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W. B. Brower
Associate Professor of Aeronautical Engineering, Rensselaer Polytechnic Institute, Troy, New York

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TUBEFLIGHT--A REVIEW

W. B. Brower, Jr.
Associate Professor
of Aeronautical Engineering
Rensselaer Polytechnic Institute
Troy, New York

ABSTRACT

A survey is made of theoretical and experimental work done as part of Project Tubeflight at Rensselaer Polytechnic Institute which has been directed at the development of a novel means of high-speed ground transportation. Tubeflight involves a vehicle, shaped much like an aircraft fuselage, which is supported by air cushion devices, and propels itself by one of several possible flow induction devices through a non-evacuated tube. The principal research areas reviewed are: the guideway, propulsion and power required, support, and small-scale experimentation.

INTRODUCTION

The need for alternative methods of inter-city transportation--particularly high-speed ground transportation--has been amply documented elsewhere and will not be repeated here. One of the proposed methods to meet these needs is called Tubeflight. It is the writer's opinion that Tubeflight is now ready to emerge from the small-scale laboratory research stage, and to enter a large-scale developmental phase. In this paper theoretical and experimental work undertaken at Rensselaer Polytechnic Institute during the last decade or so is briefly reviewed and the principal findings are summarized.

Tubeflight was invented by J.V. Foa* while at Cornell Aeronautical Laboratory in 1947. The concept was briefly described in a review(1) of future jet propulsion prospects. It was not until the late 1950's however that experimental measurements were undertaken by Foa and a few of his graduate students. At the same time it became apparent that in a few years there would be great interest in finding alternatives to the proliferating highways, the overcrowded airways, and the disappearing railroad passenger trains.

The first comprehensive description of Tubeflight in the open literature was published in 1962(2). References (3) and (4) also provide general descriptions of the Tubeflight mode of transportation.

High-Speed Ground Transportation System Requirements

The great advantages of air transport cannot be fully utilized by the traveler because of the requirement that airports be located away from population centers. Furthermore, particularly in the northeast United States, the airways system is highly vulnerable to major weather systems which, on occasion, can cause chaotic transportation tie-ups on a grand-scale. In his book(4) Senator Claiborne Pell provides grim descriptions of several of these which occured during the early 1960's. There are indications that future tie-ups will occur on an even grander scale if and when the new generation of passenger aircraft--with their remarkably increased passenger capacities--should be immobilized by the coincidence of heavy passenger loads with unflyable weather. If railroad passenger service has been eliminated by the time of the next tie-up, the severity of the tie-up should surpass its predecessors by an order of magnitude.

Ideally a high-speed ground transportation system should operate from center-to-center of metropolitan areas. The service should involve individual vehicles of large capacity to allow for the possibility of frequent departures with headways of two minutes or less, and should be capable of traveling at speeds comparable to moderately high air transport speeds. In order to guarantee all-weather operation, as well as for safety purposes, vehicles should operate within an enclosed guideway.

Such a guideway has other advantages. It provides an easy way of containing noise pollution and, since any air pollution created would also be contained within the guideway, it ensures the capability of treating the affected air to remove the pollutants. An enclosed guideway provides another advantage. It appears that the wheel-on-rail method of vehicle suspension reaches its ultimate utility somewhere in the neighborhood of 150-200 mph. At 200 mph serious questions arise on the efficiency of conventional wheel-support braking techniques. Although it is possible in this speed range that the rubber-tired wheel can provide adequate support within a guideway it is certain at high speeds that one of the air-cushion types of support--peripheral jet, jet-flap wing, ram-wing or, perhaps a combination of these--will be utilized.

Use of air-cushion support presupposes a non-evacuated guideway which, fortunately, possesses addi-

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* Professor of Aeronautical Engineering, RPI, and Director of Project Tubeflight, until January 1970. Current position, Professor of Engineering and Applied Science, George Washington University. U.S. Patent No. 3,213,802 was awarded for Tubeflight in 1965.

tional desirable operating characteristics. For example, a vehicle designed to operate within it is subject to less restrictive structural specifications on the vehicle passenger enclosure than for the evacuated guideway where the vehicle must be essentially 100% leakproof. Construction of the guideway itself is substantially simplified if the need for vacuum tightness is unnecessary. Finally, a non-evacuated tube permits use of simple vehicle braking techniques whereby the vehicle can be converted into a "piston" and its kinetic energy rapidly transferred by non-steady flow processes to the air column ahead of it.

THE TUBEFLIGHT CONCEPT

Tubeflight is a mode of high-speed ground transportation in which the vehicle moves through a tube. The basic principles of tubeflight have recently been reviewed by Foa(6). Before saying what makes Tubeflight distinctive it is useful to point out that it is not related in any way to the familiar "pneumatic dispatch" system of department-store fame. If a vehicle is moved by pumping in air behind it and exhausting that in front, it is clear that the entire air mass moves essentially at vehicle speed. But air pumping power varies roughly as the square of the diameter and the cube of the speed. If compressibility effects, which are important at high subsonic speeds, are taken into account, the power required is even greater. For example, based on incompressible flow calculations, the pumping power for a 10-foot diameter tube and 550 mph is 230,000 hp per mile of air column. It should be noted that this is not necessarily the vehicle power demand, which cannot be calculated until the headway is specified.

The key to the Tubeflight concept is that rather than move the air in the tube (and with it the vehicle) it is proposed to propel a vehicle (typical diameter of 9 feet) through a tube (diameter of 15 to 18 feet) such that the air is pumped from front to rear through the transfer passage between the vehicle exterior and guideway wall at just the rate swept out by the vehicle. On the average each particle of air is displaced only one vehicle length by passage of a vehicle over the entire tube length. The "pumps" would be conventional thrust generators, such as turboprop or turbofan engines, or by a novel method involving bladeless propellers mentioned below.

This method of propulsion is referred to as "internal propulsion" in contrast to "external propulsion" in which thrust is generated as the reaction to a force exerted on an external, stationary structure as occurs in conventional wheel traction, linear induction-motor drives and in the pneumatic dispatch mode.

An artist's version of a full-scale Tubeflight vehicle is shown in Figure 1. The vehicle resembles an aircraft fuselage in which the wings are replaced by air cushion devices for support. Such devices have a "soft footprint", and provide large clearance between the support structure and the guideway wall. They also permit the vehicle to be easily rolled in turns, which is an important factor in passenger comfort. In the vehicle shown a ducted bladeless propeller is employed for propulsion.

Although other facets of Tubeflight, such as a study of the feasibility of use of the guideway as a waveguide for power transmission, and control studies of vehicles under flight conditions have been completed, this review is limited to the areas of: the guideway; propulsion and power demands; air cushion support; and the small-scale experimental program conducted on Tubeflight vehicles.

THE GUIDEWAY

To Tunnel or Not?

It is occasionally stated, almost as an item of conventional wisdom, that guideways for any tube-vehicle system will have to lie beneath the surface. The writer does not accept such a view as being generally valid. In the center of high-population-density regions this will undeniably be the preferred way. Yet, without a radical breakthrough, tunneling costs will be sufficiently high that tremendous savings would be realized if the guideway can be located at grade, probably lying in a shallow trench.

