that it should -- the flow in the tube will be non-steady.* Since the pressure drag at subsonic and moderate supersonic speeds is always greater when the flow is nonsteady than when it is steady, and since flow fluctuations are also believed to increase the viscous stresses, an inherent nonsteadiness of the flow in the tube would have an adverse effect on power demands. An important question to be answered, then, is whether "nonsteadiness" in this situation is to be interpreted in the sense of finite-amplitude flow fluctuations or in the quasi-abstract sense of an

* No such difficulty arises when the travel speed is supersonic, because then a steady-flow solution exists no matter what flow conditions are specified as the set of initial values on the downstream side of the vehicle.
asymptotic approach to steadiness, whereby the steady-flow equations would never be exactly satisfied although the flow could be considered steady in a physical sense.

In order to answer this question, analyses were conducted by the reverse method of examining whether a trend toward steadiness could be recognized in the flow disturbances generated by a vehicle entering a long tube and traveling through it at constant speed. These analyses were carried out by the method of characteristics for nonsteady one-dimensional flow, with full consideration of dissipative and heat transfer effects. Ref. 1-3 considered internally-propelled vehicles traveling through tubes of varying lengths but revealed only a faint trend toward steadiness. A subsequent (unpublished) analysis by J. Burr and W. Webster examined the disturbances generated by a vehicle entering a half-infinite tube. The computations were carried through a distance of over 100 miles, at which point the calculated magnitudes in the neighborhood of the tube entrance became smaller than the round-off error of the computer. Up to this point no trend toward steadiness could be detected.

A different approach was suggested by the observation that the conservation equations relating flow conditions immediately upstream and immediately downstream of a tubeflight vehicle in the condition of matched internal propulsion are identical to those relating flow conditions on the two sides of a plane flame. It is possible, on this basis, to simulate the gasdynamics of the tubeflight scheme by those of a propagating flame. Since the amplitude of the disturbances is far greater in the case of the flame than in the case of an internally-propelled vehicle, the advantage of the simulation is to make the sought effects more easily observable. This simulation study was carried out (both theoretically, by the method of characteristics, and experimentally) by J. Skinner. The supersonic situation was studied first, as a test case, because it would permit direct comparison with the steady-flow solution, which, as has been noted, can always be obtained without difficulty. This analysis [2]* revealed that in the supersonic case viscosity and heat transfer have the effect of producing behind the flame (or vehicle) a region of steady flow, the extent of which increase continuously and indefinitely as time progresses. The variation of flow properties in the steady-flow region was found to be in perfect agreement with that obtained by D. Cromack, by steady-flow analysis, for the same situation [3], and the predicted behavior of the wake was also confirmed by experimental observations of the flow behind Chapman-Jouguet detonations in hydrogen-air mixtures [4]. Having thus established the validity and usefulness of the method, the analysis was extended to subsonic situations [5]. The subsonic vehicle was simulated by a heat source moving at constant speed relative to the tube wall. The analysis revealed that in this case, in contrast to the supersonic situation, viscosity and heat transfer cause the flow to be non-steady everywhere and to approach steadiness asymptotically over the entire flow field. It also revealed that velocity and enthalpy perturbations at fixed distances behind the flame approach each other very rapidly as time progresses, although it is not clear that their asymptotic distributions will necessarily coincide.

* Numbers in brackets refer to RPI reports listed in the Appendix.
These results have provided assurance that the flow relative to a tubeflight vehicle in the condition of matched internal propulsion in a very long tube can be treated as steady after all. The great wealth of available information on viscous effects and on the generation of drag in steady flow can therefore be used with confidence in the calculation of the propulsive power required in the tubeflight scheme. This calculation has been carried out by Foa [6] for a range of practical vehicle sizes, blockage ratios, and cruising speeds. Typical results are shown in Figs. I-1, and I-2, where $d_v$ and $d_t$ denote vehicle diameter and tube diameter, respectively, and $n$ is the passenger capacity of each vehicle. Also plotted in these figures, for comparison, is the calculated performance of the open-track UAC turbine-motor train TMT-5D (Ref. I-4), extrapolated to 160 mph. This train has a capacity of 232 passengers.

