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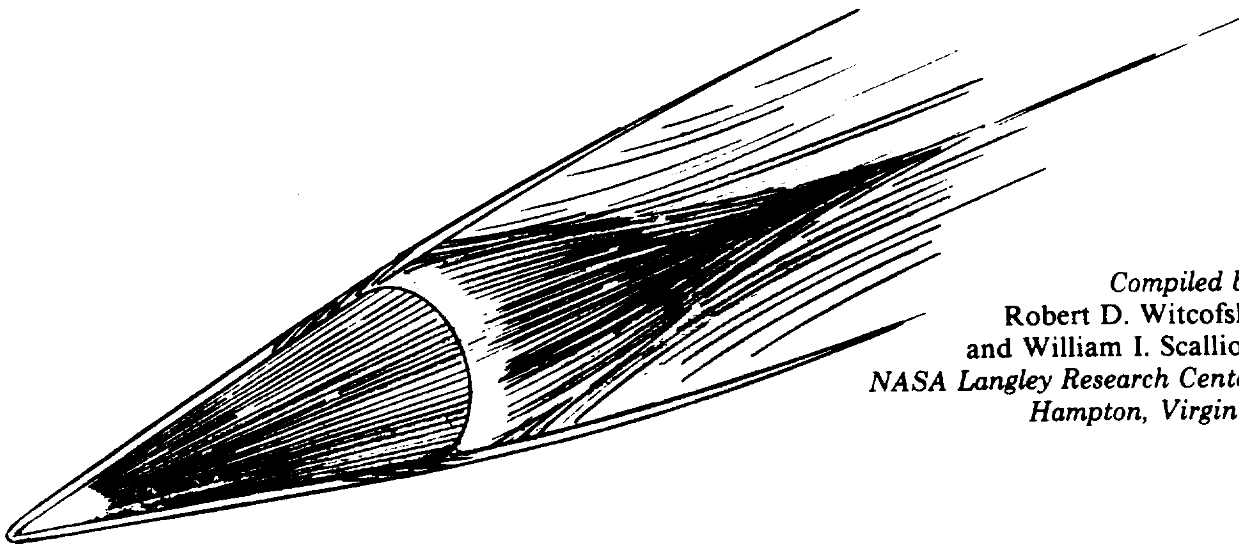
Advanced Hypervelocity Aerophysics Facility Workshop



Compiled by
Robert D. Witcofski
and William I. Scallion
NASA Langley Research Center
Hampton, Virginia

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EXECUTIVE SUMMARY

The NASA Langley Workshop on an Advanced Hypervelocity Aerophysics Research Facility was held May 10-11, 1988, at the NASA Langley Research Center. The primary objective of the workshop was to obtain a critical assessment of a concept for a large hypervelocity (V > 10,000 fps) ballistic range which has been proposed by the Langley Research Center. The purpose of the facility, which would be powered by an electromagnetic launcher, is to provide the capability to conduct fundamental and applied aerodynamic and aerodynamic/aerothermodynamic research on large, instrumented, complex vehicle models and full-scale vehicle components at velocities and densities representative of hypervelocity, flight in Earth or other planetary atmospheres. Some of the nations key experts in the areas of hypersonic aerodynamics and aerothermodynamics, electromagmetic launcher (EML) or electric gun technology, ballistic range technology, and instrumentation were assembled to assess the entire facility concept. They were tasked to define specific experiments to be performed in such a facility, to determine whether or not the facility concept was technically feasible, and to outline the R&D efforts required to arrive at a state of readiness for a preliminary facility design.

The participants in the workshop generally concluded that the subject large-scale facility was feasible and would provide the required ground-based capability for performing tests at entry flight conditions (that is, velocity and density). They also concluded that advances in remote measurement techniques and on-board model instrumentation, lightweight model construction techniques, and model electromagnetic launcher (EML) systems must be made before any commitment for the design of such a facility can be made.

The findings of the separate working groups are summarized in the following paragraphs. More detailed information may be found in the individual working group summaries in the main body of this report.

Experiments Definition Working Group

The Experiments Definition Working Group concluded that except for actual flight tests, the proposed facility represented the only other method for providing flight velocities and densities in an interference-free, clean, undisturbed free stream of arbitrary test gases. Compared with existing aeroballistic ranges, the proposed facility provides significant increases in marked improvement in terms of model size and velocity. Some of the advantages in experimental capability as cited by the group are high velocities that produce real-gas radiating flow fields; clean, undissociated free stream of accurately known composition, pressure, and temperature; base/wake flows without sting interference; wide range of free-stream conditions and gas compositions; large models; flow conditions suitable for validating flow-field codes; capability of performing "quiet" tests to study boundary-layer transition from laminar to turbulent flow; and ability to repeat tests to check experimental data or to vary test conditions.

Some limitations of the facility were also explored by the group. The molecular dissociation processes occurring in high energy shock layers scale differently than the recombination processes further downstream; therefore, it is difficult to duplicate the relationship between these processes on a scale model. However, this does not reduce the capability to validate computational fluid dynamic (CFD) codes in real-gas, high enthalpy flows. Although conditions can be scaled for the compression and inlet regions on hypersonic transport vehicle models, the physical lengths required for supersonic combustion cannot be scaled down, which may require models too long to be accommodated by the facility.

Other limitations include the following. Orientation of the models for optical observation is difficult. On-board instrumentation must be miniaturized and must withstand the magnetic field and high acceleration environment at launch. Recovery of data will be difficult, with the short test time (milli-seconds) and the difficulty of transmitting through the plasma sheath about the model. Spatial resolution of shock layer profiles will be difficult, even with larger models. Model and instrumentation costs may be high, and in the case of free-flight models, probably not recoverable.

The group stated that the types of experiments and measurements required to predict the flight characteristics of aerospace vehicles are the aerodynamic and stability and control characteristics; surface pressure distributions; and surface heat-transfer distributions, including convective and radiative components. Additional measurements are needed to calibrate/validate CFD codes for flight predictions such as shock layer shapes and locations and the distribution of properties across the shock layer including species profiles, densities, velocities, and the spatial and spectral distribution of radiation phenomena. Measurements of these properties will require large models in order to obtain adequate spatial resolution, and in conjunction with this, advanced instrumentation. The better the instrumentation, the less stringent will be the model size requirements. Boundary-layer transition characteristics, in ideal gas conditions and as affected by chemically reacting flows, are also of great interest. Large models are required to provide adequate spatial resolution of on-board measurements and to provide adequate scaling of the flight parameters.

The specific experiments listed by the group included four generic shapes: a blunt body, a slender cone, a cone-flare combination, and a blunt body with a boattail. Also included were application-specific models such as the Aeroassisted Flight Experiment (AFE), an Aeroassisted Orbital Transfer Vehicle (AOTV), and the National Aero-Space Plane. The required facility operating parameters were velocities ranging from 6,000 to 45,000 fps, and density altitudes ranging from sea level to 300,000 ft.