The objection has also been raised that the probable configuration of a pair of adjacent one-way tubes, each being 15 to 18 feet in diameter, would create an unacceptable barrier, a "Chinese Wall". Such an objection has merit, although having originated with the same highway engineer who can regard with equanimity the erection of a 12-lane highway (The New Jersey Turnpike) through a major population center, it can be partially discounted. In rural areas the tubes can be readily covered by backfilling to permit transit by wildlife. In more populated areas it would certainly be simpler to utilize the air rights over such a barrier than over a 6-lane highway, as is currently done in various places. Tunneling would be the most expensive, and last, alternative.

On the Optimum Tube Diameter

In order to reduce costs of constructing a tube guideway, it is sometimes contended that it is preferable, for a vehicle of fixed diameter, to install a tube-vehicle system which requires the smallest tube/vehicle diameter ratio, that is, a system with small clearance between vehicle exterior and tube wall. For definiteness a small-clearance system is defined as one where the tube/vehicle diameter ratio is the order of 1.01.

In the first place small clearance means that an evacuated tube must be employed (pneumatic dispatch already having been rejected) with its attendant difficulties and of potential menace to passenger safety in case of failure of cabin seal.

From the standpoint of tube construction costs the small-clearance concept also fails. For fixed vehicle diameter, for identical materials employed in the guideway construction and, under the assumptions:

(a) that the tube wall thickness is small compared to its diameter;

(b) that the permissible cross-sectional and beamwise deflections of the structure under load are proportional to its tolerances of construction and alignment;

(c) that the tolerances and permissible deformations are linearly proportional to the width of the clearance space between vehicle and tube;

then Foa(7) has shown:

(a) that the tube material costs can be almost halved when the tube/vehicle diameter ratio is increased from a reference value of 1.01 to 1.20 at which point this cost is minimum. For higher values the saving decreases to about 40% when the ratio is 1.5 and to 15% at 2.0;

(b) that the maximum permissible guideway support spacing increases monotonically and very significantly with the diameter ratio.

Figure 2, adapted from (7), summarizes these results plotted against the dimensionless clearance. The lower curve indicates that the minimum weight-per-unit-length of tube occurs for a tube/vehicle diameter ratio of 1.2. The upper shows the boundaries fixed by the two cases of wall deflection due to a concentrated load of fixed magnitude, and to the tube's own weight, respectively.

If labor costs are assumed to increase in direct proportion to the surface area to be treated, to the volume excavated, and inversely to the required tolerances then it turns out that the minimum labor cost always occurs for a tube/vehicle diameter ratio greater than 2.0. Under these plausible hypotheses it becomes clear that Tubeflight with its large tube/vehicle diameter ratios (ranging from 1.67 to 2.0) becomes highly attractive from the objective of minimizing guideway construction costs.

Estimated Costs of a Guideway

Detailed cost estimates are not available. However, preliminary cost estimates from industry and engineering consultants range from $2.5-3.0 million per pair of tubes per mile, based on 1967 dollars. This figure includes supporting structures but is exclusive of land acquisition costs. Since Tubeflight vehicles are capable of banking they are capable of negotiating fairly sharp turns much like airplanes. This enables them to utilize in many places available rights of way, such as center malls of highways, abandoned railroad beds, banks of rivers, etc.

PROPULSION AND POWER REQUIRED

It has been previously noted that Tubeflight employs internal propulsion in distinction to external propulsion where the vehicle thrust is generated in reaction to a force on the guideway structure. In internal propulsion the force is generated on board the vehicle itself by transferring air from in front of the vehicle to behind by any one of several categories of flow induction devices. When the vehicle has reached a constant speed and the flow through the transfer passage is steady the condition of "matched internal propulsion" is said to have been reached.

The analysis of Tubeflight gas dynamics has certain aspects not found in conventional internal flow analyses, some of which are exceedingly difficult to handle. Since this is an area worthy of a review paper on its own only a few of the principal references are quoted* and the most important results noted.

On Matched Internal Propulsion

A basic question to be answered for constant vehicle velocity with respect to the tube is whether or not the flow, in a vehicle-fixed frame of reference, can be analyzed on the basis that it is steady. If so, then the condition of matched internal propulsion is said to have been attained. In this frame the tube wall moves, of course, at a velocity equal and opposite to the vehicle velocity with respect to the wall and the effects of air viscosity and heat transfer at the tube boundary have unexpected, and important, consequences for the flow behavior.

As Foa(8) shows, the supersonic case presents no special analytical difficulty. However, in the subsonic flow regime, by means of a "wake stability" criterion, it is shown that a solution is possible only if the flow speed is zero with respect to the tube wall everywhere downstream of a station close to the rear of the vehicle. This behavior is borne out by linearized analyses of Hagerup(9) and Schmid(10) where it is further demonstrated that in the wake the dimensionless velocity and enthalpy perturbations are equal, and that the wakepressure becomes everywhere equal to the ambient value of infinitely far downstream.

The question was still left unsettled whether the flow is truly steady or whether the non-steady effects vanish only asymptotically with time. In a simplified model, by replacing the vehicle by a heat source moving at constant velocity relative to the tube wall, Skinner(11) shows that the flow approaches a steady-state only asymptotically, albeit rapidly, with time. This provides assurance that for practical purposes the condition of matched internal propulsion can be achieved.

Internal Versus External Propulsion

In Reference (8) the theory of power required for

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* The writer will be happy to furnish a complete Tubeflight bibliography on request.

matched internal propulsion is presented and several calculations are made comparing the power required for internal versus external propulsion for several vehicle velocities. At the lower speeds internal propulsion is not necessarily much more efficient than external propulsion but, as the speed range is extended to high subsonic or even supersonic values, the power required for internal propulsion becomes dramatically less than for an external propulsion mode. It is also shown that the flow disturbances (hence the power required) are largely determined by the mode of propulsion; i.e. the thrust required for constant vehicle velocity depends on the manner in which the thrust itself is generated. This means that such questions as whether to use a tractor or pusher propeller or, whether to dump the rejected heat from a prime mover into the transfer passage or into the flow at the rear of the vehicle, must be carefully examined for each case. Apropos of the first question, if the flow in the transfer passage is choked the propeller must be a tractor since that arrangement reduces the flow disturbances ahead of the vehicle at high subsonic speeds and eliminates them entirely at supersonic speeds.

In Reference (12) Foa introduces the analytical technique of what he calls "dynamic cycles" to study the aerodynamics of Tubeflight propulsion with particular attention to the interrelationship between travel speed, body drag, far-field flow disturbances, and power demands. The method is also applicable to steady off-design conditions. A future paper with applications is promised.

Power Demands

The task of calculating power demands for a full-scale Tubeflight vehicle has been undertaken by Foa(13) based on the theory developed in References (2), (6), (8) and Area I, Part A of Reference (14). It is assumed that all vehicles considered have a maximum vehicle diameter of d = 9 feet. The vehicle length (L_V) and weight (W_V) depend on the passenger capacity (n) as shown in the following table. The weights are based on aeronautical technology using 500 lb/ft. For speeds of 200 mph a 20% error in the weight estimate would affect the overall power 1.7% or less.

n	(ft)	(lb)
50	75	38,000
100	130	65,000
150	165	82,000
232	222.5	110,000

The minimum tube diameter considered is D = 15 ft. A smaller tube diameter is considered impractical because: it would restrict the freedom of transverse motion required for passenger comfort in maneuvers; it would increase guideway costs as previously noted as well as the power required for propulsion; and it would make it difficult if not impossible to evacuate the vehicle in case of emergency stoppage.