An important question that has so far been answered only partially is that of the effect of tube wall permeability on the performance of tubeflight vehicles. Wall permeability decreases the effective blockage ratio, hence both the frictional and the buoyancy drag, but it also makes it impossible to maintain a condition of matched internal propulsion. Low-speed experiments by Cromack [7] have revealed that with blockage ratios of the order of 0.5 the two effects practically cancel each other out over the entire range of permeabilities from zero (sealed tube) to 1.0 (open track). At higher speeds and with higher blockage ratios, when the transfer flow is choked, the net effect of permeability can be expected to be distinctly beneficial. Its actual magnitude, however, remains to be determined.


The bladeless fan is particularly well suited for application to tubeflight propulsion, not only because of its simplicity, low weight, low cost and safety, but also because it produces no reaction torque. Furthermore, its "blades" are always in sealing contact with the boundaries of the transfer passage, despite the freedom of transverse motion of the vehicle relative to the tube.

In this application, however, the operation of the bladeless fan is subjected to special constraints, of which the most critical ones are those which are imposed by the singular specifications of matched internal propulsion. Although the feasibility of bladeless propellers as thrust generators for tubeflight propulsion had already been established [1], detailed criteria remained to be developed for the design and control of these devices over the range of operating conditions that is expected to be of interest in this application. Furthermore, whereas the power demands of bladeless propellers had been compared with those of an arbitrarily selected family of conventional thrust generators, the comparison had to be extended to cover all existing or conceivable thrust generators for internal propulsion. These two extensions of the theory of bladeless fans were carried out by Foa [8]. The results provide, in the form of charts, the design and operating parameters that will satisfy the requirements of matched internal propulsion for any given vehicle at any given cruising speed. The results of the comparative analysis show that, with moderate and large spin angles, the power demands of bladeless propellers are competitive with those of conventional thrust generators in this application.
Fig. I-3.
Smoke tests in a cascade setup have revealed that it should be possible to design the primary discharge passages in such a manner that the deflection phase will be substantially completed before mixing begins. So far, however, this situation -- which is, of course, the most desirable one from the standpoint of energy transfer efficiency -- has been realized only in the wind tunnel and not in any of the rotors that have been tested in this program. The avoidance of bend-associated eddies in the emerging primary jets is, of course, far more difficult in a rotor than in a stationary wind-tunnel model.

Progress has been made in the design of a bladeless-propeller-driven vehicle (Mark IV). In this vehicle, a single compressor supplies all the air for support and propulsion. The tail end of the vehicle is shown in Fig. I-3. The rotor is of a special type, proposed and designed by W. Webster, that permits continuous adjustment of the spin angle. Fig.I-4 shows the shape of the primary orifices when the spin angle is 30°.

I-3. References


Fig. I-4.
II-1. Introduction

In order to estimate the inherent stability of tubeflight vehicles it is necessary to have adequate knowledge of the aerodynamic characteristics of their support system. Much attention has been given to studies of such characteristics for typical ground support systems.

Because of difficulties in the formulation of a mathematical model that would properly represent the flow characteristics of a tubeflight support system over its entire flight spectrum, a twin approach to the problem has been necessary. An analytical approach has been used in dealing with support systems amenable to representation by simple mathematical models, and an experimental approach in dealing with support systems which operate in, or generate, physically complicated flow fields.


The subsonic lift characteristics of two-dimensional jet-flapped airfoils in ground proximity has been investigated by Cooke in an analysis \cite{9} restricted to flight regimes in which the jet-flap flow does not impinge upon the ground (the "supercritical" flight regime). The physical situation considered is shown in Figure II-1.

Fig. II-1. Physical Model
In order to analyze separately the influence on lift of the jet-flap deflection angle, angle of attack, mean-line shape, and thickness distribution, Cooke develops a linearized potential flow model. This model is constructed by replacing the airfoil and jet-flap with an unknown source-vortex singularity distribution which is located on a line parallel to the ground as shown in Figure II-2. An image distribution is used to simulate the ground. The mathematical problem is to determine the strength of this distribution, subject to the constraint that the associated flow field must satisfy the linearized tangency conditions on the airfoil and on the jet-flap, in addition to the linearized pressure equation across the jet. The resulting mathematical model takes the form of a pair of coupled integro-differential equations for the airfoil vortex intensity and the jet-flap slope.