The group recommended additional studies to assess the facility requirements. First, a parametric study involving several hypersonic advanced CFD computer codes should be conducted to assess the impact of unknowns on the predictions of aerothermodynamic phenomena for proposed flight vehicles. Second, selected candidate experiments should be examined in more detail to study the instrumentation requirements and the sensitivity of the physical models in the CFD codes to the proposed test conditions.

Instrumentation Working Group

The Instrumentation Working Group examined the measurement requirements generated by the Experiments Definition Working Group; made assessments as to whether each particular measurement should be performed on-board the model, remotely, or both; and defined the status of the capability to make those measurements. The measurements were placed in categories based on the level of development required. These levels were defined as currently available, available with a modest amount of development, and attainable with considerable development.

Several concerns were examined by the group. One, the ability to make accurate remote measurements requires a minimum of model excursions from a predicted line of flight and a minimum of body motions. Such a requirement suggests the use of a tracked facility (one in which the model is guided by a set of tracks located in the test section). Miniaturization of on-board sensors, recorders, transmitters, and power supplies will be challenging, but feasible. The on-board instrumentation must be hardened to withstand the high accelerations and electromagnetic fields associated with the model launcher. A survey of instrumentation hardening technology was recommended. Retrieval of the on-board data by transmitting through the surrounding plasma or by storing it on on-board memory and reading it out at the end of the test period (possibly while passing through a section filled with helium) or after the model is decelerated (or destroyed) must also be critically examined. The physical size of the memory required to store the data can also be a problem.

The group examined a modular on-board instrumentation concept common to all models as an approach to reducing costs. Finally, the group concluded that although numerous problems were unresolved, most of the measurement difficulties which surfaced during their discussions would yield to a determined development effort.

EML Technology Working Group

The EML Technology Working Group concluded that the use of electromagnetic launchers to accelerate models in the proposed hypervelocity facility was technically feasible and that the key EML-related technical issues pertaining to the development of the facility were resolvable. They noted that the NASA requirements were different from those for weapons in that larger bores and much lower pressures and accelerations were needed. They felt that these characteristics would mitigate the problems associated with the small bore, high pressure guns required for weapons. Two launcher options were considered, the rail gun and the coil gun. They recommended for both options that the model/sabot be preaccelerated into the launcher at a few hundred meters per second; however, they recommended that a light gas gun not be used to preaccelerate the model to several kilometers per second. They recommended that some near term physics validation experiments, using available power supplies and facilities, should be performed to examine critical issues for the different launcher concepts. This is more easily done for the rail gun because rail gun technology is currently more advanced than coil gun technology. Also, numerous power supplies and rail gun facilities are currently operational, whereas there are only limited opportunities available for such experiments with coil guns. At the same time, in parallel with the above, some point designs/trade-offs should be performed to identify in more detail what the critical issues are. They further recommended that an architectural and engineering study on the entire facility be conducted to establish a configuration to determine the cost and identify the major issues to be addressed. The group cited an urgent need for a better requirements definition, considering such things as model sizes, acceleration loads, and the subsequent impact on the EML power supply requirements.

Range Technology Working Group

The group addressed the problems associated with flying free-flight lifting models and the advantages and limitations of a tracked facility. The ability to maintain lifting models within given bounds is inversely proportional to range pressure. Rolling of the model was cited as one effective method for keeping the model within bounds. They also pointed out that a lifting model would be extremely difficult to maintain within the range of fixed remote measurement systems. Additionally, lifting models would probably not be recoverable.

The advantages of the track are that it produces an accurate model trajectory, it allows the model to be recovered, and the range tank diameter can be reduced. The disadvantages are that wake measurements cannot be made, aerodynamic coefficients cannot be measured, and it will interfere with some flow-field studies.

The group found that the model/sabot masses given in the facility description were too small for the specified launch tube bore of 18 in. They recommended that a study of representative large model and sabot packages be performed to determine the launch mass, and therefore the energy required to accelerate the models and the accelerations the packages can withstand. The group further recommended that a study of a large light gas gun be conducted to determine the maximum size gun that can be constructed.

INTRODUCTION

Bold, new hypersonic intiatives by NASA and DOD have resulted in renewed interest in hypersonics and an increased awareness of serious deficiencies in the nation's capability to perform ground-based aerodynamic/aerothermodynamic tests at hypervelocity, high enthalpy conditions representative of flight. In order to improve the nation's aerothermodynamic research capability, the Langley Research Center has proposed a ground-based facility capable of testing relatively large, highly sophisticated, instrumented models at velocities and densities representative of hypervelocity flight in Earth and planetary atmospheres. Basically, the facility is a large ballistic range utilizing a long, electromagnetic launch tube some 18 in. in diameter to accelerate models to the desired test velocity 2,000 to 43,000 ft/s. In support of this proposed concept, a study entitled "A Feasibility Study of a Hypersonic Real-Gas Facility" was conducted for Langley by the Center for Electromechanics at the University of Texas at Austin (CEM/UT), under Grant Number NAG1-721. The results of that study were sufficiently encouraging to warrant a critical facility concept review/assessment by experts in related disciplines. Accordingly, a NASA Langley Workshop on an Advance Hypervelocity Aerophysics Research Facility was held May 10-11, 1988, at the NASA Langley Research Center. Some of the nation's key experts in the areas of hypersonic aerodynamics/aerothermodynamics and propulsion, electromagnetic launcher (EML) or electric gun technology, instrumentation, and ballistic range technology were assembled to assess the entire facility concept. They were tasked to define specific experiments suitable for conduct in such a facility, to determine whether or not the facility concept was technically feasible, and to outline the R&D efforts required to arrive at a state of readiness for a preliminary facility design.

The workshop began with a plenary session in which the workshop objectives were discussed, followed by brief presentations that addressed the needs of the aerodynamic/aerothermodynamic community, the current electric gun technology status, ballistic range testing techniques, and measurement and instrumentation techniques. The workshop participants were then divided into specific working groups:

Experiments Definition

Instrumentation and Measurement Technology

Electromagnetic Launcher Technology

Ballistic Range Technology

Each working group developed a summary of their findings which is presented in the main body of this report. Presentations and other contributions made by individual members of the working groups are presented in Appendices A through C (A - Experiments, B - Instrumentation, & C - EML). Appendix D is a transcript of the actual Range Technology Working Group meeting.

A description of the goals of the workshop, instructions to the individual working groups, and a list of questions to be addressed by the participants as appropriate to their discipline are included in Appendix E.