The range of cruising Mach numbers extends from 0.18 (137 mph) to 0.5 (382 mph). Support system clearances range from 0.1 ft at 137 mph to 0.75 ft at 272 mph and higher. To increase the vehicle performance, boundary-layer suction is provided at appropriate locations.

Included in the overall drag estimate are:

(a) the frictional drag on the body;
(b) a frictional force on the wall of the tube which, although not specifically identifiable as a drag force, is included to be conservative;
(c) a "buoyancy" drag resulting from the pressure drop in the transfer passage due to (a) and (b);
(d) the parasite drag of the support pads and suspension struts;
(e) a drag associated with the production of lift by the support pads.

The mode of propulsion chosen is a "pusher," such as a fan or propeller at the rear of the vehicle. At the critical speed the flow in the transfer passage becomes choked (Point ⓐ, Figure 3). To attain a higher cruising speed, pumping of the flow must take place ahead of the transfer passage entrance, e.g. by using a tractor-type fan or propeller. The power-required curve then follows the segment a-b until shocks appear in the transfer passage at which point the curve b-c governs. Foa points out that rather than operating a vehicle① at speed u_c, a longer vehicle of the same diameter, hence of greater capacity, can be operated. Both will have the same critical speed u_a but the longer can be operated at speed u_c without shocks in the transfer passage, thereby decreasing the propulsive power per passenger.

Figure 4 reproduces the results for D = 15 and 18 feet. Only the smaller diameter tube exhibits the peculiarity associated with choking mentioned in the preceding paragraph. Also plotted on the graph is the calculated performance of the open-track UAC turbine-motor train TMT-5D which has a capacity of 232 passengers.

It is noted that the horsepower per passenger is about the same as the UAC turbine-motor train at about 100 mph. Above this speed the Tubeflight mode becomes increasingly more efficient. Generally the power per passenger decreases when the length of the vehicle increases. There is a major advantage in operating above the critical speed. For example, at a cruising speed of 370 mph in a 16.5-foot diameter tube (data given in the original reference) the total power required is the same for all vehicles between the lengths of 75 and 222.5 feet. This corresponds to horsepower-per-passenger values of 480 for the 75-foot vehicle, and to 103 for the 222.5-foot vehicle. It is also concluded that the maximum vehicle length for 9-foot diameter vehicles is about 250 feet based on considerations of boundary layer growth rate and suction requirements.

Propulsion by Bladeless Fans

The bladeless fan is one of a class of pressure exchangers, i.e. a device in which energy is transferred from a "primary" flow to a contiguous "secondary" flow through the work of the pressure forces which the two flows exert on one another at their interfaces. The theory of the bladeless fan* is given in Reference (15) from which the preceding sentence and much of the following several paragraphs are directly quoted.

A bladeless fan arrangement is shown in Figure 5. The primary fluid in this arrangement is air which is taken in through a scoop, energized in a gas generator, and discharged, through skewed nozzles on the periphery of a rotor, into an annular interaction space between the rotor and a shroud. The rotor spins freely, and is driven solely by the reaction of the issuing primary jets. No pre-rotation is imparted to either of the two flows by fixed vanes or by other external means. Under these conditions the two flows upstream of the interaction region are parallel to one another and to the rotor axis in the space-fixed coordinate system fixed to the rotor. The pressure-exchange interaction follows from the fact that the two flows are constrained to deflect each other to a common orientation in this coordinate system. In so doing, they acquire equal and opposite angular momenta, hence different orientations, in the space-fixed frame of reference. This is shown in Figure 5, where the black and white arrows represent primary and secondary velocities, respectively, in the deflected flows. In the space-fixed reference system the interfaces move, and work is done by the pressure forces which deflect the two flows. The net work done by the pressure forces is the energy which is transferred from the primary to the secondary by pressure exchange. An important advantage of the bladeless fan is that it produces thrust without any net torque exerted on the vehicle frame. Figure 6 indicates how a Tubeflight vehicle might be propelled by a bladeless fan. The analysis of Reference (15) deals with the performance of the bladeless fan as applied to internal propulsion of aerodynamically supported Tubeflight vehicles. It is concluded that the bladeless fan is capable of satisfying the requirements of matched internal propulsion. Charts are presented for the determination of the sets of design and operating parameters that will satisfy these requirements for any given vehicle at any cruising speed. The power required for bladeless-fan propulsion is compared with that for a conventional fan or propeller and it is found that for certain values of the rotor geometry the bladeless propellers are competitive with conventional thrust generators.

Experimental data on the performance of various kinds of pressure exchangers already exist. For the Tubeflight application work is already underway but has been retarded by the unavailability to this date of certain specialized test equipment.

SUPPORT

A high-speed ground transportation vehicle operating at speeds upward of 200 mph will almost certainly employ some category of air-cushion support. The most familiar devices in current use are the plenum chamber and peripheral jet types employed in various GEM vehicles in which air is pumped either from a plenum or from a support pad beneath the vehicle and allowed to stream out into the surroundings. The flow pattern involved in this leakage requires the pressure beneath the device to exceed the exterior pressure, resulting in a lifting force. The plenum chamber device is characterized by its simplicity and reliability, and falls into a medium clearance category (1 to 2 inches of clearance, typically).

At the speeds envisioned (300 to 400 mph) for the first generation of full-scale Tubeflight vehicles there is little experimental data on the performance of plenum-chamber support systems (or any other systems for that matter). There is no reason to believe a priori that it will be possible to achieve with a plenum chamber the kind of clearance required for successful operation of a Tubeflight vehicle. Current thinking calls for about a 9-inch clearance between pad and tube wall for a full-scale vehicle at cruising speed. This means that one of the other types of support, notably the peripheral jet scheme, must be employed. Figure 7 from a study of Duffy(16) shows how a peripheral (or annular) jet configuration might be changed into a jet flap or a ram wing device by shutting off the front curtain, or both curtains, respectively. The jet flap can provide adequate lift only after some fairly high minimum forward speed has been established, whereas the ram wing would presumably require even higher speeds although the ram wing has other difficulties which might eliminate it as a prospective support system. Naturally, for a Tubeflight vehicle the support pad will be contoured to adapt to the interior of the guideway.

The RPI Moving-Wall Facility

Experimental data on an air-cushion device obtained in a conventional wind-tunnel are suspect because under actual operating conditions there is relative motion between the ground and device whereas, in a tunnel, the wall and model have zero relative velocity. Due to viscosity of the air, this motion has an effect of unknown magnitude -- perhaps profound -- on the flow pattern, hence on the performance of the support pad. The only foolproof procedure in model testing is to simulate correctly the actual wall boundary condition, which is that the wind tunnel wall under the support pad must move relative to the pad at the same velocity as the oncoming air.

In order to produce this effect the RPI 4 x 6-foot subsonic wind-tunnel test section was modified so that the supper surface could accommodate a belt which could be moved with respect to the tunnel wall. This equipment, described in Part A of Reference (14), was designed and installed under the supervision of Prof. Robert E. Duffy of RPI. It has provided some of the earliest measurements of

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* An extensive bibliography on the bladeless fan exists which is also available from the author on request.

ground effect made with proper simulation of wall boundary conditions. It is constructed to handle flows over a flat ground plane, of course, so that results from it must be interpreted for actual Tubeflight vehicles. The unit consists of a commercial platen-type belt sander modified for a high-speed operation with special variable drive and a non-abrasive fabric belt. Its overall dimensions are: width, 20 inches; length, 50 inches; belt speed, continuously variable from 15 to 200 surface feet per second.

