JOURNAL OF PROPULSION AND POWER
Vol. 10, No. 1, Jan.–Feb. 1994

Facility Opportunities and Associated Stream Chemistry Considerations for Hypersonic Air-Breathing Propulsion

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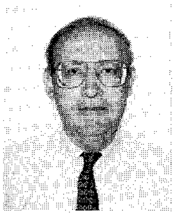

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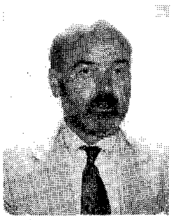

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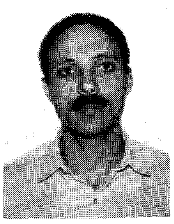

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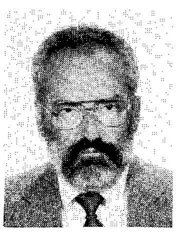

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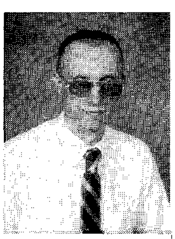

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Presented as Paper 92-3991 at the AIAA 17th Aerospace Ground Testing Conference, Nashville, TN, July 6–8, 1992; received July 17, 1992; revision received April 23, 1993; accepted for publication April 29, 1993.

I. Introduction

THE exploration and utilization of space, both near Earth and within our solar system, as well as eventually interstellar, is a continuing national goal. A major requirement to achieve this goal is affordable and reliable access to near Earth orbit. There are two obvious approaches to reducing the cost of access to space: 1) improved conventional rocketry and 2) advanced technology. Reduction in the cost of rocket launch systems requires either use of low-tech, expendable boosters, which are labor-intensive to build and launch, and therefore, only inexpensive for countries having low-cost labor, or redesigning the components of the launch system to be fully reusable and to be sufficiently reliable that the "standing army" required to launch the system can be downsized or eliminated. The advanced technology options cover a wide spectrum ranging from combined cycles incorporating hypersonic air-breathing propulsion, nuclear rockets, ground-based laser propulsion, the use of metastable excited-state high-energy fuels, to the use of antimatter fuels. Of these, only the air-breathing propulsion and nuclear rocket options have near-term prospects. This Paper concerns itself exclusively with the ground test requirements for the hypersonic air-breathing option and the facility opportunities to meet them. This general subject has been addressed in a series of papers over the past several years.[1–4] This Paper devotes particular attention to the issues of stream chemistry in propulsion facilities and simulation requirements at the upper hypersonic-hypervelocity range approaching orbital speed.

For about 35 yr, mankind has successfully flown vehicles into and through the hypersonic [$5 < M < 0(14)$] and hypervelocity [$M > 0(14)$] speed regimes, to Mach numbers of the order of 35 during lunar return of the Apollo vehicle and beyond (planetary probes). However, what has been flown are slender, axisymmetric bodies at small angles of attack (i.e., ballistic re-entry vehicles), or very blunt bodies (entry capsules and the Space Shuttle) at high angle of attack on re-entry. They have been either unpowered or rocket powered, and, except for the shuttle, typically designed for a single duty cycle. We do not have experience with reusable, slender, lifting, three-dimensional hypersonic/hypervelocity vehicles with fully integrated inlets and nozzles, and incorporating active, regenerative cooling. The reusable hypersonic/hypervelocity air-breathing engine constitutes "terra-incognita" with regard to flight performance, and raises critical new issues regarding the simulation capabilities of ground test facilities.

The engine cycle that dominates the hypersonic air-breathing concepts currently being studied and/or developed is the diffusive-burning supersonic combustion ramjet, or scramjet, which, in principle, can operate from about Mach 6 to near-orbital speeds. However, studies suggest that the oblique detonation wave supersonic combustion process may provide superior performance at the high-end of the flight path, at Mach numbers exceeding about 14.[5] In either case, ground testing of such engines presents unique facility requirements that are daunting compared to simulation requirements for hypersonic aerodynamics. These include the need to do the following:

1) Duplicate the internal flow-path, stream velocity, pressure, temperature, chemical composition, and turbulence in order to replicate the fluid physics and chemistry of the combustor.[6]

2) Duplicate the inlet shock wave system swallowed by the engine, since it will interact directly with the fuel injection and combustion mechanisms in the diffusive-burning engine or will become the combustion mechanism itself in the detonation wave engine, and the resulting internal shock system will emerge from the combustor and affect the nozzle performance.

3) Duplicate the heat load imposed on the engine internal structures by the captured airstream, which exceeds that imposed by the fuel combustion per se, as well as the associated aerodynamic and aeroelastic loads.

4) Provide sufficient test time to evaluate ignition and steady-state combustion phenomena.

The basic facility requirements can be stated most succinctly in terms of the total flight enthalpy and total pressure requirements shown in Figs. 1 and 2. [The terms total temperature (or enthalpy) and total pressure denote the values calculated following an isentropic compression of atmospheric air from the flight velocity to a stagnation condition assuming shifting chemical equilibrium. The assumption of a perfect gas, by contrast, would result in higher temperatures and lower pressures, but is considered unrealistic for hypersonic conditions.] Little latitude exists in the total enthalpy requirement since it is composed almost entirely of kinetic energy (velocity). Atmospheric variations in static temperature alter the Mach number at a given velocity point in the flight trajectory, but are inconsequential with regard to the total enthalpy at that trajectory point. On the other hand, the flight total pressure is directly dependent on the flight trajectory, and the engine total pressure additionally depends on the inlet efficiency. Obviously, the facility total pressure capability needed for combustor testing depends on the portion (if any) of the inlet being simulated. Therefore, a fairly broad free-stream total pressure band, defined by flight dynamic pressures from 200 to 2000 psf, is depicted in Fig. 2, with a cor-

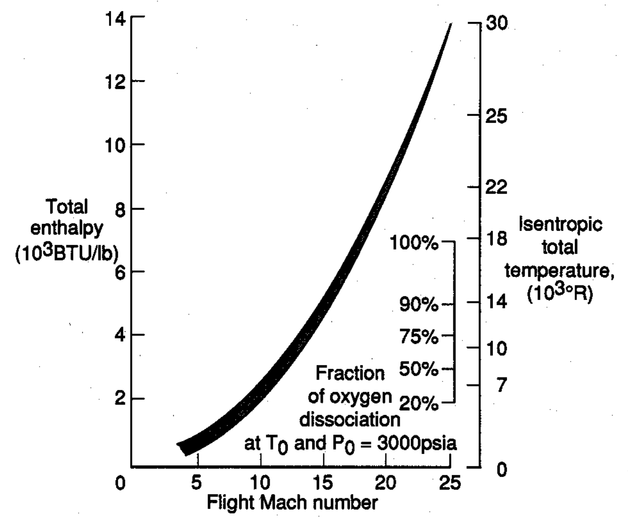


Fig. 1 Facility total enthalpy requirements for hypersonic air-breathing propulsion.

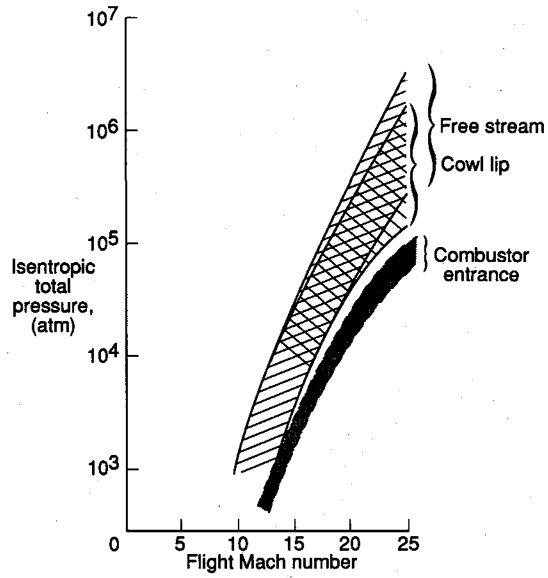


Fig. 2 Facility total pressure requirements for hypersonic air-breathing propulsion.

respondingly broad cowl lip band. The latter represents the general requirement for "freejet" engine tests. The band for combustor entrance conditions is somewhat narrower since it is defined by the static pressure which must be obtained to maintain combustion. This is typically of the order of 1 atm.