WORKING GROUP ORGANIZATION

Experiments Definition

Arthur Henderson (Chairman)	NASA Headquarters
Fred M. Smith (Executive Secretary)	NASA Langley
Ivan E. Beckwith	NASA Langley
Rodney Burton	GT Devices
Gary T. Chapman	NASA Ames
H. J. Gladden	NASA Lewis
Peter A. Gnoffo	NASA Langley
Harris H. Hamilton, III	NASA Langley
Ernest A. Mackley	NASA Langley
Chul Park	NASA Ames
Carl D. Scott	NASA JSC
Gerald D. Walberg	NASA Langley

INSTRUMENTATION

William M. Isbell (Chairman)	General Research Corp.
Lynn M. Barker	Sandia/Albuquerque
John J. Chapman	NASA Langley
Reginald J. Exton	NASA Langley
Rurich Loder	Aberdeen Proving Ground
Charles G. Miller, III	NASA Langley
Glenn R. Taylor	NASA Langley

EML TECHNOLOGY

Ian McNab (Chairman)	Westinghouse
John Barber	IAP Research
Isaiah Blankson	NASA Headquarters
Thomas N. Canning	Eloret Inst./Ames
Michael Huebschman	SDIO
Peter Kemmey	DARPA
Henry Kolm	EML, Inc.
Ja H. Lee	NASA Langley
Miles Palmer	SAIC
Gerald V. Parker	Los Alamos Nat. Lab.
Jim Scanlon	Eglin AFB
Douglas Sterrett	Eglin AFB
William F. Weldon	Univ. of Texas
Zivan Zabar	Polytechnic Inst. N. Y.

RANGE TECHNOLOGY

John Cable (Chairman)	Calspan/AEDC
Hallock F. Swift	Physics Applications Inc.
Andrew Piekutowski	Univ. of Dayton
John L. Mouring	NASA Langley

EXPERIMENTS DEFINITION WORKING GROUP (EDWG) REPORT

(Arthur Henderson, Chairman)
(Fred Smith, Executive Secretary)

INTRODUCTION

At the first session of the EDWG, each member presented his views on the following two questions:

> What experimental capabililties are required for the foreseeable future in hypersonics for which the proposed ballistic range capability is particularly well suited?
>
> What practical impediments do you see to achieving the capabilities outlined.

The content of the presentations (Appendix A) and the associated discussions focused on three prime areas for experiments definition. The single most desirable capability offered in each of the areas by the range is the ability to achieve real gas effects in quiescent, uncontaminated air. To better focus the goal of experiments definition, the group defined four questions to be answered, and broke into three subgroups to do so. The three subgroups and four questions are:

Subgroups

CFD/Real Gas Effects

- Chul Park, Chairman
- H. Harris Hamilton, II
- Peter A. Gnoffo

Fluid Dynamics/Real Gas Effects

- Gary Chapman, Chairman
- Ivan Beckwith
- Jerry Walberg
- Carl Scott

Hypersonic Propulsion

- Ernest Mackley, Chairman
- H. Joe Gladden
- Rod Burton

Questions

Is a large ballistic range with Earth and planetary orbital/entry capability required? If so, why is it required for your experiments?

What are the limitations of the ballistic range? It is clear that some of the parameters of interest are functions of absolute length and that results under these conditions cannot be scaled. How valuable is the facility when this is the case?

Define the experiments required in your area. Define the parameters to be measured, the kind of measurement distributions needed, and model sizes required.

What studies are required to adequately define your experiments, and what are the ballistic range characteristics required for your needs.

An overview of the response of each subgroup to these questions follows:

CFD/Real Gas Effects

In this subgroup we specifically addressed the question of how effective the proposed facility will be for the purpose of calibrating CFD codes for application to hypersonic, nonequilibrium, and radiating flow-field simulations.

Is the proposed facility required?

The presence of an unvitiated, well defined free stream is one of the most important requirements for aerothermodynamic studies. Alternative facilities such as expansion tubes and shock tunnels, even with possible improvements, can perform only limited tests for hypersonic CFD calibration and generally possess free-stream problems.

Compared with existing ballistic ranges, the proposed facility is superior in terms of both model size and velocity. This offers the opportunity to obtain detailed experimental data that are otherwise unobtainable.

Flight experiments can offer much help in this area. However, it is not expected that flight experiments would be able to offer consistently high quality flow-field data across the entire flow domain. Also, the opportunity to check experimental data with repeated tests is generally not available.

Because of certain limitations to be discussed shortly, we would like to design experiments for the sole purpose of validating CFD codes and handle the high temperature, real gas effects present in hypersonic flows. We envision a collaborative effort between experimentalists and CFD researchers in designing experiments and producing flow-field simulations for this purpose.

For these reasons we conclude that this type of facility is desirable.

Limitations of the proposed facility.

There exists a deficiency is scaling between the two-body collisional processes prevailing in the compression region and the three-body collisional processes in cooling/expanding regions. This scaling deficiency destroys the similitude of processes which control trim angle of attack and, to a lesser extent, radiation. However, the facility can still be used to calibrate CFD codes applied to the conditions of the experiment. As noted above, no other facility can do even this much for the velocity and model sizes being considered.

Orientation of the model for optical observation is uncontrolled. Therefore, the optical image you get may not be the one you want. This is in contrast with other facilities such as wind tunnels in which the orientation can be controlled.

Onboard instrumentation is somewhat limited due to the high "g" load during launch. One cannot perform spatial/temporal surveys with boundary layer rakes or hot wire techniques, which are generally important for study of turbulence. Again, this is in contrast with conventional facilities which can perform such tests.

The model surface roughness presents scaling problems in the study of turbulence. This problem is common to all other facilities.

Convective heat transfer problems involving chemistry, such as those involving wall catalysis, cannot scale.

Ablation effects are totally unscalable. We note that arc jets at least partly scale such phenomena.

There are serious limitations on the allowed lift-to-drag ratio for free flight. There is no control over the angle of attack.

What experiments are needed?

Generic shapes

We would like to conduct experiments with four generic shapes for the purpose of CFD code validation. The four shapes include a blunt body, a slender cone, a cone-flare combination, and a moderately blunt body with a boattail (fig. 1). The blunt body would be used to study nonequilibrium and radiative processes behind the bow shock and base flow phenomena which may be important for AOTV simulations. The slender cone would be used to study the transition from laminar to turbulent flow. The cone and flare would be used in fundamental studies of separation phenomena that occur across control surfaces. The moderately blunt body with boattail would be used to study chemical relaxation processes in compressive and expansive regions. We would want a detailed optical/spectral snapshot across the flow field at several locations including the bow shock, wake, and boundary layer. The duration of each recording should typically be 10 ns. The spatial resolution should be