In a tunnel a boundary layer builds up on the wall. By installation of suction slots in the wall just ahead of the moving ground plane, an essentially uniform velocity profile can be produced on the belt in the absence of a support pad thus duplicating the desired boundary condition. Figure 8 shows the velocity profiles for several cases.

Tests of a Peripheral Jet Device

Figure 9 shows the cross-section of the support pad for which test results were reported in Reference (16). By cutting off the front curtain it can be converted into a jet flap device. In Figure 10 there is plotted the static augmentation A (lift divided by jet momentum) versus the clearance ratio h/c (height of pad divided by pad chord) and the predictions according to several theories. As other investigators have also found, the well-known thin jet theory is not very satisfactory. Duffy's results show that Chaplin's mixing theory agrees reasonably well with experiment.

The flow from a support pad is complex and its geometry changes radically with the vehicle forward speed. Observations show, even at very low speeds, that a portion of the front curtain is carried downstream underneath the pad. As the forward speed increases, ever more of the front curtain is carried underneath. Above the speed at which all of the curtain is swept downstream the pad is said to be operating in the supercritical flow regime. Another way of looking at this is that at a given forward speed, as the blowing vanishes, the curtain is swept underneath the pad and the supercritical condition obtains. As the blowing is increased, part of the curtain blows forward, which is the subcritical condition. The transition is gradual.

Figures 11 and 12 show the lift and drag coefficients for a peripheral jet plotted versus the momentum coefficient Cj (jet momentum, divided by the freestream dynamic pressure times the planform area). The subcritical region is to the right of the dashed line. Duffy finds that when the flow is strongly subcritical there is little difference between the results of the moving and the fixed walls. In the supercritical regime the differences are marked and it is essential to simulate the proper wall boundary condition. For the jet-flap, on the other hand, it is essential to simulate the moving wall condition over the entire range of Cj, as Figure 13 indicates. Duffy also finds for a peripheral jet that even in subcritical operation thrust recovery of the order of 30% can be realized, increasing to 100% in the supercritical regime.

Contributions to the Theory of Fluid Support Devices

In Reference (17) Cooke undertakes to analyze the problem of a jet flap airfoil operating in ground proximity by the method of linearized potential flow. He deals only with the supercritical case in which the jet does not attach itself to the ground plane. An extensive discussion of the analytical techniques in computing a solution is given, and of certain limitations of the method. In the limit as the blowing vanishes the problem reduces to that of a ram wing. It is concluded that although the technique compares favorably with other procedures, additional work is required to assess how viscosity and first-order thickness and camber effects alter the utility of the potential flow solution.

Cooke(18) has also calculated exact potential flow results for peripheral jets and plenum chambers. The theoretical approach had been developed previously. Cushion pressures and discharge coefficients were calculated for several nozzle angles for height-to-thickness ratios from 0 to 6. The results show that the assumption of parallel flow at the exit can alter the computed values for cushion pressure and the discharge coefficient by as much as 10%. Cooke also calculates the theoretical discharge coefficient for plenum chambers of arbitrary lip angle from a limiting form of the equations.

SMALL-SCALE EXPERIMENTAL STUDIES

The T-2 Facility

In order to demonstrate feasibility of the Tubeflight concept work was begun early in 1966 on a facility (designated by the symbol T-2) to permit testing of Tubeflight vehicles. Through the courtesy of the Penn Central System a site was made available in the city of Rensselaer, N.Y., about 10 miles south of Troy, which was essentially flat and permitted a straight run of 2000 feet, about the minimum thought useful.

The tube consists of a steel pipe welded into a single piece with mean inside diameter of 12.35 in., 0.203 in. wall. The welding process requires special care -- compared to pipeline industry standards -- to ensure that internal lips are not left. Since in this length a 100°F temperature change involves a length variation of 18 inches the pipe is supported by saddles at 20-foot intervals along its length. Transducer stations consisting of modified Threadolets are welded on the upper surface of the pipe at 10-foot intervals. These accommodate either transducers or pipe plugs so that the pipe can be sealed off for pneumatically powered cleaning operations.

Figures 14 and 15 are two views of the T-2 Facility. At the launch end, Figure 15, the tube end is housed in a wooden shed and is equipped with a special starting gate (valve) which is necessary only during the acceleration phase. Next to the shed is an office-site trailer which houses the speed-recording instrumentation.

The speed-recording instrumentation has evolved gradually from the original system which involved photoelectric transducers triggered by a light source on board the vehicle. For a variety of reasons this eventually proved unsatisfactory. The final transducer employs a silicon photovoltaic cell which activates a high-gain, AC-coupled, 3-stage amplifier with an emitter-follower output. This unit emits a pulse when a vehicle interrupts a light-source located on the opposite wall of the tube and transmits the pulse over a coaxial cable to the recording equipment located in the trailer.

The time-interval between two consecutive pulses is measured by a counter, fed to a coupler unit and eventually punched out on paper tape. If desired the output from the tape can be readily converted to magnetic tape and fed to a computer.

The Tubeflight Test Vehicles

A series of Tubeflight test vehicles has been designed and constructed, and in most cases tested. They are designated:

Mark I -- A small, light-weight, demonstration vehicle employing plenum chamber support. The vehicle, 4 feet long, weighing 12 pounds, was built under the direction of H. Hagerup under an NSF grant. Its first successful flight (and the first flight of any air-cushion-supported Tubeflight vehicle) took place in March of 1967. During the course of its several flights it reached a top speed of 23 feet per second during a 2000-foot run.

Mark IIa and IIb -- These two vehicles are essentially identical except that IIa lacked the top pair of support pads installed in the IIb-model, Figure 16. Propulsion is by a pair of Rossi-60 engines, rated at about 2 hp, driving special fiberglass propellers. Support is provided by a pair of 120°-arc peripheral-jet support pads, supplied by an AiResearch blower rated at 20 in. H_2O pressure rise, at 22,000 rpm. The blowers are also driven by Rossi-60 engines. The IIb model has a pair of 60° support pads at the top to keep the vehicle away from the tube roof as the flow speed increases. Test results for the Mark II vehicles are given below. Diameter of all Mark II vehicles is $d = 7$ in. The vehicle lengths vary, depending on the configuration, from 8 to 13 feet, and the weight of IIa, IIb from 65 to 75 pounds.

Mark IIc -- This vehicle, shown in Figure 17, is a simplified version of the preceding two. The entire center body of the vehicle including the support pads has been replaced by a 7-inch diameter cylinder in which was installed a pair of specially machined, precision balanced, 3-wheel supports, fore and aft. The wheels are mounted to be tangent to the inside of the T-2 Facility so that no lateral or vertical motion of the vehicle is possible. The Mark IIc vehicle is driven by a single, Rossi-60 engine in a pusher configuration. The vehicle weight in the 8-foot long configuration, is about 40 pounds.