Further definition of facility requirements must distinguish between 1) facilities needed to perform basic research and technology development relating to operability and performance of engine components and complete engine flow-paths; and 2) true engine development facilities needed to demonstrate durability, as well as operability and performance, of full-scale, flight-weight, flight-rated engines. For simplicity, we will refer to these as "propulsion research facilities" and "engine development facilities," respectively. It is important to bear in mind the very different, but essential, roles these two types of facilities play. The research facilities must be relatively inexpensive, since several different types, tailored to specific engine components, speed ranges, etc., will certainly be needed. Furthermore, they must be relatively inexpensive to use, since a broad range of engine design parameters need to be evaluated, and CFD modeling of hypersonic/hypervelocity engines must be extensively and critically verified. The development facility will necessarily be large, expensive to build, and expensive to run. It is unlikely that even the most economically advanced nation can afford more than one facility of this nature. Therefore, it must be very carefully conceived, planned, designed, and constructed. Compromises in flow quality (e.g., chemical composition) may be necessary to achieve test time or to meet affordability criteria. One of the many applications of the propulsion research facilities, in concert with demonstrated CFD modeling capabilities, will be to define the essential requirements of the engine development facility through sensitivity analyses.

Given a total pressure limit of less than 40,000 psi for all currently operating wind tunnels and shock tunnels, it is clear from Fig. 2 that the current facility base simply does not possess the requisite capability to properly address high hypersonic or hypervelocity propulsion, from either the research or development perspective. Additionally, at total enthalpy levels exceeding about Mach 8, the production of nitric oxide at levels exceeding that which would enter the combustor in flight becomes a potential simulation problem. At total enthalpy levels exceeding about Mach 12, the further depletion of molecular oxygen and its replacement by atomic oxygen becomes a major simulation problem. The (approximate) levels of total temperature and molecular oxygen depletion at those temperatures are indicated in Fig. 1. Clearly, a test facility that creates high levels of oxygen dissociation and fails to achieve recombination in the test section is of dubious value for air-breathing propulsion research, and must be scrutinized carefully as an engine development facility. The character of the freestream turbulence produced by hypersonic/hypervelocity test facilities and its interaction with transition and turbulent mixing is largely unknown. What then are the prospects for ground test facilities in this arena?

II. Advanced Hypervelocity Facilities

A. Propulsion Research Facilities

The principal discriminant between the test facilities to be described in this section and the engine development facilities to be described in the following section is test time. The reflected shock tunnel (RST) has been the experimental mainstay of hypersonic/hypervelocity research for more than 30 yr. The application of this type facility to hypersonic air-breathing propulsion research has been extensively described in Ref. 4. Reflected shock tunnels create the required total pressure and total enthalpy by generating a strong shock wave that reflects off the end of a shock tube, thereby creating a reservoir of stagnant gas (behind the reflected shock) which is expanded through a converging-diverging nozzle. The maximum total enthalpy that can be generated is proportional to the shock velocity, which, in turn, is related to the initial ratios of sound speed and pressure between the driver gas and test gas. The maximum total pressure is limited by the mechanical strength of the driver and shock tubes. Thus, the performance of RSTs is effectively bounded by tube strength and driver gas sound speed. The latter consideration has led to use of light gas drivers, electrically heated driver tubes, combustion-heated driver gases (H_2-O_2-He mixtures) and, most recently, to compressively heated drivers using a heavy free piston, each with increased performance. Among the free piston-driven RSTs in current operation are T4 (University of Queensland, Brisbane, Australia), T5 (California Institute of Technology, Pasadena, California) and the world's largest, HEG (Gottingen, Germany).[7] The last named location has achieved total enthalpy levels as high as about Mach 8 flight conditions (based on Fig. 1), at a total pressure of 952 atm, and with reported test times approaching 2 ms when operating in a tailored interface mode.

The costs of such facilities are relatively modest considering the levels of energy that can be created. The test times are, however, very brief, typically measured in milliseconds. They are therefore considered unsuitable as engine development facilities since the engine hardware barely begins to warm up before the test period is over. This is, however, a blessing in disguise, since very inexpensive model hardware (e.g., aluminum) can be used, and large, uncooled windows can be put in the model to permit flow visualization; also, optical diagnostic instrumentation can be used that is impractical or impossible to use in long duration facilities (even at lower total enthalpy levels).

Regardless of their other advantages for propulsion research, RSTs (like any other wind tunnel that contains the test gas at or near the stagnation temperature) suffer progressively worsening stream chemistry problems as the simulated flight Mach number increases above about Mach 8 or 9. The first stage of this problem is the formation of nitric oxide and atomic oxygen in the plenum. The extent of recombination to molecular oxygen and nitrogen in the facility nozzle is dependent on the facility total pressure and nozzle expansion rate and length, to some degree. Generally speaking, however, the nitric oxide is extremely stable and whatever level exists at the nozzle throat will persist to the test section. Furthermore, as will be discussed in Sec. III, increasing total pressure enhances nitric oxide formation in the plenum, although atomic oxygen is suppressed. Since nitric oxide has nearly the same molecular weight and specific heat as nitrogen and oxygen, it is an innocuous contaminant for aerodynamic tests. However, it is a well-known catalyst for hydrogen-air ignition, and the effective heat of combustion of hydrogen in nitric oxide is about 36.5% higher than in molecular oxygen. The general level of molecular oxygen, reaching the test section of typical RSTs is plotted in Fig. 3. Again, the actual level for any particular facility will vary depending on factors such as total pressure, facility size, nozzle expansion rate, etc. The pressure of atomic oxygen in the test stream will greatly enhance hydrogen-air ignition rates, especially at low static temperatures. The effective heat of combustion of hydrogen is about 104% higher in atomic oxygen than in molecular oxygen. Consequently, this stream chemistry problem is significant at about Mach 10–14 test conditions.

Another class of research facilities are collectively referred to as "hot shot" tunnels. These employ direct heating of the test gas, usually by electrical discharge. The test times are generally longer than reflected shock tunnels, but the test conditions tend to decay with time. In addition, the dissociation problem is usually worse than in RSTs, due to the extreme temperature nonuniformity in an arc discharge and relatively low total pressures at which such hot shot tunnels operate. Hot shot tunnels have not been used in this country for a number of years. However, a unique tunnel in Russia that falls in this general category has recently been described.[8,9]

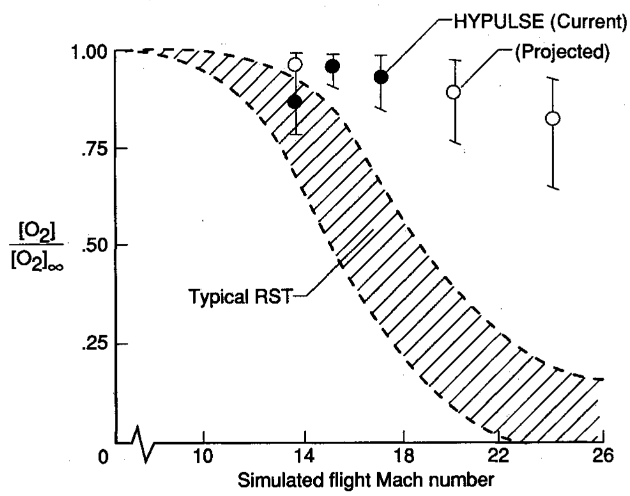


Fig. 3 Depletion of molecular oxygen in the test section of typical reflected shock tunnels and in the HYPULSE expansion tube.

Referred to by its designers as a piston gasdynamic unit (PGU), it employs nonisentropic compressive heating of the test gas, rather than electrical discharge. A large, heavy free piston is used to compressively heat the test gas by means of an essentially isentropic process to a high pressure, e.g., up to 40,000 psia and moderately high temperature. The gas is then impulsively admitted to a chamber where additional shock heating occurs, albeit at a loss in total pressure, and then to a second, pressure regulated, chamber which is the plenum section of the tunnel. Two operational PGU facilities are reported to achieve total temperatures and total pressures comparable to an electrically heated, helium-driven shock tunnel (about Mach 10 conditions), but with test times up to 1–3 s (as compared to 1–3 ms). Throat integrity becomes a major consideration with the thousand-fold increase in test duration. Active cooling is required to prevent melting when using nitrogen as the test gas, and additional countermeasures (as yet undescribed) must be taken to prevent burning out the throat when using air as the test gas.

It does not appear likely that the PGU concept can be extended to propulsion research at significantly higher flight Mach numbers where airstream dissociation becomes a major consideration. However, the present PGU tunnels offer the prospect of virtually unlimited test time (relative to a shock tunnel) for research into flow establishment processes in a combustor environment. Furthermore, the PGU concept offers possibilities for the first stage of a two-stage engine development facility which will be discussed in the following section.

An arc-heated wind tunnel concept[10] described in the next section as the electrothermal wind tunnel (EWT) can also be operated in a single pulse mode. In this mode it is, in essence, a "hot shot" tunnel. Unlike prior electrically heated hot shot tunnels, the EWT is capable of very high total pressures, e.g., 100,000 psia, since the arc is discharged through liquid air. For reasons that will be discussed subsequently, this increase in total pressure does not eliminate stream chemistry limitations. The primary application of the EWT is likely to be as the first stage of an engine development facility. Nevertheless, a pilot version of the EWT operating in a pulse discharge mode would constitute a useful propulsion research facility for the flight Mach 10–14 range. At higher flight Mach numbers, stream dissociation, as well as total pressure, become considerations which favor another type of propulsion research facility; the expansion tube.