The procedure used by Cooke for finding solutions of these equations involves representing the airfoil vortex distribution and the jet-flap slope in a continuous manner by trigonometric series with unknown coefficients. Appropriate singularities are introduced, which account for discontinuities at the airfoil leading and trailing edges. After this is done, it is possible to evaluate the integro-differential equations. However, due to the complicated nature of ground influence, all integrations must be performed numerically. The analysis then reduces to solving a set of linear algebraic equations for the unknown coefficients, which are ultimately evaluated by a pivotal point method. The airfoil lift and jet-flap shape are found by integrating the solutions for the airfoil vortex intensity and the jet-flap slope.

In this report, the results of sample calculations for an airfoil at a ground clearance of one-half the chord \( h = 0.5 \) are presented. To illustrate camber effects a parabolic mean line is used. Results for the linear contributions to the sectional lift coefficient, \( C_L \), due to jet flap deflection \( \frac{\partial C_L}{\partial \theta} \), angle of attack \( \frac{\partial C_L}{\partial \alpha} \), and camber \( \frac{\partial C_L}{\partial y_{cm}} \), are shown in Figures II-3, II-4, and II-5 respectively. At low momentum coefficients the asymptotic approximation \[ \frac{\partial C_L}{\partial \alpha} \approx \sqrt{2C_j} \frac{\partial \alpha}{\partial \alpha} \] is used to predict the jet-deflection contribution. Also shown in these figures are the jet-flap shapes \( \frac{\partial y_{flap}}{\partial \theta} \), \( \frac{\partial y_{flap}}{\partial \alpha} \), and \( \frac{\partial y_{flap}}{\partial y_{cm}} \) with distance downstream for a momentum coefficient, \( C_j = 1.0 \).

Cooke has noted that the lift coefficient can be obtained to engineering accuracy using nine pivotal points. Determination of the jet-flap shape is not as satisfactory, however, due to the fact that the distance downstream to which these calculations may be carried is restricted by the presence of unbounded downstream errors. An assessment of Cooke's analysis indicates that the camber and thickness problems do not involve significant additional complexity over the jet-flap deflection and angle of attack problems. This is important because generalized solutions of the former two problems are not available.

An alternative method for solving the linearized potential problem is presented for airfoils in ground proximity without jet-flaps. In this procedure the image singularity distribution is taken to be the away-from-ground distribution. The airfoil vortex intensity may then be calculated by classical techniques. This alternative procedure can be considered as the first step of an iterative process. Subsequent solutions for the airfoil vortex intensity may then be used to represent the image system better.
The first iterative results of the variation in the lift-curve slopes \( \delta C_{L}/\delta y \), \( \delta C_{L}/\delta \alpha \), \( \delta C_{L}/\delta V \), and \( \delta C_{L}/\delta \theta \) with ground clearance for an airfoil having a parabolic mean line and an elliptical thickness distribution are shown in Figure II-6. A comparison of these predictions with conformal transformation analysis and the results of the pivotal point calculation indicate that the iteration method for solving the linearized equations has applicability for moderate clearances. However the iteration method clearly illustrates the importance of considering thickness effects in ground proximity.

II-3. Aerodynamic characteristics of support systems. Experimental studies.

An experimental determination of the subsonic lift and drag characteristics of the tubeflight support system described in [1] has been completed. There is ample evidence in the literature that the proper simulation of all boundary conditions is important when testing bodies in close proximity to boundaries. The proper wall boundary condition in the Rensselaer tests was simulated by replacing one wall of a wind tunnel with a platen-type belt sander whose movement produces a moving ground plane [1, 10].

The model used in [10] was one in which a substantial portion of the lift was generated by the upper surface. Furthermore, the model geometry was such that it could be operated equally well as a ram wing, a jet-flapped airfoil, or a peripheral-jet ground-support system. Tests were conducted over a range of ground clearances and angles of attack and in those instances where blowing was used the blowing rate was adjusted so that the support system operated in both supercritical and subcritical flight regime. The intent of these tests was to determine a) the lift characteristics of a ram wing, peripheral-jet, and jet-flapped ground support systems at subcritical and supercritical speeds, b) the magnitude of jet-momentum recovery as thrust, and c) the effects of angle of attack.