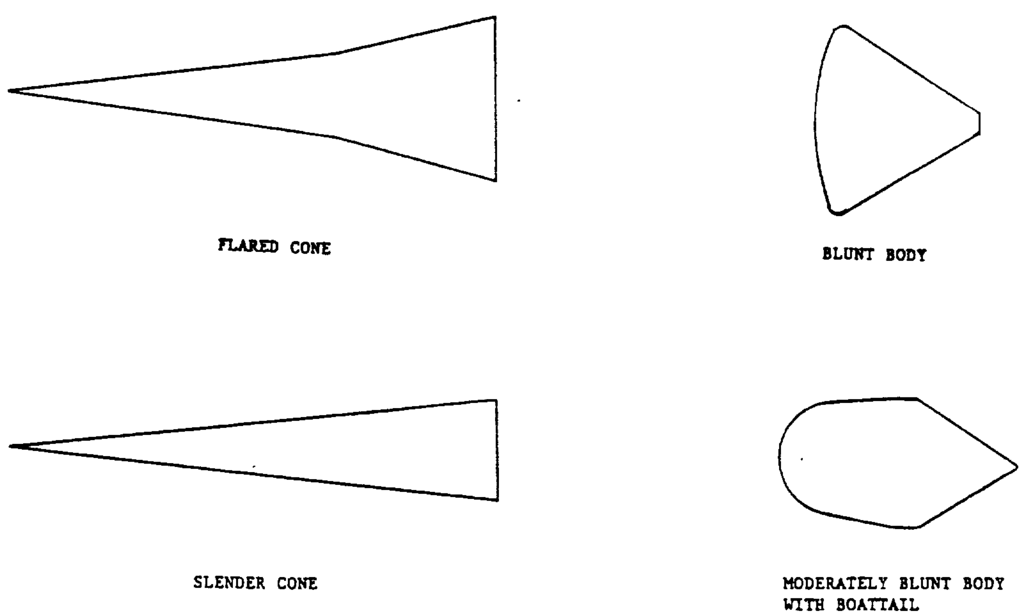


Figure 1. Four generic shapes proposed for CFD code validation.

0.1 mm if the body is 30 cm in diameter or 0.05 mm if the body is 15 cm in diameter. At this time we still prefer the larger diameter body because of the ability to better observe relaxation zones. The desired flow-field quantities include density, species number density for O, N, NO, N2, NO+, O+, N2+, translational temperature, vibrational temperature, electron temperature, and the streamwise velocity component. The resolution requirements are relaxed for the base flow profiles in which we could accept a 1 mm resolution for the 30 cm model. We would like 5 to 10 stations instrumented in this way.

Multiple exposures of these optical/spectral recordings at one station are desired in order to study the temporal variation of the field. The interval of exposure should be about 5 μs for a free-stream velocity of 9 km/s or 10 μs for a free-stream velocity of 4.5 km/s. We would not necessarily require multiple exposure measurements of all quantities or over the entire profile.

In addition to flow-field measurements, we would require surface measurements for pressure, temperature, and heat transfer rates. The surface heating includes both convective and radiative heating. The convective part is further subdivided into catalytic and noncatalytic walls. The total number of channels for these measurement should be at least 100. All of these data must be taken over a period of 100 μ s or less for the study of quasisteady flow over the forebody. The data should be collected over a period of 5 μ s for the study of unsteady phenomena. Here again, it may not be necessary to collect information for all quantities over this time period. Surface measurements should be made at intervals of 10 ms and should be synchronized with the collection of the flow-field data.

These measurements would be needed in both free flight and track modes. The free flight modes are necessary for the study of the base region. The tracked modes are preferable for the forebody studies as they would provide a better defined trajectory.

Application models

In addition to the generic models described above, we would want to conduct experiments with application-specific models such as AFE, AOTV, and NASP. For such models the surface measuring instruments must be located strategically, in places where CFD simulations are typically the most severely challenged, due to topological difficulties or complex fluid dynamic phenomena. Because these are lifting models, some free flight tests would be required to study aerodynamic coefficients.

Parameters

Operating parameters for the facility should meet the following velocity requirements.

NASP .... 6 km/s
AFE/AOTV .... 10 km/s
Mars return ..... 14 km/s

We would want to simulate the free-stream density that occurs at altitudes from 30 to 90 km. It is probably sufficient to scale the density at these altitudes in order that the Reynolds number of the flight vehicle matches the Reynolds number of the model in the proposed facility. However, it is likely that we would want to perform some fundamental studies at low Reynolds numbers (large Knudsen numbers) to study hypersonic, rarefied gas flows.

The facility should be designed so that a model with a lift-to-drag ratio of up to three can be tested.

<u>What other studies are required?</u>

There is no question that the present VFD codes available for studying hypersonic flows and real gas effects are in serious need of calibration, particularly with regard to the thermodynamic and transport properties and the physical models dealing with chemical kinetics, thermal relaxation processes, and radiation. Two types of studies are recommended in order to assess the need of the proposed facility. First, a parametric study involving several hypersonic simulation codes should be performed to assess the impact of unknowns in the physical models on the prediction of aerodynamics and aerothermodynamics of proposed flight vehicles. This has already been started to a limited extent for the AFE. Second, selected candidate experiments should be examined in more detail to assess the instrumentation requirements and the sensitivity of the physical models in the CFD codes to the proposed test conditions.

Fluid Dynamics/Real Gas Effects

This subgroup looked at issues concerned with boundary layer transition, turbulence modeling and flow structure.

Is the proposed facility required?

The low disturbance and chemically clean nature of the free stream make the ballistic range a unique tool to study fluid dynamics in the presence of real gas effects. There are many hypervelocity vehicle design issues that require an understanding of the fluid dynamics. Hence, there is a need for a large ballistic facility. The exact size will be discussed later.

Limitations of the proposed facility.

The ballistic range does not, however, duplicate full scale flight, and should be considered as a simulation of some aspects of the flow. The most important factor here is the inability to simultaneously scale 2-body chemistry and 3-body chemistry. The model size must be sufficiently large to be able to provide a range of conditions to activate both 2-body and 3-body chemistry. For example, if the body is large enough to obtain equilibrium chemistry on the AFE forebody for a large range of density, it will be possible to have an afterbody flow from equilibrium to nonequilibrium 3-body conditions.

What experiments are needed?

Many experiments are important. The following is a short list that is consistent with Fig. 1 in the workshop information package:

Boundary Layer Transition - Here the object is to test the effects of real gas on the transition Reynolds number as well as the influence of pressure gradients when real gas effects are present. These tests can be made on simple geometries at speeds from 3 to 8 km/s. These should be done in the absence of ablation. The range could also be used to study the effect of roughness and particulates on transition.

Turbulence Modeling - Turbulence modeling requires extensive flow-field data (correlations, etc.) that may be difficult to measure in flight or a range. Hence, much of this work will be done in perfect gas facilities. The range can be used to test for real gas effects on the modeling. This can be done with heat transfer measurements.

Flow-Field Structure - This requires a broad class of experiments including base flow, separation, shock boundary layer interaction, vortices and viscous/inviscid interaction. These will require surface measurements like pressure and heat transfer as well as distributions throughout the flow fields of parameters like density, pressure, local flow angle, velocities, species concentrations, etc. The range of conditions encompasses velocities from 3 to 9 km/s, and Reynolds numbers, based on characteristic length and diameter dimensions for both blunt and slender bodies, from 10^2 to 10^8.