It should be noted, a priori, as pointed out in Ref. 11, that the stream dissociation chemistry can be correlated with the plenum entropy evaluated at the plenum pressure and temperature. This correlation also clearly indicates the futility of looking at moderately increased plenum pressure to alleviate the problem, since entropy varies with the logarithm of pressure. In addition, strategies for compensating for oxygen dissociation limitations in a RST have been devised[12] which have potential utility where dissociation levels are not excessive, and/or where static temperatures are so high as to attenuate the effects of test gas dissociation. However, it is clearly desirable to avoid the problem altogether, if possible, when conducting research in hypervelocity propulsion, especially in oblique shock-induced combustion or oblique detonation waves, which can be sensitive to upstream chemical state.

Operation of a shock tunnel in a nonreflected mode alleviates the dissociation problem to a certain extent, but at the price of sharply reduced test time. A better solution to this problem is to operate in an expansion tube or expansion tunnel mode.[13,14] An expansion tube uses an incident shock wave to impart only a portion (typically about one-third) of the energy to the test gas. The remainder of the energy is imparted by a system of unsteady (i.e., traveling) expansion waves which act on the moving test gas. Very high velocities (e.g., 17 kft/s) with correspondingly high total temperatures and total pressures (e.g., 15,000°R and 22,000 psi) can be achieved with an unheated helium driver gas at modest initial pressure, e.g., 5500 psia. The important points in regard to this type of facility are as follows:

1) The gas is never contained at its total temperature prior to reaching the test section, so the stream dissociation problem is alleviated.

2) The gas is never contained at its total pressure, hence, the tube strength requirements are correspondingly alleviated.

3) The total pressure achieved is a multiple of the initial driver pressure, and the magnitude of the multiple increases with increasing driver gas temperature.

Obviously, there is a penalty to be paid for all these performance advantages; test time. However, the penalty is not as severe as might be anticipated. In an expansion tube, test time is determined by wave processes and can be increased by increasing tube length until a limit is reached associated with boundary-layer attenuation of the shock speed. This limit is a considerably weaker function of total enthalpy (or simulated flight Mach number) than is the test time limitation in a RST. In a RST, contamination of the test gas with driver gas becomes the limiter on test time at high enthalpy, rather than reflected wave cancellation ("tailoring") requirements, resulting in a fairly rapid dropoff in useful test time as simulated flight Mach number increases. Further comparisons of test time are discussed subsequently.

A comparison of the molecular oxygen fraction reaching the test section in the HYPULSE facility with that for typical RSTs is presented in Fig. 3. The range shown at each current operating point for HYPULSE reflects the extremes of equilibrium chemistry behind the incident shock followed by frozen chemistry through the unsteady expansion (worst case) and equilibrium throughout (best case). The data symbols represent prior approximate finite rate chemistry calculations.[14,17] Recent finite rate chemistry calculations confirm that, in general, equilibrium is not achieved behind the incident shock, and frozen chemistry does not prevail throughout the expansion. The combination results in an end state closely approximated by the assumption of equilibrium throughout than the previous results indicated, although that is not the actual kinetic process by which the end state is reached. Virtually negligible oxygen dissociation is calculated at flight Mach numbers from 13 to 17, and oxygen dissociation levels as low as 5% can be projected to Mach 25.

It is important to realize that Fig. 3 is based almost entirely on the theoretical, finite rate chemistry calculations for ideal, one-dimensional flow in the various facilities. The only direct measurements of gas composition under conditions where substantial dissociation occurred were taken some years ago in the T3 facility at the Australian National University. The data agreed quite well with the theoretical calculations using air chemistry. On the other hand, with regard to the HYPULSE facility, additional calculations also show that a finite "holding time" before the Mylar diaphragm in the facility ruptures could cause a momentary shock reflection, resulting in oxygen dissociation levels that approach a RST. It is not currently known to what extent this phenomenon actually occurs, or whether it is offset by other nonideal effects, such as entrainment of the leading front of the test gas (which would be processed by a reflected shock) into the tube wall boundary layer. The well-known counterpart of such nonideal effects in RSTs is the occurrence of driver gas (e.g., helium) contamination of the test gas, which becomes a progressively more serious problem as total enthalpy is increased.

Such considerations serve to point out the importance of making thorough calibration measurements, including chemical composition in particular, in hypersonic propulsion test facilities. Unfortunately, relatively little has been done to date in existing facilities. However, direct quantitative measurements of dissociation products and contaminants (e.g., driver gas) must be a priority in high enthalpy facilities.

Just as the addition of a free piston driver has increased the performance capability (as measured by total temperature, total enthalpy, or velocity) of RSTs by boosting the driver gas temperature and sound speed, addition of a free piston driver to an expansion tube, such as HYPULSE, can substantially increase its performance. However, in this case it means increasing both total temperature and total pressure. The latter quantity, in particular, can be increased to levels from 10 to 100 times higher than any current or contemplated RST or other type facility. A calculation of the isentropic total pressure and total temperature capability of the HYPULSE facility with the addition of a free piston driver[15] is presented in Fig. 4. (The isentropic total pressure and isentropic total temperature are again defined as the stagnation values calculated following an isentropic compression of air in shifting chemical equilibrium, from the calculated test section conditions in the expansion tube. This is entirely consistent with the definition of flight values used in Figs. 1 and 2. It is also considered the most reasonable basis for comparison with other hypersonic wind tunnels in which the flow is expanded from a stagnation condition to the same test section conditions as exist in the expansion tube. However, it is important to recognize that such expansions are almost invariably nonisentropic due to finite-rate chemical reactions. These effects can greatly alter the ratio of stagnation pressure-

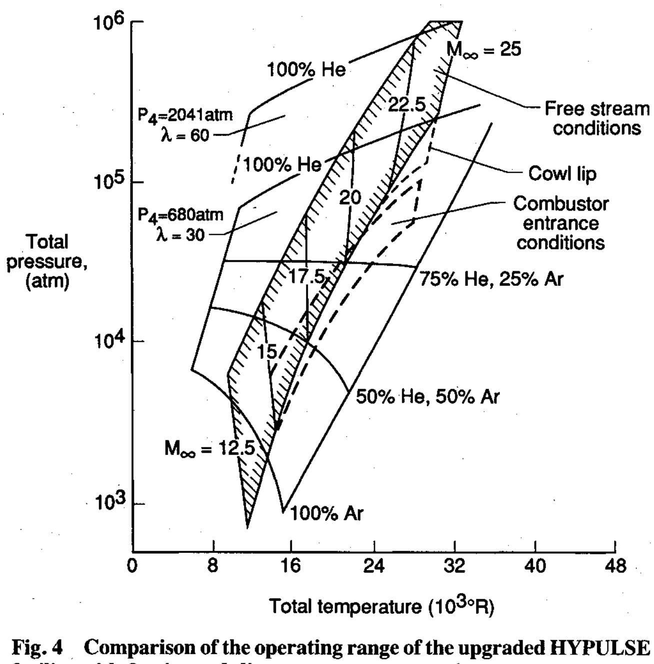


Fig. 4 Comparison of the operating range of the upgraded HYPULSE facility with freejet and direct connect test requirements.

to-static pressure in the test section, e.g., as well as the chemical composition of the test gas. Thus, facility comparisons must be very specific with regard to what test conditions are being matched relative to flight and/or to expansion tube test conditions.) The total pressure and total temperature requirements for the duplication of freestream and combustor entrance conditions from Figs. 1 and 2 are cross-plotted here with the flight Mach number as a parameter. The freejet requirements are not shown here, but they are intermediate between the two bands (Fig. 2). The operating map of the upgraded (by addition of a free piston driver) HYPULSE facility is shown for two sets of operating parameters. The full map is for a compression ratio of 30 and diaphragm burst pressure of 10,000 psia (680 atm), with the driver gas composition being varied parametrically from pure helium to various helium-argon mixtures to pure argon. This operating range is well within the design limits of the free piston unit.[15] An additional map is partially shown in Fig. 4 in which the compression ratio is increased to 60, and the diaphragm burst pressure is increased to 30,000 psia, the design limit of the unit.

It can be seen from this figure that complete duplication of the combustor entrance conditions, as required for direct connect tests, can be achieved out to orbital speeds without stressing the upgraded facility. In addition, freejet tests are possible out to flight Mach numbers in the 17–20 range also without stressing the facility, and out to orbital speeds by going to the facility design limits. No other near-term propulsion research facility concept known to the authors is capable of producing the requisite total pressure for freejet tests in these near-orbital to orbital speed range. (Two stage concepts, employing MHD for example, which will be discussed in the next section, are potentially competitive in this regard, but do not represent nearly so mature a technology.)