Typical of the experimental results obtained are the lifting characteristics of a jet-flapped and peripheral-jet support system presented in Figures II-7 and II-8. Also it has been determined that substantial thrust recovery can occur. For example, a jet-flapped airfoil or a peripheral-jet support-system operating in the supercritical flight regime can produce thrust recoveries of the order of eighty to one hundred percent. In subcritical operation the thrust recovery is reduced 0(20%→40%) but still remains significant. In general, the thrust recovery increases as ground clearance decreases. Experimental results which illustrate this effect are shown in Figure II-9.

II-4. Inherent stability calculations.

Using the results of [1, 9] in conjunction with the aerodynamic stability derivatives of a body traveling in a tube calculated by Goodman (Ref. II-1) the inherent stability in pitch and heave of two typical tubeflight vehicles have been determined.

One of the two vehicles was supported by ram wings and had the following
Figure 11-7

LIFT COEFFICIENT vs MOMENTUM COEFFICIENT

Jet Flap \( \alpha = 0 \degree \)

\( C_j = 0.066 \)
\( x = 0.32 \)
\( x = 0.197 \)
\( x = 0.264 \)

LIFT COEFFICIENT

\( C_l = \frac{1}{2} \rho V^2 \)

MOMENTUM COEFFICIENT

\( C_j = \frac{V_j}{\frac{1}{2} \rho V^2} \)
Figure II-8

Effect of Forward Speed on the Lift Coefficient of a Peripheral Jet

Momentum Coefficient $C_d = \sqrt{\frac{1}{2} \rho \omega V_\infty^2 dc}$
Momentum Coefficient \[ C_g = \frac{1}{2} \rho V^2 \]

Peripheral Jet \( \alpha = 0^\circ \)

- \( L_d / L_c = 0.066 \)
- \( = 0.098 \)
- \( = 0.132 \)
- \( = 0.247 \)
- \( = 0.264 \)

Figure II-9  Thrust Recovery
characteristics:

**Vehicle Body**
- a) Ellipsoid of revolution
- b) Length = 100 feet
- c) Diameter = 9 feet
- d) Weight = 100,000 pounds (ellipsoid is considered to have a uniform weight density)

**Support System**
- a) Airfoil shaped (two dimensional aerodynamic lift characteristics are determined from [9].
- b) Number of pads = 4 (two fore and two aft of vehicle center of gravity)
- c) Pad-to-tube wall clearance = 9 inches (at a design cruise speed of 375 mph)
- d) Pad circumferential arc = 120 degrees

For this vehicle, operating in a tube of fifteen feet in diameter, it has been determined that:

1) if the vehicle pad size is chosen such that the pads operate at a zero angle of attack at a cruise speed of 375 mph, then the vehicle is dynamically unstable, independent of the location of the pads along the body;

2) to produce a dynamically stable vehicle at this speed it is necessary to operate the support pads at an angle of attack of approximately 10 degrees, and

3) from a stability viewpoint it is more desirable to have many small chord pads operating at a high angle of attack than a few large chord pads operating at a low angle of attack.

A more detailed discussion of this analysis is presented in [1].

Similarly Cooke (Reference II-2) analyzed the inherent stability of a tubeflight vehicle supported by a jet-flap ground-effect system. In his analysis the vehicle and support system parameters were chosen as

**Vehicle**
- a) Modified ellipsoid of revolution
- b) Length = 137 feet
- c) Diameter = 9 feet
- d) Weight = 90,000 lbs max
  = 60,000 lbs min

**Support System**
- a) Jet flapped airfoil (adjustable jet flap deflection)
- b) Circumferential arc of pads = 120°
- c) Clearance = 8-12 inches

Again the guideway diameter was chosen as 15 feet.