What other studies are required?

Adequate instrumentation with appropriate resolution is essential to justify building a large range. The exact size of the launch capability required is dictated by the chemical scaling requirements and instrument resolution.

A study is required to determine the proper size of models required taking into account both chemical scaling and model resolution requirements. A study is also required to determine in more detail the types of instrumentation needed, those available, and where research is needed to fill gaps. In addition, a study needs to be undertaken to size the range itself, considering such effects as model thermal behavior, flight dynamics, and data acquisition requirements.

Hypersonic Propulsion

Is the proposed facility required?

The majority of the work done in the hypersonic-propulsion area would be done in existing wind tunnels and ballistic ranges. The new facility would be used as a check on those data. This check is particularly needed for experiments where real gas effects are important.

Limitations of the proposed facility.

Because combustion tests require an approximately 10 ft long model, they probably could not be performed in the range. A minimum model cross section would be 10 in. × 10 in. for other experiments. A tracked model with a sting would be acceptable.

Again, because of length limitations, experiments in which three-body reactions are important (such as on the NASP afterbody) could not be performed.

Because of model complexity and thus cost, model soft catch and recovery is required - a difficult task.

What experiments are needed?

a) Interaction of shock with inlet boundary layer.
b) Interaction of shock with inlet leading edge.
c) Airframe/propulsion integration aerodynamics.
d) Film cooling and skin friction on nose tip and in a combustor.
e) Fundamental fuel/air mixing studies.

These experiments would be performed over $M = 10 - 20$. They would require wall measurements of heat transfer, pressure, and temperature. The shock interaction studies would require free-stream measurements of density and temperature. The mixing studies would require skin friction measurements. The airframe/propulsion aerodynamics would require density and velocity around the model, as well as forces and perhaps moments.

Instrumentation resolution requirements appear to be well within those for other experiments such as reentry vehicles.

What other studies are required?

Experiments studies are needed to better define the facility requirements. A survey is required of the data base. Consideration must be made of existing or the modification of existing facilities as alternate approaches.

INSTRUMENTATION WORKING GROUP SUMMARY

William Isbell

(This is a transcript of Mr. Isbell's oral summary.)

The goal of the Instrumentation Working Group was to determine the experimental techniques by which measurements could be made in support of the Experiments Group. The first chart (I-1) describes the major areas of study of interest to that group and the types of measurements to be attempted. The types of measurements and the accuracies and numbers of data points to be obtained will be a challenge in that many of the measurement requirements flowed down by the Experiments Group exceed the capabilities of any current facility. Dissecting the overall measurement problem and separating it into individual requirements, however, brought light and hope to the discussion. Some problems were solved, some problems were defined, and some problems were shelved for later consideration. Note that, although numerous problems were unresolved, the basic feasibility of making most of the measurements was established.

The major areas of interest to the Experiments Group are shown in Chart I-2. They include:

1. The validation of CFD codes, with emphasis on real gas effects. Required measurements include detailed characterization of flow fields and heat transfer to model surfaces.

2. Measurements of integrated effects. Forces and moments must be measured.

3. Dynamics of propulsion systems. Scramjet propulsion wil be activated onboard subscale models. Inlet and nozzle flow fields and temperatures will be measured.

With regard to the characterization of the flow field (Chart I-3), the Experiments Group requires a measurement of the physical geometry of the model in flight and the capability to visualize the nature of the flow field. In order to validate their theoretical models, the Group wants measurements of the temperature field and measurements of the degrees of disassociation and ionization. They also require data on the species number densities.

The resolutions they require are "challenging," to say the least. For adequate accuracy, one hundred data points must be obtained between the projectile and the bow shock, a distance typically of 1 cm. Thus a resolution of a 0.1 mm is needed. That is almost a showstopper, although techniques for obtaining this resolution were discussed. Additionally, the Experiments Group wants to know the overall density distribution in the shock layer, the electron temperature, and the measurements of the turbulence in the wake; and they want to obtain a velocity profile throughout the entire bow shock. One of their keynote problems, wake characterization, requires a measurement of the temperature, the turbulence, and the density; and it requires information on the degree of dissociation and ionization.

Two of the parameters to be measured on the model itself are the velocity and the model position. These must be made with extreme precision because one measurement traverses the bow shock while the other measures the position of the nose of the model. Resolution of 0.1 mm in the bow shock implies an equally accurate knowledge of the model position at the time of the measurement. To make matters even more difficult, the duration of the measurement is very short. For 0.1 mm resolution at 10 km/s launch velocity, the measurement must be made in 10 ns.

Additional requirements include the measurement of acceleration of the model in all axes and the measurement of the model temperature over the entire surface. The Experiments Group suggested that 100 points of measurement of surface temperature and 100 points of measurement of pressure will be required. This is the level of measurement commonly performed in the wind tunnels. Note, however, that conventional (as opposed to impulse facilities) wind tunnels have the ability to operate for many seconds. The hypervelocity launch facility will have the capability of operating for only tens of milliseconds. Transmission of thousands of grid points will be needed in this time, implying an extremely high data transfer rate.

The Experiments Group needs to measure stress and strain within the projectile itself, the shape change, the ablation, the flow along the wings, and the surface pressure. We took these requirements and asked, "Should they be performed onboard or offboard?" On Chart I-4 are the various flow-field and model parameters to be measured and where the measurement must be made. The black circles in the chart indicate that the technique is either currently available or is available with a modest amount of development. The open circles indicate that the technique is available with development. The x in the area of velocity profiles indicates we were not sure how to perform this measurement, especially if it must be done onboard.

Several suggestions were made for velocity profile measurements. There are two basic approaches. The first is to take a "snap shot" of the model at one given point in time, probably in 2 or 3 dimensions. This must be performed on the order of every 10 ms of flight. The specified time interval, 10 ms, is a result of a very long discussion about how rapidly things change. Although we frequently tend to think of the flight of the model as being in quasi-equilibrium, this is not the case. The model is pitching and making other strange and wonderful moves. If you do not measure often enough, your data will not be valid.

This method of characterizing the flow field is the technique that is being used now in current ranges and wind tunnels. It is not clear that the amount of money available will make those measurements better. It may be better to spend the money on instrumenting the model itself. This would require the use of onboard techniques to measure the parameters involved.

Chart I-3 indicates possible parameters for onboard measurements. Now, as you might guess, there are a series of problems with this concept, as shown in Chart I-5. As we know, it is necessary to harden both against g forces and electromagnetic fields. Acceleration levels may be on the order of 10,000 to 50,000 g. Initially, 10,000 g was the design point, but this level had a way of increasing with time. If you cannot afford a very long launcher, you are going to have to accept higher g forces, so 10,000 to 50,000 g may be an appropriate goal for acceleration hardening. Strategic Defense Initiative Organization (SDIO) and DoD are looking at various technologies that will lead to hardening at this level. We need a survey of that technology.