Although the facility performance maps in Fig. 4 are based on theoretical performance calculations, they are supported by operational data reported in Ref. 16 from a quarter-scale version of the upgraded HYPULSE facility, designated TQ, at the University of Queensland. This facility, which has a maximum diaphragm burst pressure of approximately 330 atm, achieved isentropic total pressures from 10,000 to 30,000 atm at total temperatures of the order of 30,000°R, and velocities from 27,500 ft/s to nearly 30,000 ft/s, using a pure helium driver. Using air as the driver gas, total pressures of 9000–10,000 psia at about 11,000°R and velocities of about 13,000 ft/s were also achieved, consistent with the predicted effect of driver gas composition. In view of the small tube diameter of TQ (about 1.5 in.), only a single pitot probe could be used to infer test conditions in the inviscid core flow. Viscous losses are expected to be more predominant in TQ than in the full-scale facility, and the existence of an inviscid core of larger diameter than the pitot probe is unconfirmed. Accordingly, a factor of two total pressure loss in the TQ data is not unexpected. Therefore, the degree of agreement between this data and the calculations is considered quite acceptable to support the projected full-scale performance.

The test time of the expansion tube will be indirectly increased by addition of a free piston driver in that the increased operating pressure (and hence, Reynolds number) will diminish viscous attenuation of the incident shock. This, in turn, will allow lengthening the tube from its current configuration. Using an additional 30 ft of available 6-in. tubing to reconfigure for optimum test time with free piston operation leads to more than doubling the useful test time. A comparison[15] of useful test time, expressed in terms of the product of test time and test gas velocity to form a "test slug length," is presented in Fig. 5. [Estimates of test time for the HYPULSE (UPGRADED) facility are based on operation with helium-argon driver gas mixture tailored to achieve combustor entrance conditions while maximizing test time. The HYPULSE (CURRENT) line is faired through actual operating data with cold helium driver gas.] (The maximum permissible model

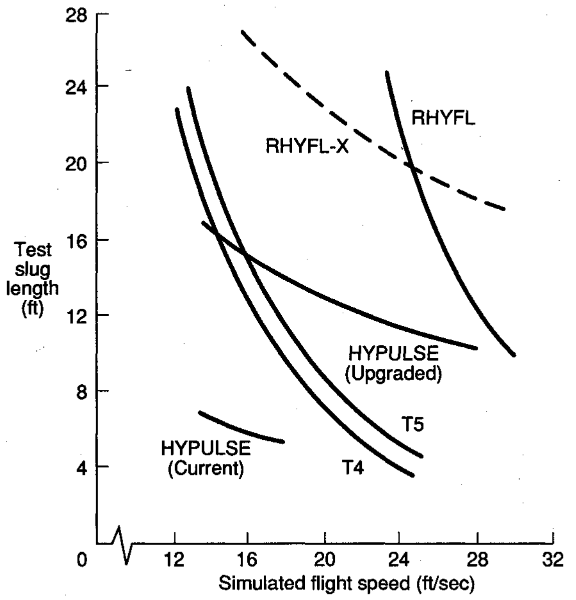


Fig. 5 Comparison of test slug lengths for various free piston-driven hypersonic test facilities.

length over which steady flow can be established is generally estimated to be ⅓ (laminar) to ½ (turbulent) the test slug length.) The calculated test times implied by this figure have, in actuality, been exceeded in T4 and T5 by running in an "untailored" mode in which total pressure decays with time, but driver gas contamination is delayed.

RHYFL is a very large free piston RST which was initiated by the Rocketdyne Division of Rockwell International, but never completed. Since all the major components of the RHYFL facility were built and are in storage, it is interesting to speculate as to the performance it could achieve if reconfigured to operate as an expansion tube. The total enthalpy and total pressure capabilities would be virtually identical to the upgraded HYPULSE facility, since maximum compression ratio and maximum diaphragm burst pressure are about the same. However, the test time would scale up in direct proportion to the increased size of RHYFL. We have assumed that additional sections of acceleration tube would be acquired to maintain the same length-to-area ratio as HYPULSE. Accordingly, the test time would then scale up as the square of the ratio of tube diameters (8 in./6 in.), yielding the estimate of test slug length denoted as RHYFL-X in Fig. 5. A test time of about 2 ms could be achieved at 15,000 ft/s, yielding a test slug length of 30 ft or an allowable engine length of 10 ft, at this condition. Due to the driver gas contamination problem in RSTs mentioned earlier, RHYFL-X would actually achieve longer test times, of the order of 0.8 ms, than RHYFL itself at simulated flight speeds above 24,000 ft/s, while simultaneously avoiding the extreme stream dissociation problems of RST operation at these enthalpy levels.

Clearly, if the components of the RHYFL facility are ever assembled, consideration should be given to configuring them such that both the reflected shock tunnel and expansion tube/tunnel modes of operation are possible. This arrangement would offer a very formidable propulsion research facility with optimum capabilities over the flight spectrum.

We have said very little to this point regarding expansion tunnels. This mode of operation involves adding a divergent nozzle to the end of the acceleration tube. The function of the nozzle at typical expansion tube operating conditions is to increase the test section Mach number from perhaps half the flight Mach number at the end of the acceleration tube to about three-quarters of the flight Mach number. This will approximate flow conditions behind the vehicle bow shock and permit freejet tests of engine (i.e., inlet-combustor-nozzle) models. Since the velocity will change very little through the nozzle, the density will vary inversely with the area ratio, the pressure will drop correspondingly, and the chemical composition will likely remain unchanged. The HYPULSE facility is currently operated in the tube (rather than tunnel) mode because the attainable total pressure is barely adequate for direct or semidirect connect combustor experiments. However, the total pressure capability that addition of a free piston driver would provide would make the tunnel model of operation both feasible and attractive for freejet engine tests.

It is significant to note that, since an expansion tunnel nozzle is entirely divergent, a skimmer-type design with a sharp leading edge can be employed.[13] The diameter of the skimmer can be selected to capture only the central inviscid core flow and bypass the tube wall boundary layer. Thus, a "fresh" hypersonic laminar boundary layer will grow on the nozzle wall, and the radiated noise typical of a turbulent boundary on a nozzle will be avoided. Furthermore, a skimmer nozzle can be mechanically isolated to minimize the propagation of facility vibrations associated with, e.g., diaphragm rupture. Consequently, it appears that an expansion tunnel is potentially capable of very "quiet" operation. Although it is premature to speculate on the suitability of this type of tunnel for hypersonic transition studies, it seems safe to state that the likelihood of facility induced augmentation of turbulent mixing rates is extremely remote.

It should be clear from the preceding discussion that we would rank the free piston-driven expansion tube/tunnel as the premier propulsion research facility opportunity for the following reasons: 1) total enthalpy capability to super-orbital speeds; 2) total pressure capabilities sufficient for freejet engine tests from Mach 12 to 25; 3) low stream chemistry distortion due to oxygen dissociation; 4) potential for "quiet" flow in the test section; and 5) availability of one operational facility (HYPULSE) requiring only the addition of a free piston driver, and availability of all the major components of a larger scale (longer run time) facility (RHYFL-X).

B. Engine Development Facilities

In order to unambiguously interpret test data and relate model performance to a full-scale engine, close, if not exact, simulation of all the relevant flow characteristics of the test gas is required. Proper simulation of the flow physics and chemistry at hypervelocity conditions requires duplication of the local temperature, density, velocity, gas composition, and scale. The latter implies that the model must be appropriately sized (preferably to full scale) to closely simulate the residence time of the gas in the engine, and particularly in the combustor, where the time required to mix and react the fuel and oxidizer is of the order of the residence time. In addition, the facility test time must be sufficient to allow establishment of thermal equilibrium in the engine structural panels and establishment of viscous-dominated phenomena, such as separated flow regions, and to simulate nonadiabatic and catalytic wall effects, although the latter is less critical at these flight conditions. All facilities currently in operation are limited in one or more of these requirements because they cannot produce the requisite energy levels for sufficient duration, and/or cannot obtain the proper distribution of energy among the various energy states of the test gas, i.e., translation-rotation, vibration, and dissociation.

Propulsion test facilities will be required which provide from several seconds up to minutes of test time. In addition, flight certification requirements are such that the μs-to-ms run times of pulse facilities cannot cumulatively provide the total testing times required. Finally, for developmental purposes, one prefers engines or engine components that are (or near) full scale, since, for example, nonequilibrium chemistry phenomena are not readily scaleable.

The two methods available for adding energy to a fluid to obtain the required test conditions are thermally—through pressure and temperature, and kinetically—through velocity.

The more effective means of energy addition is a combination of the two which has been shown[13,14,17,18] to be capable of duplicating both the total enthalpy and total pressure, as well as the mixture composition. However, in keeping with the stated limitations, the power and size requirements are such as to confine the facility discussed in Refs. 13, 14, 17 and 18 to submillisecond test times, thereby precluding its use as an engine test facility (although, as discussed in the previous section, it has been shown to be useful as a hypervelocity propulsion research facility).