For operation in the supercritical flight regime, Cooke determined that the above vehicle will possess inherent stability if three support pads are used (one each, fore and aft and one at the center of the body); each pad being inclined at an angle of attack of approximately two degrees.
Stability analysis and determination of the flight characteristics of tubeflight vehicles using peripheral-jet ground-support system are continuing at the present time.

II-5. References


CHAPTER III

STABILITY AUGMENTATION AND ACTIVE CONTROL

III-1. Introduction

Work on project Tubeflight during the period covered by this summary report has been primarily concerned with an analytical and computer study of active control requirements for the tube vehicle. Some effort also has been devoted during the past year to a participation in the design and construction of a roll controller for the Mark II test vehicle.

This chapter covers the following activities: (a) formulation of appropriate mathematical models of the vehicle dynamics and synthesis of an automatic roll controller; (b) development of a flexible digital computer program to simulate the vehicle motion under a wide range of operating conditions and to evaluate the performance of the roll controller for small and large disturbances; and (c) specification of the non-conventional vehicle sensors required to implement the roll controller.

III-2. Mathematical models and controller synthesis

A high-speed vehicle traveling in a non-evacuated tubular guideway should be capable of maintaining adequate clearances between the tube wall and the vehicle body and a proper angular orientation with respect to the guideway at all times. These design objectives must be fulfilled in the presence of any random disturbance force and torque that might be present in actual flight, and despite imprecise knowledge of certain vehicle parameters, such as its actual speed, mass and moments of inertia, etc.

To describe the vehicle's response to flight disturbances, and to modify the response characteristics, if necessary, by means of active control system, a mathematical model of the vehicle dynamics with six degrees of freedom has been developed [11, 12]. One can derive specialized models, e.g., a linear, two-dimensional model, etc., by appropriate simplification of this general model. Since many important subsystems of the vehicle such as the fluid suspension system (support pad), vehicle frame, and propulsion system, etc., affecting the vehicle motion have not yet been designed, certain important assumptions had to be made regarding the nature of forces and torques acting on the vehicle. It was assumed that the lift force generated by a support pad during a constant speed cruise had two components -- one dependent on the clearance and the other on the rate of change of clearance. The former provides a restoring force inversely proportional to the vehicle-to-wall clearance while the latter provides a linear damping force proportional to time rate of change of the clearance. The lift forces produced by the air pressure distributed over the support pad surface were approximated by an equivalent point force acting through the vehicle center line from the center of the pad. (See Figure III-I).

* Numbers in brackets refer to RPI reports listed in the Appendix.
Justifications for these assumptions have been discussed elsewhere \[13\]. The aerodynamic forces and moments due to the fuselage moving in proximity to the wall are also not well characterized quantitatively at present, but their destabilizing effect (Ref. III-1) is readily included in the linearized model of the vehicle dynamics. However, the overall character of the vehicle's response to small disturbances was found to be primarily influenced by the assumed characteristics of the support pad and of the guideway-vehicle geometry.

The mathematical model of the vehicle dynamics based on the assumptions stated above exhibited an unstable coupling between the roll and lateral modes while all other modes were found to be well damped. Such instability, however, can be effectively eliminated by applying a control torque about the vehicle's roll axis which is proportional to the vehicle's roll-error rate.

These conclusions, initially obtained from the analysis of a linear vehicle model with six degrees of freedom, have been corroborated by digital simulations of the nonlinear vehicle dynamics. Further validation by flight tests of appropriately scaled models of the vehicle is needed before these conclusions can be accepted as a basis for the vehicle design. However, the analysis of the mathematical models provides guidelines for the flight test program and will prove useful in analyzing the flight test data.

III-3. Digital simulation program.

A flexible digital computer program was developed to simulate the vehicle motion with six degrees of freedom both in a straight tube and around a curve \[12\]. In the simulation of the vehicle's motion around a curve, the vehicle was assumed to be traveling down the guideway with a constant forward speed while varying its banking angle up to 45 degrees. The desired banking angle was chosen so as to maintain the vehicle's vertical alignment with the resultant of the gravitational and centripetal forces. Furthermore, the vehicle was subjected to flight disturbances while negotiating the curve in order to test the performance of its onboard roll control system. The flight disturbance was simulated by introducing initial errors in the vehicle's roll angle and lateral displacement etc. Typically, when the control torque amplitude was limited to 2000 ft-lb, then for a vehicle entering a curve with 0.1 radian error in its roll angle, the feedback control system reduced the error to .02 radian as it came out of the curve.