Miniaturization of sensors, recorders, and transmitters will be a problem. Things have to be small, and they have to be light, since there are restrictions on the weight and the volume. There are going to be problems with the batteries, in this regard, in that there can be a problem with heat dissipation when you activate the rail gun. You need sensors for pressure, temperature, acceleration, absolute velocity fields, stream components, perhaps measurements of control movements and components that move inside the projectile. There are many possible problems with the electronics, and as this facility is studied in more depth, these problems will keep coming out.

A major concern with onboard measurement techniques is the ability to get the data out (Chart I-6). Several methods are available, but they will require considerable development. If it is possible to transmit the data through the wake or the bow shock, this may be the preferred technique. You can also save and transmit, which means placing the data in a memory onboard and then transmitting as the model passes through a section that is either evacuated to eliminate the wake or bow shock or perhaps filled with helium or some other gas to decrease the interference. (Note that transmission may be easier at radio end optical frequencies. Transmission through wakes and bow shocks as a function of frequency needs examining.)

Another technique involves an onboard memory which is read out post-test. This requires a soft recovery, although if you are willing to destroy the model, you might use the flight recorder technique to save only the memory.

Regarding the memory size you will need, if you are going to take as many data points as we have discussed, and either save it and then transmit it, or save it and then read it out at a later time, the memory can become physically very large. Obviously, more study is needed on this aspect.

Chart I-7 depicts the unresolved problems that we see for the onboard measurement techniques. Can we transmit the flight data through the boundary layer; can the electronics survive; will shielding be required; and how heavy will that shielding be? Basically, can we measure the flow-field parameters that are required? The answer to most of these questions is yes, although it will be expensive. The idea that we worked on is how to make the measurements affordable. To accomplish this, you make the system modular. By building the system by blocks at a time, you can plug various sensors into a basic framework which is flown each launch. The framework carries the functions we have been discussing, the memory and the transmission system. Sensor and a signal conditioning package(s) go into this standard module. Since the framework accommodates many of these packages, the system can be tailored for a given test and can minimize the cost per launch.

Given all of the problems above, is it possible to make the measurements required of an advanced hypervelocity launcher facility? Our conclusion is that most or all of the problems discussed here will yield to a determined development effort. Where seemingly insurmountable obstacles were discovered on a given technique, alternative techniques were proposed. Undoubtedly, there will be technology shortfalls, and the accuracies specified by the Experiments Group will not be obtainable in some areas. But that has been the history of diagnostics from the beginning of experimentation. Somehow, progress manages to be maintained.

INSTRUMENTATION PANEL

- MAJOR AREAS OF STUDY
  - CFD VALIDATION
  - INTEGRATED EFFECTS
  - PROPULSION SYSTEMS
- OFF-BOARD MEASUREMENTS
  - FLOW-FIELD CHARACTERIZATION
  - SURFACE TEMPERATURES
  - INSTRUMENTATION STATIONS
- ONBOARD MEASUREMENTS
  - PARAMETERS
  - DATA RECORDING/TRANSMISSION
- UNRESOLVED PROBLEMS
  - NUMEROUS
- SUMMARY STATEMENT
  - BASIC FEASIBILITY

5/12/88 WKSHP02

Chart I-1

STATEMENT OF MAJOR AREAS TO BE STUDIED

- CFD VALIDATION/REAL GAS
  - FLOW- FIELD CHARACTERIZATION
  - HEAT TRANSFER AT SURFACE
- INTEGRATED EFFECTS
  - FORCE AND MOMENTS
- PROPULSION
  - SUB-SCALE MODELS OF PROPULSION SYSTEM

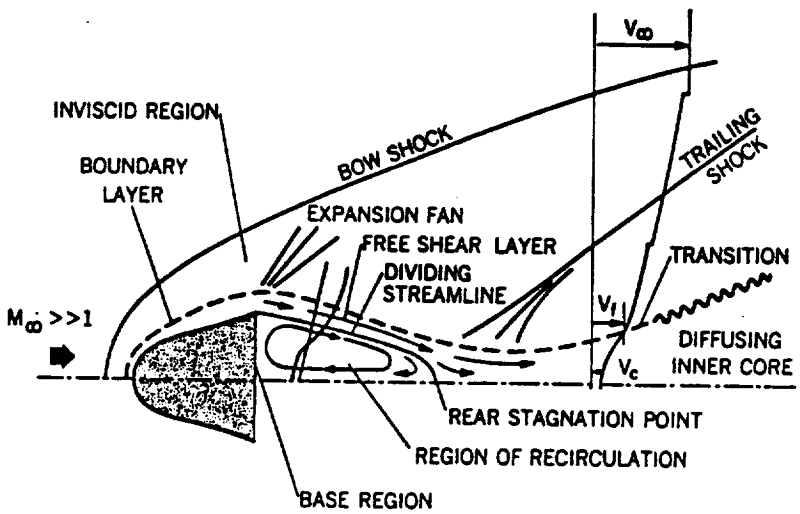
WKSHP51

Chart I-2

FLOW FIELD CHARACTERISTICS

BOUNDARY LAYER

- GEOMETRY
- TEMPERATURE, INCL. VIBRATIONAL TEMP.
- DISSOCIATION/IONIZATION; SPECIES NO. DENSITIES
- DENSITY DISTRIBUTION
- TRANSLATIONAL TEMP; ELECTRON TEMP.
- TURBULENCE
- VELOCITY PROFILE



WAKE CHARACTERIZATION

- TEMPERATURE
- TURBULENCE
- DENSITY
- DISSOCIATION & IONIZATION

MODEL PARAMETERS

- VELOCITY
- POSITION
- ACCELERATION
- TEMPERATURE
- ATTITUDE/ORIENTATION
- STRESS/STRAIN
- SHAPE CHANGE
- SURFACE PRESSURE

Chart I-3

- ● AVAIL
- o AVAIL W/DEV
- x CAN'T BE DONE (?)