The first-named method of energy addition is by far the most common, and is the only one that has been applied to an engine test facility. Simply stated, the energy is added by various means to a fluid virtually at rest, then the hot, high-pressure fluid is expanded through a nozzle to obtain the test conditions. Although the total temperature requirement for hypervelocity simulation can be met, the principal disadvantage of this approach is an inability to contain the total pressure required to match flight conditions or to obtain the proper test gas composition. Hence, either the test static pressure is sacrificed or the pressure is obtained at the expense of excessively high static temperature, but the test mixture composition is incorrect in either case due to contamination with chemical contaminants from the air heater or to early freezeout of gas dissociation products in the nozzle, or both.

The long run-time facility options in the flight regime above Mach 8 include 1) direct combustion (vitiated air) with makeup oxygen supplied to bring the test gas O_2 level back to 21% by volume; 2) thermal storage heater-based (e.g., pebble bed heaters); 3) arc heater-based; 4) the related EWT; 5) magnetohydrodynamic (MHD) flow-accelerators; 6) supersonic through-flow fans (STF); and 7) the extremely large expansion tube (ELET). Considerations of energy lost to the plenum chamber walls, as well as arc stability and electrode burnout in the case of arcs, generally limit direct combustion and arc facilities to a maximum total pressure of about 200 atm, corresponding to perhaps Mach 7 free jet and Mach 10 direct connect testing (Fig. 2). Advanced concepts could conceivably extend these limits somewhat; e.g., the gas-fired zirconia-brick storage heater-plus-subsequent H_2-O_2 vitiated heater conceptualized in Ref. 19 might reach Mach 12, direct-connect total pressure, and total enthalpy levels, but with a test gas composition different from air, and the NASA Ames Research Center 100 MW arc tunnel[20] is reported to be capable of attaining Mach 12–13 direct connect total enthalpy levels, but at significantly lower total pressures than required for full simulation, as well as incorrect mixture composition.

The RST and free piston-driven expansion tube (FPET) were discussed in Sec. II.A. The EWT concept is detailed in Refs. 10 and 21 and is shown schematically in Fig. 6. High-pressure liquid air is introduced into a small diameter "capillary discharge" chamber where it is subjected to a continuous, high-power arc discharge. This massive energy addition vaporizes the air and elevates it to high pressure and temperature. The nature of the arc is such that the problem of arc stability is nonexistent; however, the structural integrity of the capillary wall and electrode survivability are obvious considerations. Downstream of the capillary is a larger mixing chamber wherein additional liquid air is injected to protect the chamber walls and to arrive at the desired total pressure and total temperature (10–20 katm, 8000-11, 500 K, typically) prior to entering the facility nozzle.

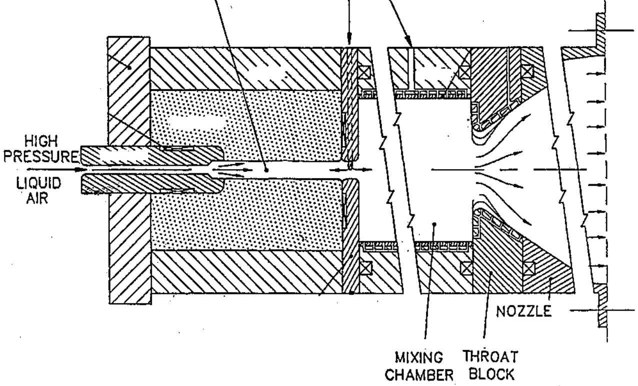


Fig. 6 Schematic of the EWT concept.

Conceptually, significant mass flow rates can be produced for time periods ranging up to minutes. In practice,[10] a large-scale development effort will be required focusing on the following major areas, in addition to that of structural integrity mentioned above:

1) Facility nozzle throat heat transfer—the enormously high total pressures and temperatures, above, perhaps, Mach 15 create throat wall temperatures and heat fluxes which will require very creative solutions to ensure survivability of the throat. Heat-sink concepts and transpiration cooling do not initially appear promising[10]; hence, ablative throat inserts and/or other innovative concepts must be examined.

2) Electrical power supply—the power requirements for a full-scale development facility will be enormous, regardless of the type of facility contemplated. Assuming a Mach 20 total enthalpy operating condition and an EWT electrical operating efficiency of 50%, it is estimated that 40 MW will be required per kg/s of test flow. If full-scale hardware is to be tested, then mass flow requirements will be on the order of 100 kg/s, resulting in an enormous power requirement. This will be by far the largest single expenditure in the acquisition of such a facility. For subscale (say, $\frac{1}{5}$-scale) hardware, Ref. 10 estimates that 650 MW is necessary at similar enthalpies and efficiencies. In this realm, it was concluded that the flywheel generator represents the option of choice by virtue of its relatively low installation, operating, and maintenance costs and good safety aspects. Although this technology is not new (flywheel generators are used to power the Tokamak magnets at Princeton), these are not "off-the-shelf" pieces of equipment. Clearly, some development effort will be required here as well.

3) Significant dissociation of test gas oxygen—this major issue is addressed in Sec. III. It is noted here that significant nitric oxide (4–6 mole %) will be present in the test gas at all conditions above Mach 10, and atomic oxygen will be difficult to completely recombine above Mach 15 without the use of catalysts (e.g., water).

On the basis of the work in Refs. 10 and 21, it is fair to conclude that the EWT is a promising performer up to, perhaps, flight Mach 14. The problems enumerated above become grossly magnified above this level, relegating the concept to the category of "long range." If, on the other hand, the EWT is employed as the front end of a two-stage concept, in which it supplies the test gas to the second stage at conditions below, say, Mach 14-equivalent, it then becomes far more attractive on a nearer-term basis. The second stage would then be assigned the task of adding the additional energy required to reach, e.g., Mach 20–25 total enthalpies and pressures. Hopefully, as well, this energy addition could be accomplished without further significant contamination of the test gas.

A conceptually promising second stage is the MHD accelerator. This concept is the subject Ref. 22, wherein the first stage was assumed to be an arc heater operating at $P_t = 200$ atm, and supplying "air" at $T_t = 4751$ K, $H_t = 6.650$ MJ/kg (2859 Btu/lbm). A nozzle placed between the arc heater plenum and the MHD accelerator (Fig. 7), accelerates the test gas flowing at 22.1 kg/s to the following conditions: 20 atm, 3266 K, 2306.3 m/s ($M = 2.161$). The gas conductivity was calculated to be 57.95 mho/m with the addition of a 2% potassium seed and a baseline magnetic field strength of 8 T was assumed. With these numbers, a one-dimensional MHD code

Table 1 Energy and power requirements for an MHD accelerator[22]

Flight Mach number	15	20	25
Total power, MW	175	458	755
Current density, A/cm^2	25	50	70
Power density, KW/cm^2	5.07	10.37	16.10

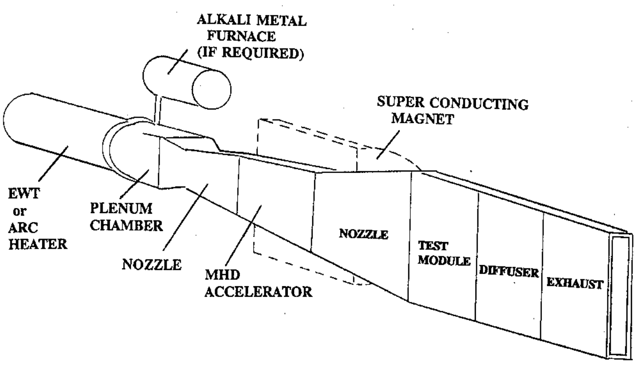


Fig. 7 Conceptual EWT/MHD accelerator facility configuration (after Ref. 22).

calculated the energy and power requirements for a 1000 lbf/ft^2 trajectory simulation (Table 1).

Reference 22 concludes that the capability of such a facility is "beyond all current facilities and is technically feasible based on current state-of-the-art technology." When one considers the fact, however, that significantly higher levels of energy addition in the first stage may be possible using the EWT, the possibility of an EWT/MHD facility appears even more attractive than an arc heater/MHD combination. The reasons for this are the potential for significantly lower power reductions in the MHD second stage and/or the ability to operate with lower ionization levels resulting in reduced contamination of the test gas. Alternatively, the concept suggested in Ref. 23, wherein nonequilibrium ionization is achieved solely as a consequence of the imposed electric field which supplies power to the device, is even more attractive since no test gas contamination occurs (i.e., no seed is required). Electric fields of the order of 100 kV/m appear sufficient to ionize nitric oxide, resulting in electrical conductivities high enough to permit reasonable MHD accelerator performance. Calculations in Ref. 23 suggest that combustor direct connect conditions approaching flight Mach 20 may be achievable. This would likely be assured with an EWT first stage since, for the same input power, lower ionization levels would be required. Thus, assuming feasibility of the EWT concept, the EWT/MHD combination may prove to be the facility of choice for achieving full total enthalpy and total pressure simulation above about flight Mach 14 for test times of the order of seconds.