Although the vehicle motion around a curve was simulated for a constant forward speed, the computer program is capable of simulating the vehicle motion with variable forward speed if the dependence of lift and drag characteristics on the forward velocity is specified. The computer program can also simulate the vehicle dynamics corresponding to many different curve geometries and torque programs, and any combination of various fluid suspension systems and vehicle configurations that may be investigated in the future.

III-4. Sensors for onboard control system.

It has been mentioned that a control torque proportional to the vehicle's roll-error rate is needed to eliminate the unstable coupling between the roll
and lateral modes. In a straight tube, the required measurement of the roll-error rate can be accomplished by a simple rate gyro mounted along the roll axis of the vehicle. On the other hand, when the vehicle is negotiating a curve, it is necessary to measure the difference between the actual roll angle and the programmed roll angle of the vehicle along a prescribed path. The measurement of the vehicle's roll angle with respect to an accelerating frame along the programmed path can be made by means of a damped pendulum which rotates in a plane normal to the direction of travel. Schmidt [14] and Kwon [15] have shown that such a pendulum could measure the vehicle's roll error to a good approximation if it was appropriately compensated by a rate gyro and filtering network. A mathematical model of the compensated pendulum was incorporated into the onboard controller of the linear vehicle model, and the motion of overall system was simulated in a straight tube with satisfactory results [11].

III-5. Reference

CHAPTER IV

HIGH-FREQUENCY ELECTRICAL POWER SUPPLY

IV-1. Introduction.

The investigation of the supply of high frequency power to a tube guided vehicle has proceeded in four areas.

a. The generation of the appropriate mode in the tube.
b. The propagation of power through the tube.
c. The reception of power by the vehicle.
d. The rectification of received high-frequency power in the vehicle.

The use of a frequency of 220 megahertz in a tube with a diameter of 18 feet was chosen for investigation. With this choice, the tube as a waveguide is highly overmoded and, in particular, supports three circularly symmetric propagating modes TE_{01}, TE_{02}, TE_{03}; but the TE_{01} mode is a very efficient mode for propagation of power, having an attenuation per unit length in an ideal cylindrical waveguide which is one-fourth of the attenuation per unit length in the fundamental TE_{11} mode.

IV-2. Problems investigated.

The methods used to supply power must satisfy the following specific constraints.

The structure used to couple power to the tube must permit unimpeded passage of the vehicle. It must also avoid setting up high standing waves, since at the very high power levels of 10 to 20 megawatts which are required, high standing waves may result in the ionization of the air in an unevacuated tube.

The receiving structure must not adversely affect the aerodynamic properties of the vehicle.

A reasonably high efficiency is required of all parts of the system.

The scattering to modes other than the TE_{01} due to practically unavoidable deviations of the guide from a perfect cylinder must be kept reasonably small.

IV-3. Progress toward the determination of feasibility.

A considerable degree of progress toward the determination of feasibility in all four of the areas described above has been made.

In the area of reception of power by the vehicle, an initial study of reception by circular dipole arrays was made during the first year [16].

* Numbers in brackets refer to RPI reports listed in the Appendix.
However, it was realized near the end of that study that the Riblet coupler was a much more promising solution [17]. During the second year it was established by experiment that such a receiver could receive 96% of the power incident in a $\text{TE}_{01}$ mode. The results of the study of centered conducting rings described in [16] was used to estimate the scattering matrix of the Riblet coupler and explain some features of the experimental data.

To some degree progress on the receiver design provides insight to the problem of coupling to the $\text{TE}_{01}$ mode in the tube for the purpose of generating the mode, since a similar structure can be used for that purpose. However, since the dimensions of the input coupler are roughly twice as large as the receiver, its mode structure is correspondingly more complex and more work should be done to determine if the same level of coupling efficiency can be obtained with the larger structure. Some work in this direction which is actually in progress involves the experimental determination of the scattering matrix of the larger Riblet coupler.