Mark IIIc -- The Mark IIIc vehicle employs the same vehicle support and nose sections as Mark IIc but the powerplant is a modified McCulloch Mc-100 engine as shown in Figure 18. The engine rpm is stepped up by a 2-to-1 gearbox transmission which in turn transmits power through a special, counter-rotating gearbox to a pair of 3-bladed, fiberglass, adjustable propellers of 11 in. diameter. The engine is expected to deliver upwards of 15 hp at 10,000 engine rpm. The vehicle weighs about 60 pounds.

Mark IV -- The Mark IV vehicle is designed to test the bladeless fan propulsion scheme. As shown in Figure 19, the rotor of a bladeless fan has been mounted at the rear of an air-cushion center body for the purpose of illustration. The fan will be supplied by a 3-stage AiResearch axial fan supplying 1000 cfm at 90 in. H_2O pressure rise, which requires about 20 hp to drive it. However, due to lack of a suitable, vibration-free power supply for the fan, testing of this configuration has not yet been possible.

Notes on the Peripheral Jet Pad Design for the Mark IIa, IIb Vehicles

To fix the design parameters for the first Tubeflight air-cushion support pads, two-dimensional thin jet theory was employed. Allowing for what turned out to be an insufficient margin of error it was calculated that a 120°-arc pad with a 9-inch chord and a 90°-angle jet curtain should produce about 0.6 in. of clearance and 30 pounds of static lift, with air supplied by the AiResearch blower selected. The radius of the pad lower surface was chosen to give a uniform 0.6 in. clearance from the tube bottom.

A number of factors contributed to the complete failure of this design. The Rossi engine proved incapable of sustained operation above 19,000 rpm. This loss in blower output coupled with higher internal duct losses than estimated, resulted in only an 8-to-10 in. H_2O pressure increment at the jet curtain exit. Further, it became evident that a pad, which is concentric with the tube (and therefore of smaller radius) at design clearance, has very poor performance in close proximity to the wall since the pad tip clearance is still about 0.3 in. when the ℄ is touching bottom. This appears to be an undesirable aerodynamic configuration since the potentially most efficient part of the pad (the ℄) has little or no curtain while the least efficient (the tips) has it all. The worst factor was the unforeseen inadequacy of thin jet theory which predicts clearances about double the measured value. The consequence was that in the tests the pad lay supinely on the tube bottom while the air blew ineffectually from the tips.

In the second design a number of changes were introduced. The pad chord was increased to 18 in. and the jet curtain angle to 45°, directed inward. Further, the pad external radius was made equal to the tube radius. This meant that the tip clearance was only 0.3 in. when the ℄ clearance was

0.6 in. Happy to report, this design hovered very well, lifting up to 50 pounds without bottoming. Future designs of Tubeflight air-cushion pads will require considerable additional research before the most desirable configuration can be determined.

Tests of the Mark II Vehicles

Tests of the Mark II vehicles in the T-2 Facility were begun during the summer of 1967 after the instrumentation system had been checked out. The test program was plagued by an unending series of failures of the Rossi engines, principally in the pair driving the blowers, due to overheating, but also less frequently in the propulsion engines. Since each test required successful operation of all four engines to maintain flight the situation became one of attempting to increase reliability. (Note: the reason both propulsion engines must operate to maintain flight is that a failure of one creates in an unbalanced torque which results in an overturned vehicle).

Nevertheless a number of runs of varying flight length were made which enabled us to ascertain that the Mark IIb had a top speed with the Rossi-60 powerplants of only about 28 fps which is much less than the 50-60 fps determined by a rough performance calculation. It was tentatively concluded that the deficiency was due to 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, essentially creating a separated flow from the pads and raising the vehicle drag.

As a means of checking this hypothesis, tests were run on a Tubeflight air-cushion pad in the T-3 Facility, a special wind tunnel(19) constructed under an NSF grant especially for Tubeflight experimentation. Its cross-section is identical to the T-3 Facility and has a 12-foot long test section with a clamshell door. As completed the tunnel can operate with a model at a tube/vehicle diameter of 1.5, with a tunnel speed of 270 fps. It was verified that the basic problem was the air-cushion pad design. Because of the small-scale the pad thickness ratio is greater than would be necessary in a full-scale vehicle. The effects of pad-body interference coupled with separation of the flow downstream of the pad -- even in the no-blowing condition -- resulted in a drag about twice that of the body alone.

It was decided to abandon temporarily flight tests of fluid-supported vehicles and concentrate solely upon the propulsion question. To check out the power-demand theory of Foa, the Mark IIc vehicle was constructed, powered by a single Rossi-60 engine. To counteract the torque a counterweight was placed inside the vehicle shell. The series of Mark IIc tests is reported in Reference (20). The highest speed obtained was about 75 fps.

The power required to propel the Mark IIc and Mark IIIc wheel-supported vehicles, based on the theoretical work previously described, has been computed by Foa and Messina, Reference (21). Figure 20 gives the principal results, the power required as a function of cruising speed with vehicle length as parameter. In order to obtain the thrust horsepower it is necessary to have available the propeller performance data. Tests of the Mark II propeller were run in the T-3 Facility by Graham and Messina(21). They conclude that the power demands of the Mark IIc vehicle tests lie within a few percent of the predictions of Foa and Messina in the speed range 70-75 fps.

Tests of the Mark IIIc Vehicle

The power plant of the Mark IIIc utilizes a drastically modified Mc-100 engine. To eliminate undesired vehicle rotation in flight arising from engine torque, a custom-made, counter-rotating gear box was designed which transmits the power to a pair of 3-bladed, adjustable-pitch propellers. Static tests of the Mc-100 were begun late in 1968 and resulted in a series of crankshaft and power-train failures. This problem was traced to the vibration characteristics of the modified engine whereby the addition of the gear box and propellers apparently results in a torsional natural frequency lying close to the operating speed of the engine (range 6,000-10,000 rpm). To eliminate these failures a special Coulomb-friction damper was designed and installed on the flywheel end. This unit has eliminated the failures completely and is of sufficient interest that its theory and operation will be described in a future paper.

The Mark IIIc vehicle has been operated at low power settings at speeds up to about 110 fps. Higher speed tests await better weather at the T-2 Facility.

In order to pinpoint the Mark IIIc power demands it is necessary to run a new series of propeller efficiency tests in the T-3 Facility. To drive the propellers, special Task Inc. wind-tunnel-model electric motors are employed. Their use has required construction of a special 30 KVA, 3-phase, variable-voltage, variable-frequency power supply. This unit is now in operation and will permit completion of the measurements over the next few months. The final Mark IIIc tests will be reported at that time.

CONCLUDING REMARKS

The undertaking of an engineering project of the scope of Tubeflight at an engineering school is a rather rare event. With the limited resources available it is not surprising that mistakes were made. In particular, it is useful to note that progress was severely hampered in the small-scale experimental studies by the selection of the T-2 tube diameter of 12.35 in. ID. This limited the choice of available powerplants to small, internal combustion engines, driving propellers. If the tube size had been 30 in. ID, a turbofan could have been utilized which would have eliminated the subsidiary work of trying to make the Mc-100's work in our application. Of course, a 30-inch tube would have significantly increased costs and would have required a much longer tube for testing. The whole scale of the operation would have stepped up, probably beyond the capability of a school to handle it within an academic program.

It is the writer's opinion, along with those of his colleagues, that the Tubeflight concept is ready for an intense industrial development -- of at least half scale for fluid-supported vehicles. However, for wheel-supported applications in the range of 150-200 mph it is likely that a full-scale development could be undertaken immediately. There are a number of timely applications possible. To cite an example: in the feeder lines which must be built to serve the next generation of jet airports which will be located rather far from the centers of the major cities they will serve. New York, Miami, and Los Angeles are important candidates in this category.