PARAMETER	ON BOARD	OFF BOARD
FLOW FIELD		
VIB. TEMP		o
TRANS. TEMP		o
ELECTRON TEMP		o
SPECIES DENSITIES		o
VELOCITY PROFILE		x
DENSITY PROFILE		●
MODEL		
WALL TEMPS. (100)	o	
PRESSURES (100)	o	
MODEL ACCEL	o	
VELOCITY		●
ORIENTATION		●
SHAPE CHANGE		●
STRESS/STRAIN	o	

Chart I-4

ON-BOARD INSTRUMENTATION ISSUES

ISSUES - G-HARDENING & EMP
- MUST SURVIVE ORIGINAL LAUNCH ENVIRONMENT

* G-HARDENING
10,000-50,000 g
SDIO & DOD PUSHING TECHNOLOGIES
NEED SURVEY OF TECHNOLOGY
CHIP LEVEL INTEGRATION
INTEGRAL DESIGN TO STRUCTURAL PART OF MODEL
BATTERIES

* MINIATURIZATION
WEIGHT AND VOLUME RESTRICTIONS
BATTERIES
HEAT DISSIPATION
REDUCE POWER/ENERGY REQUIREMENTS

* ELECTRONICS
CMOS (AFFECTED BY HEAT), LOW ENERGY REQ'MTS
MAY NEED COOLING - UMBILICAL?
- NEEDS QUANTIFYING
- LEAP PROGRAM

MODULARITY

* SENSORS
1) PRESSURE
2) TEMPERATURE
3) ACCELERATION
4) LOCAL VELOCITY FIELD
5) STRAIN ON COMPONENTS
6) CONTROL MOVEMENTS
7) DYNAMIC PRESSURE (Q)

Chart I-5

OPTIONS FOR DATA RECORDING FROM MEASUREMENTS ON-BOARD MODEL

1. TELEMETRY
   - REAL TIME TRANSMISSION
   - SAVE AND TRANSMIT
   - RADIO AND OPTICAL FREQUENCIES
2. ONBOARD MEMORY
   - SAVE AND POST-TEST READOUT

CONSIDERATIONS

- TRANSMISSION THROUGH SHOCK LAYER
- MEMORY SIZE
- TRANSMISSION RATE
- MEMORY SURVIVABILITY

5/11/1988 FACILITY WORKSHOP

Chart I-6

UNRESOLVED PROBLEMS (ONBOARD)

- Can we transmit flight data through the boundary layer?
- **Will onboard electronics survive the EMP of the launch?**
- How can we measure the flow field velocity profile?

DESIGN PROBLEMS (ONBOARD)

- Hardened sensors, electronics, power supply
- Memory recoverable in a "black box"

wkshp50

Chart I-7

EML GROUP SUMMARY

Ian McNab - WESTINGHOUSE

(This is a transcript of Dr. McNab's oral summary.)

Ian McNab:

I would like to say that I enjoyed the two days that we have been here. All the members of our working group did a super job and contributed to a good and open discussion. Also, I have enjoyed meeting members of a totally different community.

To refresh your memory, Fig. EML-1 is the general outline that we were trying to work towards through the day and a half we have had since yesterday morning. From the requirements definition (Fig. EML-2) and fundamental physics (Fig. EML-3), we get into the energy and power requirements for the launcher and can then review and critique various accelerator concepts. The major ones: the rail gun; the coil gun, which has various subtypes; and electrothermal guns are discussed below. We tried to characterize the performance of the preferred system but held off on that because we felt we were in danger of trying to develop a point design and that was not appropriate for the limited time we have here. We did define the critical issues and will share that with you, followed by our recommendations.

Various different concepts for the rail guns, coil guns, and for the electrothermal guns were considered. (See Fig. EML-4.) We never really finished characterizing these in the limited amount of time we had here. But just to give you a flavor of this in terms of demonstrated velocities, rail guns achieve velocities in excess of 6 km/sec. These are small-scale guns, generally with a projectile mass of a few grams. By contrast the coil guns are at a state of development which is characterized by velocities less than 1 km/sec, but with large masses. Electrothermal guns are characterized by intermediate velocities on the order of 3 km/sec.

There are some limiting technologies for each of these. For example, for the electrothermal guns, it is the sound speed of the gas. Rob Burton gave us a presentation on a proposed high temperature version of the electrothermal gun called HVAC in which an attempt will be made to increase the speed of sound so that very high velocities can be achieved. However, although the equipment is ready to be demonstrated, it has not yet been proven; and as a result of time constraints, we did not give much more attention to the electrothermal gun at this stage.

Also, pointed out on Fig. EML-4 is that demonstrated forces in rail guns are up around the meganewton level, and you can see from Fig. EML-3 that for the job that NASA wants to do here we need about 1.4 meganewtons. So we are getting into the right ball park in terms of force. Efficiencies of up to about 28 percent have been demonstrated in the larger rail guns at this stage. At lower velocities appropriate to coil guns, probably higher efficiencies should be inserted in the table (Fig. EML-4), but we never completed this table.

Question:

Ian, did you discuss the light gas gun in your group?

McNab:

No, we did not, although we did discuss hybrid guns, rockets on carriages, and ramjet accelerators. I think the conclusion was that we should stick with these two main areas - rail guns and coil guns - right now and try to evaluate then a little more.

That major common issues for both options are shown in Fig. EML-5. Clearly the main issue is to get a successful demonstration of 10 + km/s. It is particularly important that should be done at low accelerating pressures. The kind of guns that the EM gun community has been developing to date have had small bores to accelerate high density materials, like long rod penetrators for anti-armor applications. The accelerating pressures in those guns are very much higher than required for this application.

We did feel that if you look at the total facility - from power in at one end to decelerating the model at the other end - that the EM launcher itself is probably a small fraction of the total cost of that facility - no more than a few percent. From that point of view, it seems that there is a possibility that if you want to increase the launcher length from the values that John Cable talked about yesterday (from 200 m) to maybe 300 or 400 m it would be relatively insignificant compared to a range that is 3.2 km long, which is the kind of length talked about yesterday. That thought might offer some flexibility to the designer of the model, to the designer of the sabot, or even to the designer of the accelerator.

There are some restrictions and also some opportunities for the launcher configuration. Various different options are available, and NASA could have two or three different launchers being powered by a single power supply. There was a general feeling in the group that we would like to avoid hybrid concepts in which light gas guns are injecting into the EM launcher at high velocities. Both the rail gun and the coil gun will probably benefit by having some pre-injection of the projectile to a few 100 m/s. But the general feeling was that hybrid concepts could give you the <u>worst</u> of both worlds rather than the best of both worlds. A couple of groups (Sandia National Laboratory/Lawrence Livermore National Laboratory/Los Alamos National Laboratory) (SNL/LLNL/LASL) have looked at the use of light gas guns as pre-injectors for very specific reasons that relate to the high pressure operation of their guns with plasma armatures. That restriction may not apply here, since it may be possible to use solid or hybrid armatures as opposed to plasma armatures.

The specific issues that we developed for rail guns or coil guns are shown in Figs. EML-6 and 7. In addition we did try to identify relevant R&D tests that could be accomplished or addressed to allow us to identify those critical issues (see Figs. EML-8 and 9), a major one being the demonstration of a high velocity. We noted that there were limited opportunities available for those kinds of experiments in coil guns. However, there are several rail gun facilities available now, or coming shortly, in which the high velocity capability may be demonstrated in a relatively small bore. To make the kind of experiments relevant to the NASA interest will require the experimental conditions to be redirected to address the specific issues mentioned above, particularly the opportunity for using hybrid or solid metallic armatures. Note that current high velocity rail guns mostly use plasma armatures. We did also point out that several large facilities are available to do large bore experiments, but the experiments to be done need definition. We have a similar kind of viewgraph for the coil gun (Fig. EML-9).