In the area of rectification, the work in the first year was largely devoted to the consideration and testing of a wide variety of solid state rectifying components. As a result of this effort the heterojunction diode was selected as the most promising device and work in the second year has centered around intensive development and testing of rectifier circuits making use of heterojunction diodes. This work is reported in [18] and has yielded efficiencies of 72% and a rectified power of 28 watts from a single junction. During this period a test facility with a capability of 1000 watts was constructed. Further work toward a rectifying package using several junctions to handle a power level of several kilowatts is proposed.

In the area of efficient propagation of energy in the $\text{TE}_{01}$ mode, work during the first year involved testing the effect of separation of the end plates of a cylindrical cavity tuned to resonate in the degenerate $\text{TE}_{01}$ and $\text{TM}_{11}$ modes on the purity of the $\text{TE}_{01}$ mode. Since such separation considerably enhanced the purity of the $\text{TE}_{01}$ mode, an effort was made to predict analytically the effect of equally spaced gaps in a cylindrical guide on the coupling to other modes from the $\text{TE}_{01}$ mode. Since such coupling usually decreases as the difference in propagation increases, it was necessary to find the propagation constants of a cylindrical guide with equally spaced gaps.

It has been shown in [19] that the effect of such a structure on the $\text{TE}_{01}$ mode is second order in the gap width but that the effect on non-circularly symmetric modes is first order in the gap width. A computer program which calculates the propagation constants of such a structure to the first order in the gap width has been written and produced the data in [19]. However, the attenuation for modes other than the circularly symmetric modes due to radiation from the gaps is smaller than expected and indicates that further analytical and experimental work is required.

The experimental work now in progress on the determination of the scattering matrix of the Riblet coupler can be extended to the approximate determination of the scattering matrix of a small gap which will help check the analytical work done so far.
IV-4. Conclusions.

The feasibility of a high frequency power supply for a tube guided vehicle involves investigations and development beyond the state of the art in over-moded waveguides and solid-state rectification at high frequencies. However, the considerable progress made in a relatively short time with moderate support indicates considerable promise if extrapolated to the time at which such a system might be constructed. Current investigation is providing results at a reasonably high rate and continued effort should produce a corresponding increase in the precision to which the problem of feasibility is understood.
CHAPTER V

SMALL-SCALE EXPERIMENTATION

V-1. The T-2 facility.

The facility used to test scale-model tubeflight vehicles (Facility T-2) consists of a welded-up steel pipe, 2000 ft long, with a mean inside diameter of 12.45 in. [20]. The pipe axis has been aligned to ± 1/32 in. of straightness in the horizontal and vertical planes. A view of T-2 looking from south to north is shown in Fig. V-1.

The facility is instrumented to detect vehicle motion by the means of transducer stations located on the tube vertical centerline at 10-ft intervals. Photoelectric cells are used which are triggered by lights carried by a vehicle. Pulses generated at the transducer station are transmitted to the signal processing and recording equipment which is housed in a 10x40 foot office-trailer located adjacent to the launching end of the tube. The flight performance data is acquired in the form of a punched paper tape which can be decoded by hand for rapid evaluation of vehicle performance, or by computer which gives vehicle speed and acceleration versus vehicle location in the tube.

V-2. The Mark II vehicle design and flight tests.

A detailed account of this activity is given in [21].

The overall test program involves the following vehicles:

Mark I -- A small, light-weight demonstration vehicle using the plenum chamber support. This vehicle, 4 feet long, weighing 12 pounds, was built under the direction of H. Hagerup, and was financed under an NSF grant. Its first successful flight took place in March of 1967, and during the course of testing ultimately reached a top speed of 18.8 feet per second during a 2000 foot run.

Mark II -- This vehicle is about 12 feet long and weighs between 65 and 75 pounds depending on the support pad configuration. It employs the peripheral jet support pads and two model aircraft engines (rated at 1.8 HP) driving propellers for propulsion.