An alternative candidate second stage is STF.[24–26] Apparently first discussed in Ref. 24, the STF is a mechanical means to impart additional energy to a supersonic airstream. As its name implies, the air enters and leaves with supersonic axial velocity, the velocity is increased across the device, and the static pressure is constant or drops. While the concept offers considerable benefit as a stage of a turbofan engine for long-range supersonic flight,[24,25] it also has the proper theoretical characteristics to function as the second stage of a hypersonic engine test facility. A recent application of lifting surface theory to the performance of a STF[26] demonstrates the potential for factors of two to four increase in total enthalpy at an entrance Mach number of 1.5. Their results also indicate increasing total enthalpy amplification with increasing entrance Mach number.

To the authors' knowledge, use of a STF in this context has not been previously examined in any detail. There are a number of serious considerations that must be addressed, e.g., viscous losses on the blades and nonuniform wake flow downstream, shock losses, and thermal protection of the blades.

The two types of STF configurations considered in Ref. 24 are 1) fixed or moveable inlet guide vanes upstream of the rotor, the vanes turning the flow off-axis, and the rotor stage returning the flow to an axial direction (Fig. 8); and 2) a rotor followed by stationary guide vanes, or stator, to reorient the flow axially (Fig. 9). Reference 24 demonstrates that the two configurations are comparably efficient and Ref. 25 opts for the second configuration. This also seems preferable in the present context since it would attenuate the periodic rotor wake effects reaching the test section.

Thermal protection of the blades is a serious problem, but perhaps no more daunting than the nozzle throat cooling problem. One potential approach[6] is to eliminate the stator

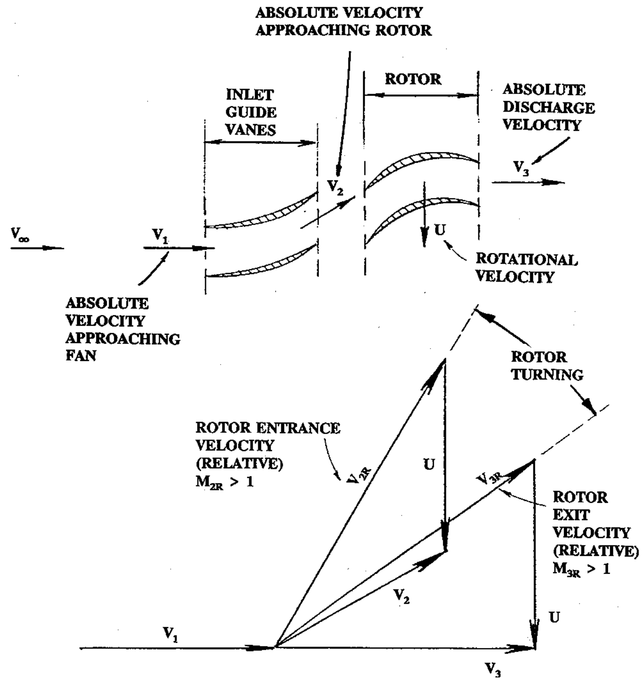


Fig. 8 Supersonic through-flow fan with inlet guide vanes.

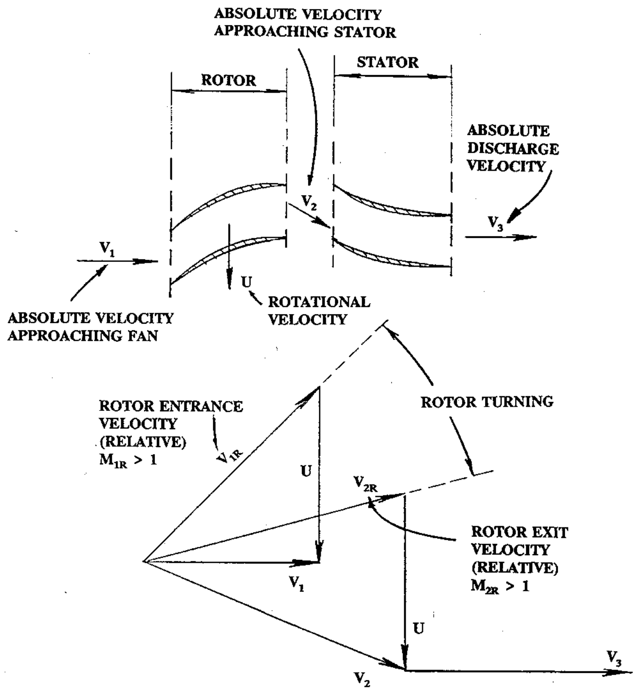


Fig. 9 Supersonic through-flow fan with exit stator.

Table 2 Requirements for an expansion tube/tunnel as an engine development facility

Test time, s	Overall length, miles	Shock tube diameter, ft	Piston tube diameter, ft
0.1	3	5.6	16.8
1.0	30	17.7	53.0
10.0	300	55.9	167.7

and place the hub of the rotor outside the wind tunnel. The blades would then be intermittently subjected to the high enthalpy stream as they passed through the tunnel and to a cooling stream while they were outside the tunnel. The rotor, with appropriately designed contour, would uniformly deflect the airstream to a new flow direction, at which the test section would be aligned.

Although the STF concept is clearly quite immature compared to MHD at this time, it does have the advantage of avoiding the use of a seedant as required by conventional MHD. Also, the flow distortion due to wakes may be no worse a problem than that due to Hall currents in MHD accelerators. Being a purely mechanical device, potentially powered by energy stored in a flywheel, for example, the STF may logically integrate with a PGU-type first stage.

Finally, since the free piston-driven expansion tube/tunnel was identified in the preceding section as the propulsion research facility of choice, it is reasonable to ask whether it can be scaled up to meet the test time requirements of an engine development facility. Using the upgraded HYPULSE facility as a baseline, and assuming that boundary-layer effects will be preserved by maintaining the ratio of length-to-area of the tubes, the estimates of overall length and tube diameters are obtained (Table 2).

A facility in the 3–30 mile length range is not unreasonable, e.g., as compared to high energy particle accelerators. However, tube diameters beyond about 6 ft, with internal pressure ratings of 5000 psi (acceleration tubes) to 30,000 psi (piston compression tubes) are difficult to contemplate. An equally serious diameter scale-up problem is diaphragm characteristics.

As a result, scale up to an extremely large expansion tube/tunnel (ELET) suitable as an engine development test facility has more serious limitations associated with tube diameter than with length. Reduction of the area ratio between piston compression tube and shock tube, and/or use of multiple, parallel tubes, seems imperative. Diaphragm materials and rupture mechanics suitable for the larger tubes must be developed, or replaced by multiple fast-acting valves.

In summary, the two-stage EWT/MHD facility concept appears to be the best opportunity to achieve the hypersonic-hypervelocity test capabilities required of an engine development facility. However, considerable component feasibility, development, and integration work remains to be done on both stages. The PGU facility is a viable, low-risk first-stage candidate, but is ultimately less capable than an EWT. The EWT integrates more logically with MHD, and the increased performance of the EWT relative to a PGU or conventional arc first stage correspondingly reduces the energy that the MHD unit must provide. The STF concept is a potential backup to MHD, but is clearly less mature and probably less capable. The ELET concept is limited by tube diameter scale-up problems to test times which are probably one-tenth to one-hundredth that of the EWT/MHD concept, which is limited only by the power supply.

III. Nonequilibrium Stream Chemistry Effects in Research and Engine Development Facilities

As mentioned in Sec. II, significant dissociation of the test gas will be present in most facilities that reproduce stagnation conditions corresponding to hypervelocity flight. In addition to dissociation, both ionization and vibrational relaxation effects, which can also significantly alter test gas properties, must be assessed on a facility-by-facility basis.

A. Vibrational Relaxation

In an important paper Boudreau and Adams[27] present persuasive arguments that a large number of anomalous performance characteristics encountered in hypersonic wind tunnels result from the effects of vibrational relaxation. For example, errors of as much as 25% in freestream Mach number were experienced in AEDCs arc-driven tunnel F, along with smaller, but still significant, Mach number errors in other facilities. The mechanism for these errors hypothesized in Ref. 27 is 1) significant energy tied up in the vibrational mode in the plenum; 2) freezing of the vibrational mode just downstream of the facility nozzle throat; and 3) a sudden de-exitation of the vibrational mode, releasing significant energy, resulting from the presence of condensed water vapor (and, perhaps other contaminants) in the test gas which acts as a highly effective "third body." The calculations presented in Ref. 27 lend credence to this hypothesis.