For the full-scale fluid-supported vehicles, Figures 21 through 23 give an artist's version of how the system might appear in several different situations. The decision to build such systems must be made soon if they are to be ready in the '70's. The writer hopes to be forgiven if, at a Space Congress, he suggests that the Age of Tube Transportation is at hand.

ACKNOWLEDGMENT

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The writer also wishes to express his thanks to Mr. Arthur E. Poole, President, Poole Construction Co. who donated the cost of construction of the T-2 Facility, and to Mr. Charles Defendorf, Chief Engineer, Penn Central System, who arranged for the use of the site on which the T-2 Facility is located.

It is a genuine pleasure to acknowledge the stimulating relationships with those of my colleagues on the faculty of RPI who have participated in Project Tubeflight. This review draws heavily on their reports and publications and on those of a number of our graduate and undergraduate students. It is also highly appropriate to call attention to the devoted work of our technical staff, particularly in the construction and operation of the T-2 and T-3 Facilities, and in the construction of the series of models mentioned in the body of this article.

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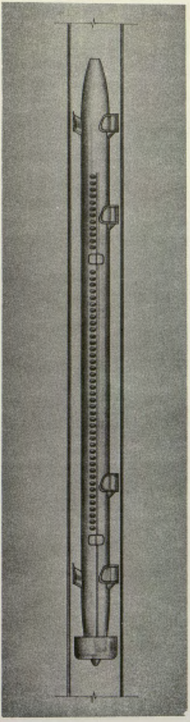

Figure 1. Artist's Version of Full-Scale Tube-flight Vehicle With Ducted Fan at Vehicle Nose, From (6).

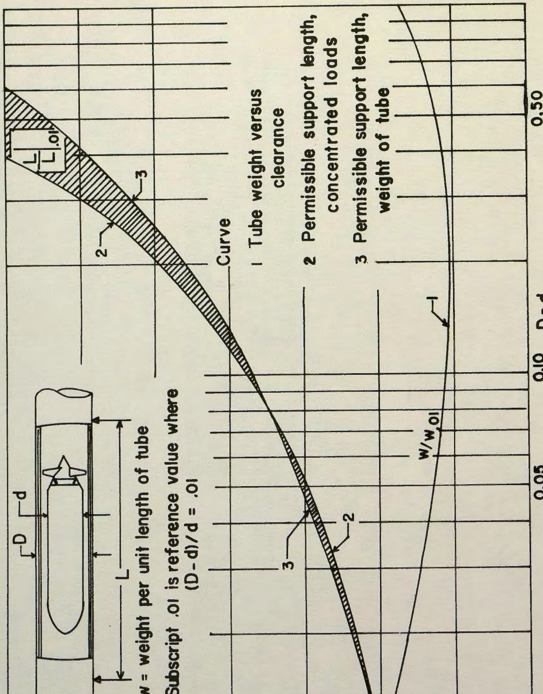

Figure 2. Tube Weight and Tube Length between Supports Versus Dimensionless Clearance, From (7).

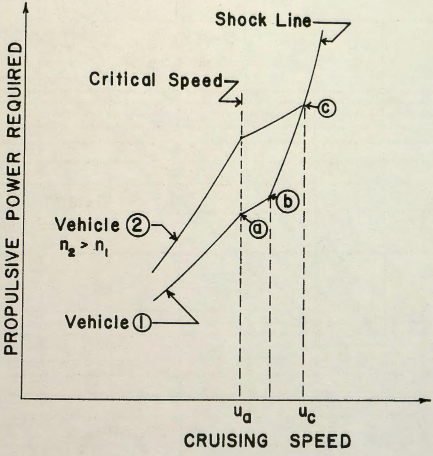

Figure 3. Reduction of Propulsive Power Required Per Passenger Above the Critical Speed, From (13).

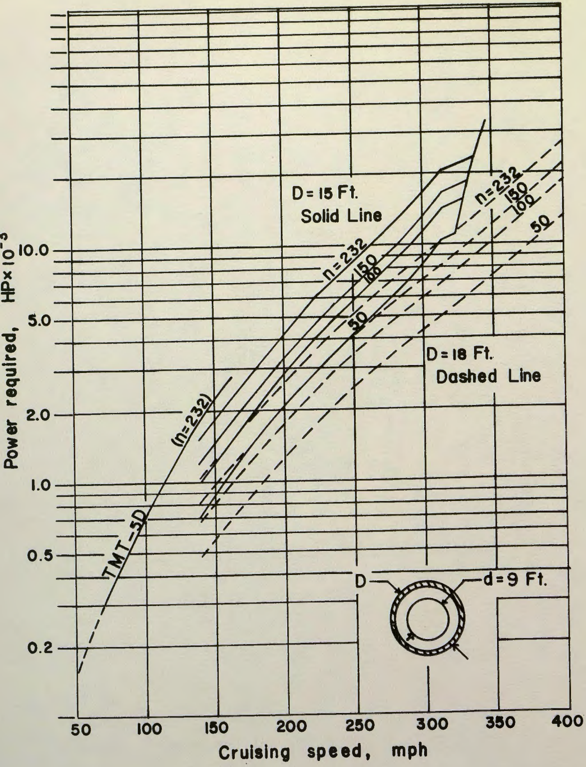

Figure 4. Power Required for Two Tube/Vehicle Diameter Ratios, From (13).

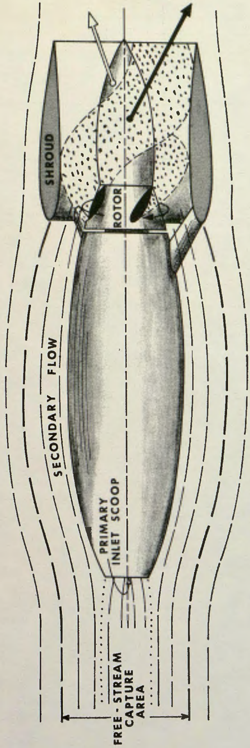

Figure 5. Schematic of a Bladeless Fan, From (15).

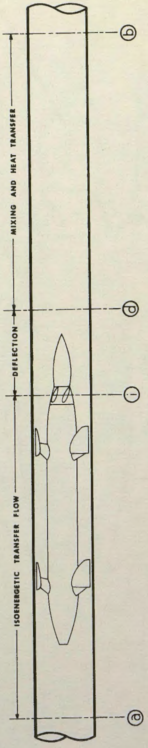

Figure 6. Tubeflight Vehicle With a Bladeless Fan, From (15).

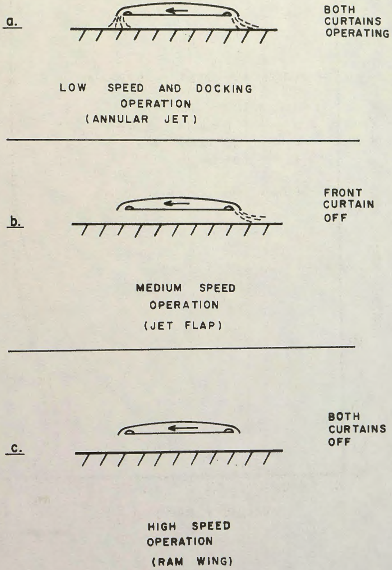

Figure 7. Operational Configurations of Tubeflight Support Devices, From (16).