Mark III-- This vehicle is related to Mark II but employs modified McCulloch "100" engines (single pusher or tractor and pusher) driving three-bladed counter-rotating propellers. The vehicle is essentially complete and ready for testing at this writing.
Fig. V-1. T-2 Facility looking from south to north.
Mark IV -- A completely different design. A modified McCulloch "101" engine will drive an AiResearch blower producing a flow rate of 1,000 cubic feet per minute with 90 inches of water pressure rise. Part of the air will be bled off for peripheral jet support; most of it, however, will drive a fluid-bladed propeller. This vehicle is under construction at this date.

Figure V-2 is a photograph of the Mark IIb version which differs from Mark IIa only in that the latter has no upper support pads and is 9 lb. lighter.

A summary of the tests of Mark II vehicle is given in the accompanying table. In flight #7 the highest speed 27.7 ft sec\(^{-1}\), and the longest flight 1790 ft were attained. This speed is well below the expected maximum speed of over 50 ft sec\(^{-1}\) which had been predicted for it. The reason for this deficiency is believed to be blockage of the transfer passage due to the front curtain from each support pad being folded back over the dorsal surface of the pad and swept to the rear when the vehicle is in forward motion.

V-3. Planned work.

To verify this hypothesis a series of tests is planned for the Mark III vehicle in which tests results can be compared for the peripheral-jet and the jet-flap configurations, the latter of which is obtained by blocking off the front curtain. In addition, modifications will be undertaken to eliminate failure of the support engines which had been operated above their rated rpm. New propulsion units will also be tested developing about 10-12 times the horsepower of the Mark II units.
Fig. V-2. The Mark IIb vehicle.
<table>
<thead>
<tr>
<th>Flight No.</th>
<th>Vehicle</th>
<th>Date</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>1000</th>
<th>Maximum</th>
<th>Flight Length</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Mark IIa</td>
<td>8/24/67</td>
<td>15.4</td>
<td>18.1</td>
<td>16.8</td>
<td>17.6</td>
<td>13.0</td>
<td>18.8 @ 480</td>
<td>710</td>
<td>Commercial props. Rear prop destroyed at launch</td>
</tr>
<tr>
<td>4</td>
<td>&quot;</td>
<td>8/28/67</td>
<td>2.4</td>
<td>4.2</td>
<td>3.6</td>
<td>1.4</td>
<td>-</td>
<td>6.4 @ 20</td>
<td>650</td>
<td>Front propeller destroyed just after launch.</td>
</tr>
<tr>
<td>5</td>
<td>Mark IIb</td>
<td>10/5/67</td>
<td>16.3</td>
<td>20.3</td>
<td>23.6</td>
<td>26.0</td>
<td>16.0</td>
<td>27.7 @ 520</td>
<td>1790</td>
<td>Vehicle stopped after blower engine overheated, tailed off and then failed.</td>
</tr>
<tr>
<td>6</td>
<td>&quot;</td>
<td>10/9/67</td>
<td>20.0</td>
<td>25.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>25.1 @ 90</td>
<td>130</td>
<td>Special prop on rear engine on flights #6-9, left-front side curtain jammed in upposition at about 90 ft. Vehicle turned over on its back due to unbalanced moment.</td>
</tr>
<tr>
<td>7</td>
<td>&quot;</td>
<td>10/12/67</td>
<td>18.5</td>
<td>20.5</td>
<td>17.2</td>
<td>8.3</td>
<td>-</td>
<td>22.2 @ 80</td>
<td>600</td>
<td>Rear engine bearing failure, and support engine piston failure.</td>
</tr>
<tr>
<td>8</td>
<td>&quot;</td>
<td>10/23/67</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15.4 @ 20</td>
<td>30</td>
<td>Support engine failure just after launch.</td>
</tr>
<tr>
<td>9</td>
<td>&quot;</td>
<td>10/30/67</td>
<td>17.4</td>
<td>24.6</td>
<td>19.7</td>
<td>-</td>
<td>-</td>
<td>27.5 @ 190</td>
<td>330</td>
<td>Support engine failure.</td>
</tr>
</tbody>
</table>
APPENDIX

PROJECT TUBEFLIGHT REPORTS
September 1966 - November 1967

1. Project Tubeflight Phase I Feasibility Study, Rensselaer Polytechnic Institute, September 1966, (Clearinghouse No. PB 174 085).