Calculations made by the authors suggest that in many facilities as much as 20% of the total internal energy in the plenum may be tied up in the vibrational mode. Clearly, given numbers of this magnitude (or even substantially lower values), both the design and subsequent characterization of the facility nozzle must account for vibrational relaxation. Typically, the simple harmonic oscillator model of Landau and Teller (L-T) has been used to assess vibrational effects. Work dating back to (at least) the 1960s (Ref. 28) suggests that the L-T model, while successful in predicting vibrational relaxation rates downstream of shock waves and other flows undergoing compression, tends to underpredict these rates in expanding flows. Reference 28 found that, for the expanding flows they examined, vibrational relaxation times were about 15 times faster than those predicted by L-T.

In a recent paper, Ruffin and Park[29] revisit this question using the theory of Schwartz, Slawsky and Herzfeld (SSH) to calculate transition rates. In addition, multiple quantum level vibration-translation (V-T) and vibration-vibration (V-V) transitions were permitted. Their results for the two-dimensional nozzle of Ref. 30, wherein pure CO at total conditions of 4000 K, 14.8 atm was expanded through a (mostly) straight-wall nozzle having a 5.7-deg half-angle, are shown in Fig. 10. The experimental vibrational temperature measured by Ref. 30 near the nozzle exit is also shown in Fig. 10. Although the SSH theory produces a slight improvement over L-T, it seems clear that major deficiencies remain in our current understanding of this phenomenon. Figure 11 shows the computations of the present authors for the configuration of Ref.

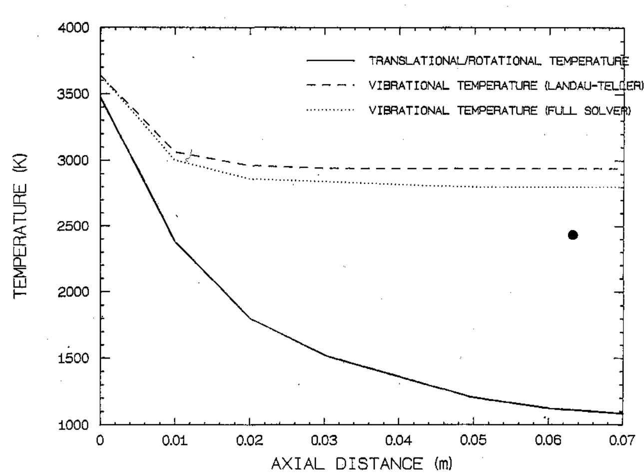


Fig. 10 Computed temperatures and the experimental point from Refs. 29 and 30, respectively.

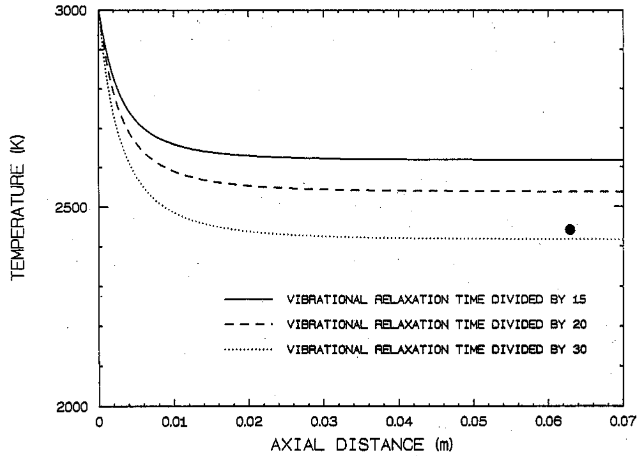


Fig. 11 Computed vibrational axial temperature profiles using a GASL one-dimensional code.

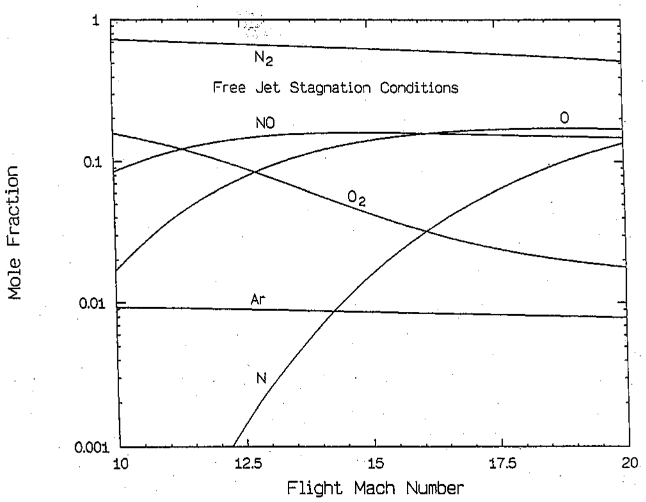


Fig. 12 Equilibrium major species concentrations for a 1000-psf flight path.

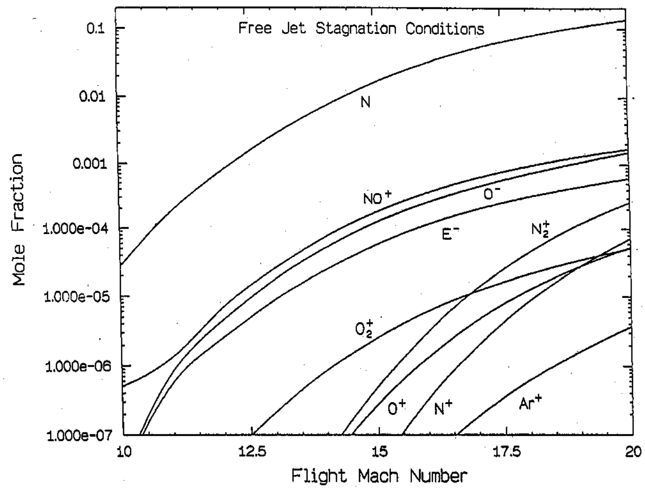


Fig. 13 Equilibrium minor species concentrations for a 1000-psf flight path.

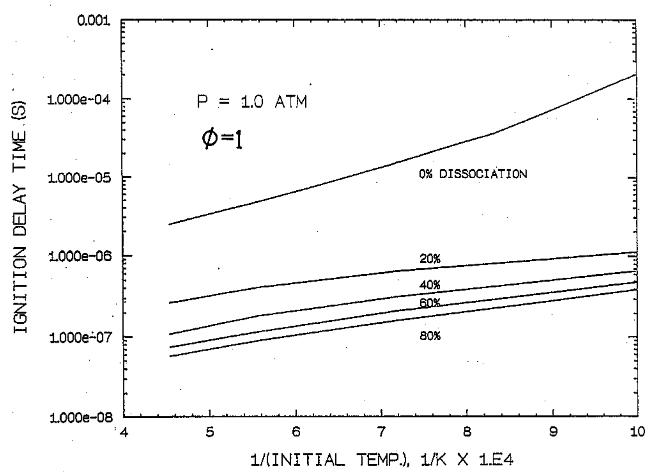


Fig. 14 Effect of oxygen dissociation on the ignition delay time.

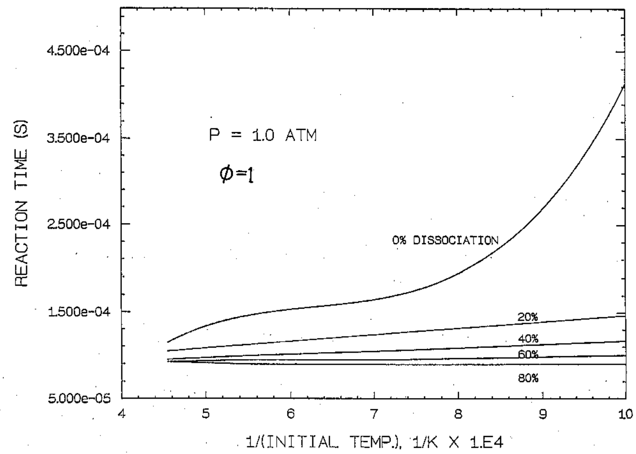


Fig. 15 Effect of oxygen dissociation on the reaction time.