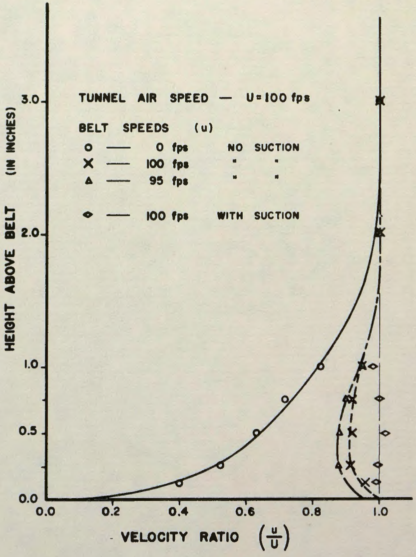

Figure 8. Velocity Profiles of Flow Over a Moving Wall, From (16).

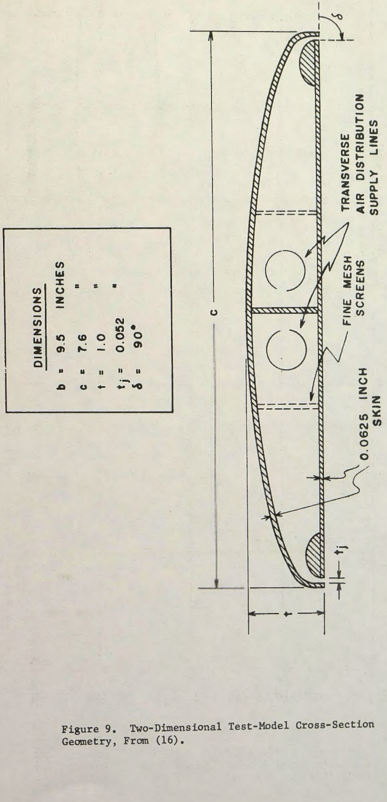

Figure 9. Two-Dimensional Test-Model Cross-Section Geometry, From (16).

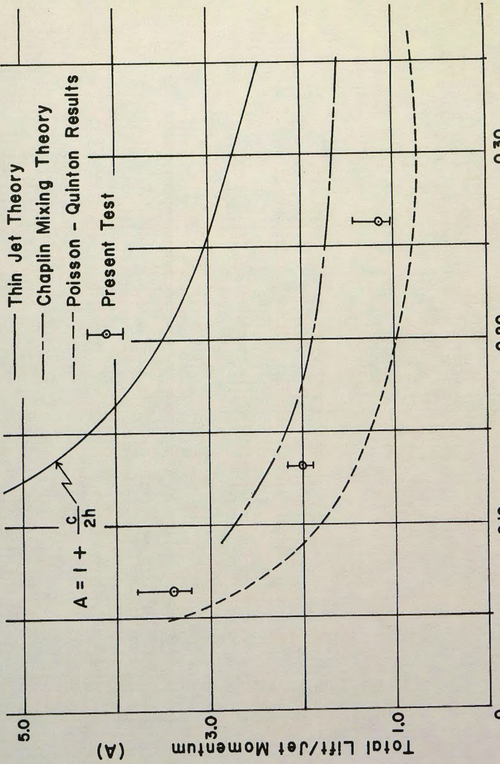

Figure 10. Static Augmentation of a Peripheral-Jet Device Plotted Versus Ground-Clearance Ratio, From (16).

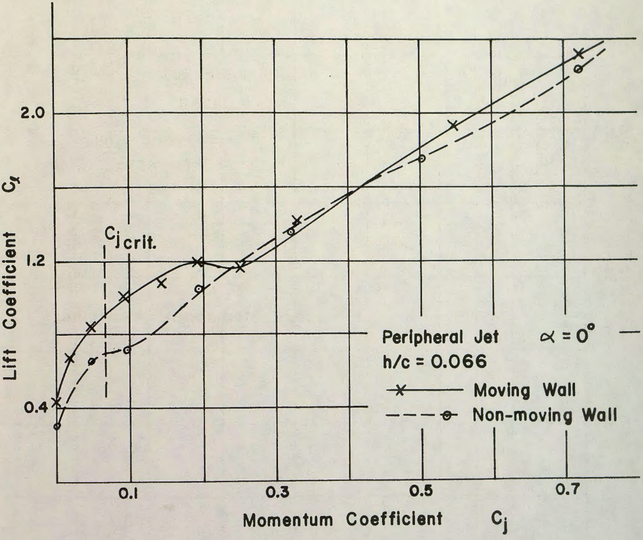

Figure 11. Lift Coefficient Versus Momentum Coefficient, Peripheral Jet, From (16).

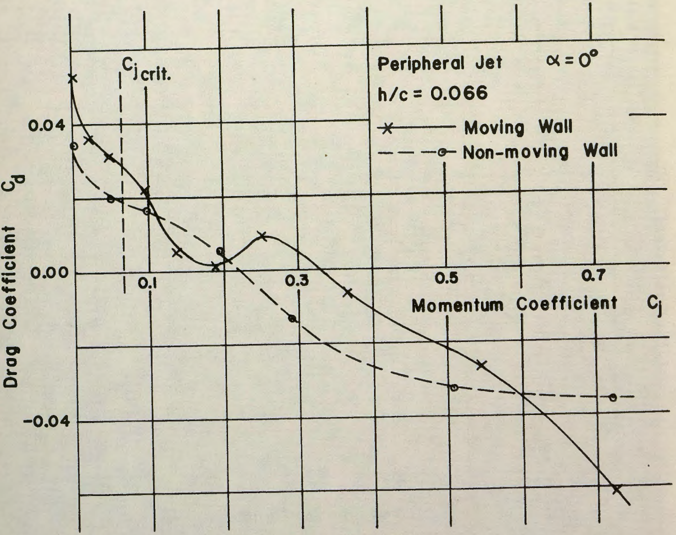

Figure 12. Drag Coefficient Versus Momentum Coefficient, Peripheral Jet, from (16).

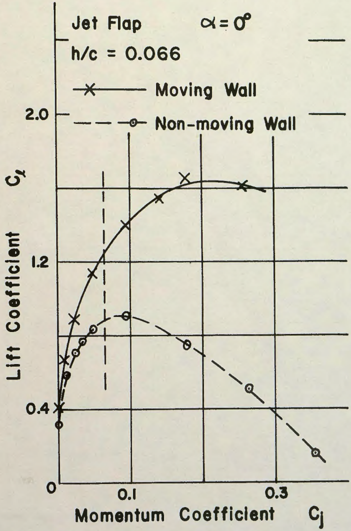

Figure 13. Lift Coefficient Versus Momentum Coefficient, Jet-Flap, From (16).