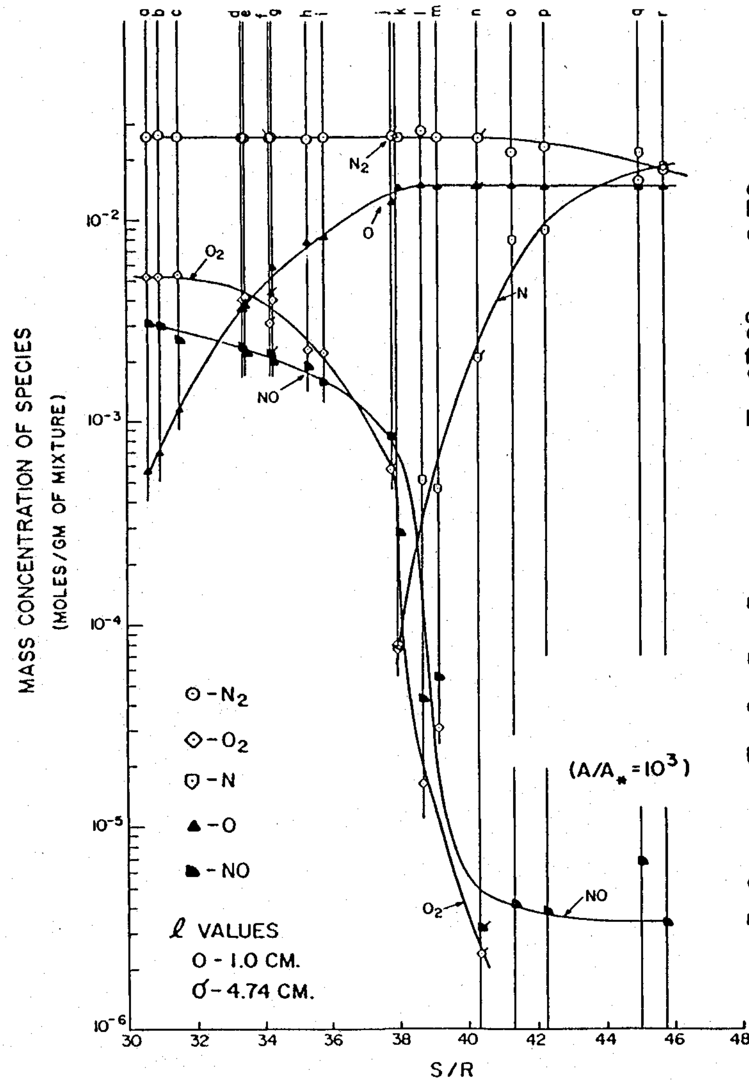
30 in which the CO L-T vibrational relaxation time was arbitrarily divided by 15 (the value recommended by Ref. 28), 20, and 30. As seen, a division by a number closer to 30 is required to produce agreement with the experimental result.

It is the opinion of the authors that insufficient attention has been devoted to vibrational relaxation effects in facility nozzle design. References 31 and 32 do incorporate provision for its inclusion; however, little evidence exists in the literature that these tools have been generally utilized. The questions to be asked are 1) are significant quantities of energy tied up in the vibrational energy mode? If so, then 2) how much of that energy is recovered during the nozzle expansion and where in the nozzle does the principal vibrational deexitation occur (i.e., in accordance with the hypothesis of Ref. 27 discussed above)? These questions must be regarded as being of first-order importance by designers of hypervelocity facilities.

B. Chemical Nonequilibrium

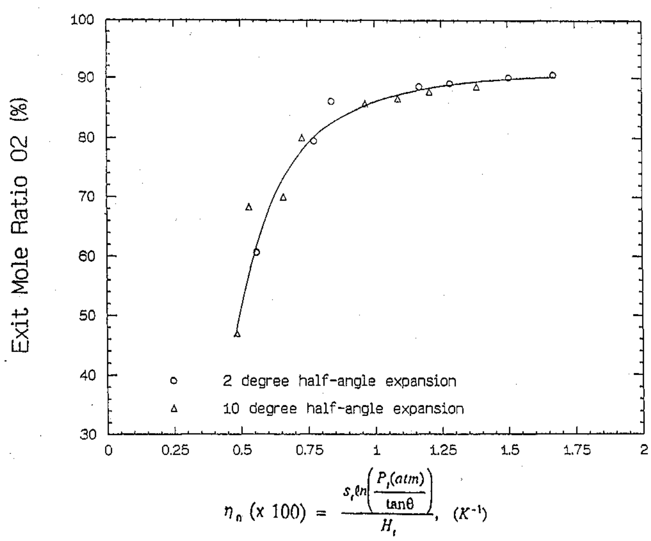
In facilities in which the test gas is stagnated, diatomic oxygen and nitrogen will dissociate, resulting in significant equilibrium concentrations of such species as NO, O, and N. Figures 12 and 13 show equilibrium species mole fractions as a function of simulated flight Mach number for free-jet testing at total enthalpy and total pressure for a flight dynamic pressure of 1000 lbf/ft^2 (from Ref. 10). The increasing levels of charged species as M_∞ increases (Fig. 13) will be significant in determining seeding requirements for a conventional MHD accelerator, as discussed in Sec. II.B. If significant recombination does not occur in the facility nozzle, the test gas will likely be unsuitable for experiments in which chemical reactions play a significant role; i.e., combustion, nozzle expansions, and inlet boundary-layer chemistry. This is because the relatively high level of contaminants (O and NO, in particular) significantly alters the ignition delay and reaction times of all fuel-air combinations. Figures 14 and 15 illustrate this point for stoichiometric H_2-air mixtures at 1-atm pressure. As can be seen, order-of-magnitude reductions in t_{ig} and t_r may result from even relatively low levels of dissociation.

As mentioned in Sec. 2A with regard to levels of dissociation in airflows expanding from a stagnation state, Harris[11]



	T_5, °K	P_5, ATM	H/RT
a	4000	100	72
b	6000	1000	120
c	8000	3309	170
d	10,000	4497	245
e	8000	1000	187
f	4000	6.8	85
g	6000	100	138
h	8000	362	202
i	12,000	6041	356
j	6000	10.2	157
k	8000	100	235
l	10,000	527.8	334
m	15,000	8957	560
n	6000	2.7	173
o	8000	30	283
p	12,000	747.5	500
q	8000	10	348
r	15,000	1066	700

Fig. 16 Correlation of facility nozzle exit species with the stagnation entropy.[11]



$$\eta_n\ (\times 100) = \frac{S_t \ell n\left(\frac{P_t(atm)}{\tan\theta}\right)}{H_t},\ (K^{-1})$$

Fig. 17 Correlation of molecular oxygen at the facility nozzle exit.[10]

has demonstrated that species concentrations correlate well with reservoir entropy S_t/R (Fig. 16) and that for facility nozzles having area ratios greater than about 1000 and l values of the order of 1–5 cm [$A/A^* = 1.0 + (x/l)^2$], the concentrations are effectively frozen at their reservoir values. A corollary is that the facility nozzle expansion rate will not affect these species concentrations. On the other hand, Ref. 10 correlates nozzle exit O_2 concentration (ratio of calculated O_2 to that in standard air) as a function of the parameter $S_t \cdot \ell n(P_t/\tan\theta)/H_t$, where θ is the conical nozzle half-angle, demonstrating some effect of nozzle expansion rate (Fig. 17). It seems reasonable to conclude that the rate of expansion, if sufficiently gradual, will play a role in determining species recombination rates. A similar conclusion is reached in Ref. 34. The price to be paid, of course, is in longer facility nozzles with coupled viscous and heat transfer effects that must be investigated a priori.

Most of the problems discussed here regarding facility nonequilibrium chemistry effects are mitigated in facilities which add energy mainly in the form of velocity to the flowing test gas. Such facility concepts are the expansion tube, the MHD accelerator, and the STF, as discussed in Sec. II. Reference 35 concludes that the expansion tube, along with a magnetic annular arc tunnel, wherein cold test gas having a high total pressure is accelerated to supersonic velocities by means of a pulsed magnetic arc and further accelerated in a diverging nozzle, are the single-stage facilities of choice. In keeping with the conclusions reached here, Ref. 35 concludes that the MHD accelerator is an optimum second-stage facility.

IV. Conclusions

Examination of the chemical kinetics problems in hypersonic air-breathing engine test facilities clearly indicates that the preferred facility concept must avoid containment of the test gas (air) in or near a stagnant state at its total temperature. Increasing the total pressure is relatively ineffective in promoting recombination in the facility nozzle, and counterproductive with regard to suppression of nitric oxide. From this viewpoint, facility concepts that impart only a portion of the required energy in the form of static temperature and the remainder in the form of velocity (directly, rather than through a steady expansion of the flow) are preferred. The only "single stage" concept that operates in this fashion is the expansion tube/tunnel. However, several two-stage concepts are also feasible.

Of the various Propulsion Research Facility concepts examined in this study, only the free piston-driven expansion tunnel offers a near-term opportunity to achieve the total pressures required for direct connect and freejet engine tests out to orbital speeds. Additionally, it offers total enthalpy capabilities to superorbital speeds, low stream chemistry distortion due to oxygen dissociation, and the potential for "quiet tunnel" performance. Other promising concepts having, ultimately, competitive capability employ two stages, e.g., an EWT with an MHD accelerator, or a PGU, with a STF. However, these will require considerable development efforts that are only justified by their potential for long run duration, thereby qualifying them as candidate engine development facilities. The EWT/MHD concept appears to be the most mature, but still long-term, opportunity in this context.

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