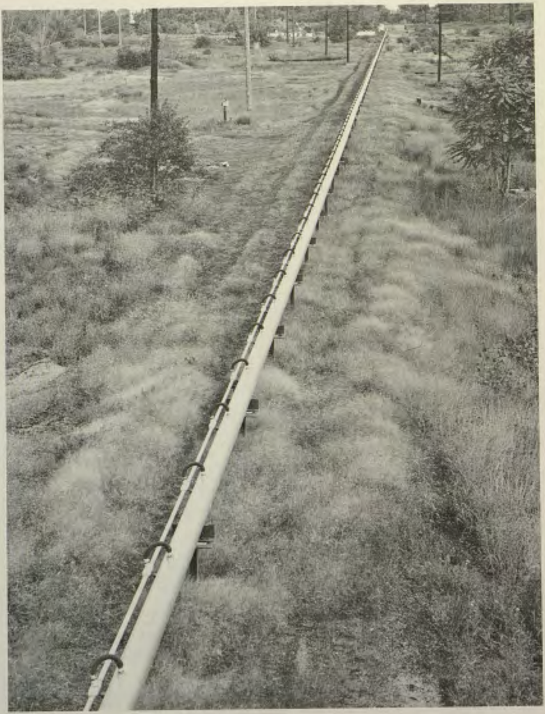

Figure 14. The T-2 Facility Looking Toward The Launching End.

Figure 15. The T-2 Facility, Launching End.

Figure 16. The Mark IIb Vehicle.

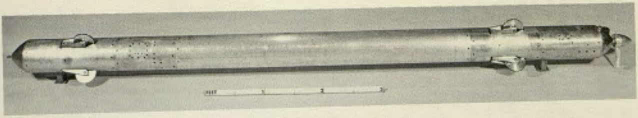

Figure 17. The Mark IIc Vehicle.

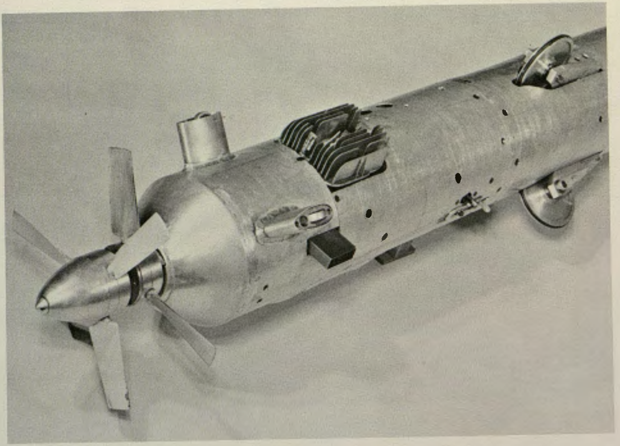

Figure 18. The Mark IIIc Power Plant.

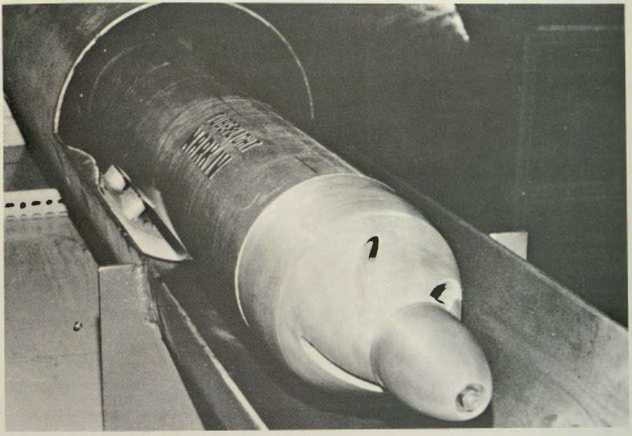

Figure 19. The Bladeless Fan Rotor for the Mark IV Vehicle.

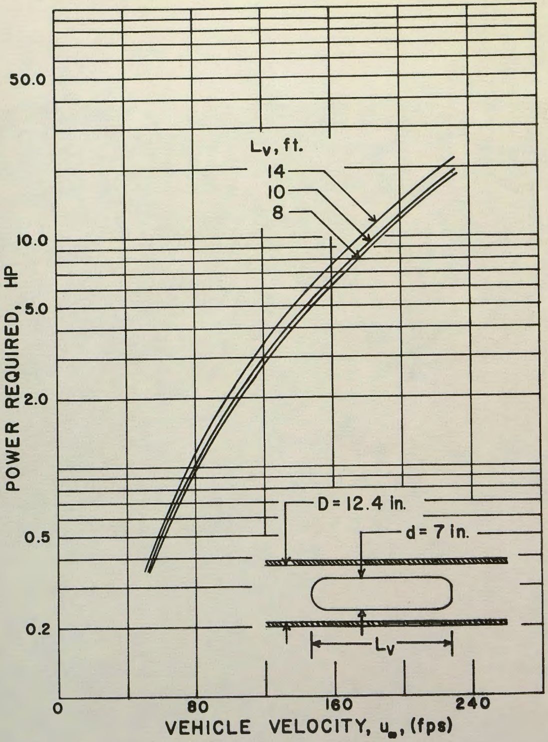

Figure 20. Power Required for Mark IIc and Mark IIIc Wheel-Supported Vehicles, From (21).

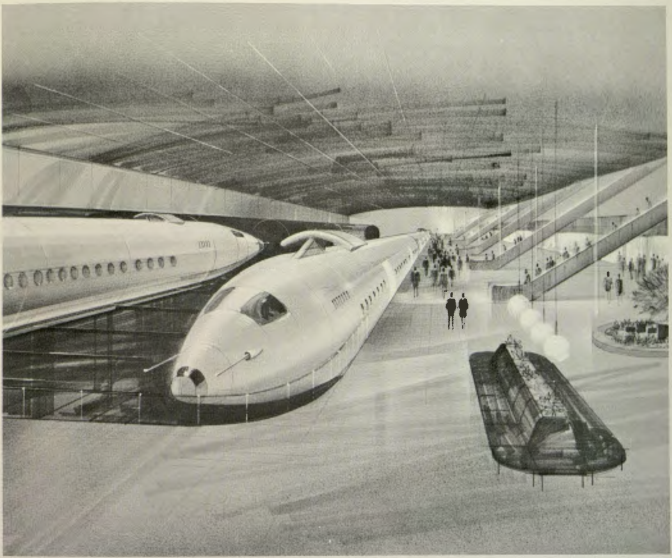

Figure 21. Artist's Version of Tubeflight Vehicles Docked at a Terminal.

Figure 22. Tubeflight Structure for Crossing a River.

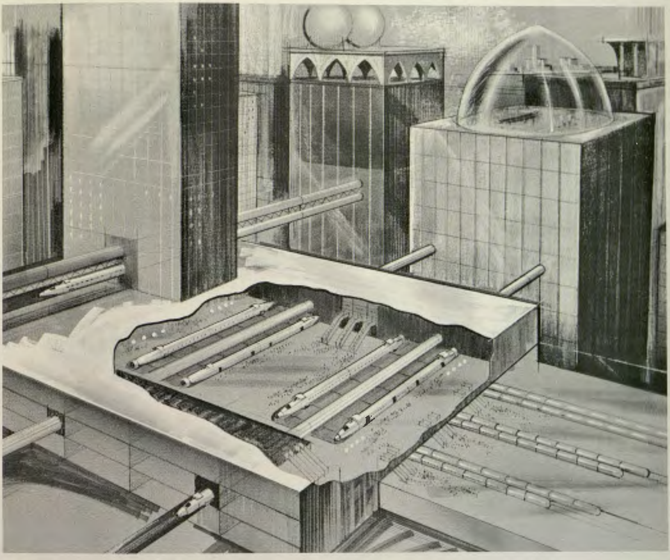

Figure 23. Tubeflight System in a Major City.