We also talked about power supplies in some detail to verify for the community here there are quite a number of ongoing power programs that could serve a basis for the kind of experiments I just discussed.

Earlier yesterday I showed how many gigajoules and gigawatts were required to do this job. Fig. EML-10 and Figs. EML-11 and 12 are listings current or soon-to-be-operational facilities. You can see that there are available facilities that give tens of megajoules and gigawatts of instantaneous power, the kind of numbers that will be needed for the NASA job. This is on the lower side of the requirements. Ultimately the requirements would be much larger than this, but it indicates that we are making progress on the path to the requirements. Fig. EML-13 summarizes our recommendations on the power supplies. Note that a modular design is recommended.

I have three final viewgraphs here. The first one is Conclusions (Fig. EML-14). We felt that the EML technology was applicable to this mission for NASA and was feasible to do this job. That is not to say that all the problems have been solved, but nevertheless it looks technically feasible. We could not see any show stoppers that would cause us to throw up our hands and walk away and say, "there is no way it can be done." Velocities of 6 km/s have been demonstrated with small systems, and on the whole, the scaling looks favorable. We will have to go from the small bore guns that are being demonstrated now to the larger bore, lower pressure requirements in which we limit acceleration to tens of thousands of g's, as opposed to the hundreds of thousands of g's that we have been used to trying to live with in the anti-armor and similar programs.

We urgently felt the need for a better requirements definition. How big is the model that needs to be accelerated, what kinds of g's it can withstand, and what are the other conditions that go along with that? We noted that the power supply itself is a high capital cost item which will be driven by the launcher concept, although as I mentioned earlier, the launcher itself may not be a high capital cost item in the entire system.

Question: (Hal Swift)

You said the launcher, do you mean the launcher and its power supply?

McNab:

I meant the accelerator. This should say accelerator rather than launcher, I guess.

Question: (Hal Swift)

Just the barrel, not the power supply?

McNab:

My guess is that the barrel itself would be a few percent of the total cost of the facility while the power supply might be tens of percent of the entire cost.

Recommendations (Fig. EML-15). We would like to see a definition of launch requirements, and we think NASA should hold together the body of expertise that is in this room to provide that to the EML experts who basically want a mass, acceleration, and diameter number so that we can go off and design some kind of launcher.

We felt that some near term physics validation experiments, using available power supplies and facilities, should be done to look at the critical issues for the different launcher concepts. At the same time, in parallel with those, some point designs and/or trade-offs should be done to allow us to identify in more detail what the critical issues really are. People felt strongly that if we did just one of these (e.g., just do the validation experiments) how would we know that we are addressing the correct issues? Conversely, only doing paper point designs might not leave us with enough time to reach the 1992 time scale. My feelings, and the feelings of some of the people in the group, were that we should try to do both of these things in parallel. The point was made that we should really have an entire facility study done, perhaps done by an architect engineering firm to see what it is like, what it is going to cost, and what they foresee as the major issues that are to be addressed. That would provide a context in which we could address the problems that relate to the accelerator. There was also a feeling that, although today's exercise has been very useful, NASA would benefit from an advisory committee to provide access to, or advice on, the existing EML programs as they are developed through DOD and SDIO programs and, in some cases, with internal R&D funds of the companies.

The very last thing which we did was to look at what a program plan would look like, looking at fiscal years from now through 1992. The target was, if we understood yesterday's discussion correctly, to let a contract the end of fiscal 1992 to start the detailed design and construction on this facility. You can look at this both ways: (1) you could work backwards from 1992 to see when you need the proposals in, when is the RFP to go out, when is the definition required for that RFP, etc., or conversely (2) we can start in 1988 and see what is needed now, e.g., we need a phase 1 requirement definition now, so that FY '89 funds can be used to start an effort on the phase 1 facility design and on physics validation experiments, which may take up to perhaps a year or more. Those two things would then come together to give a phase 2 milestone for a requirement definition by, say, late 1990, which allows NASA to go into the phase 2 point design which will be the basis for the Request for Proposals (RFP) definition. This is really a NASA program planning exercise, not particularly appropriate for the EML group, but what we felt was of interest was that when you look at where we are now (6 km/s with a few grams) and compare that with the confidence level that we need to be able to say (by 1991) that we can get 14 kg to 10 km/s, how much time do we have and what needs to be done in that time frame to give us a feeling of confidence that NASA could let a contract in 1992 for the amount of money that would be needed to perform this program. That's all I have. Comments or questions?

Question: (Bill Isbell)

Can you cut that time by a factor of two or four? You're talking about six years away from the first test.

Answer: (McNab)

We understood that at the end of 1992 was a time frame that NASA was aiming at so we worked back from that. We could have worked another schedule, I'm sure we could.

Question: (Bill Isbell)

If they had not specified 1992, might you have wound up with 1991 or 1992?

Answer: (McNab)

If you have money everything can be compressed. However, I think we already felt that the amount of time left to do physics validation experiments was probably pretty small, which is why you see the dotted line continuing through 1991. It is the question of risk that you have to address.

There are many military systems that are out in the field in which development has done in parallel with production. You make mistakes that way and you pay a lot of money to do that, but if you want to meet schedule that is what you have to do.

Comments: (Bill Isbell)

I wasn't sure just how much you were thinking of schedule based on that 1992 number you were given.

Response: (McNab)

We tended to feed back from the 1992 number, so it is not sacred by any means.

If you take more risk, the time could be reduced, but if you want minimum cost, I think you tend to do the studies and experiments in series.

Comments/Question: (Hal Swift)

Even with the federal bureaucracy, do you really need a solid 12-month year from the time the RFP is released until the contract is working?

Answer: (McNab)

That is not my labor grade to answer that question.

Comment: (Sterrett)

We agree that that (i.e., 12 months) is optimistic!

Comment: (McNab)

We would benefit from a longer meeting to allow us to address these issues in more detail.

AGENDA

- REQUIREMENTS DEFINITION
- FUNDAMENTAL PHYSICS
- ACCELERATOR CONCEPT & EVALUATION
- PREFERRED SYSTEM(S) - DESCRIPTION, PERFORMANCE & COST
- CRITICAL ISSUES
- RECOMMENDATIONS

Fig. EML-1

REQUIREMENT DEFINITION

PARAMETER	SYMBOL	VALUE	COMMENTS
MODEL MASS	M_m	10 kg	
LAUNCH VELOCITY	V_L	6 to 10 km/s	
LONGITUDINAL ACCELERATION	A_L	10^5 m/s^2	
SABOT MASS	M_S	4 kg	PER UT ASSUMPTION. SABOT DESIGN NEEDED.
MODEL CHARACTERISTIC DIMENSION	L_M	0.5 m	
MAGNETIC FIELD AT MODEL	B_M		EFFECT ON INSTRUMENTATION AND STABILITY.
B-DOT AT MODEL	$\dot{B}_M$		
TRANSVERSE ACCELERATION	A_T		

Fig. EML-2

FUNDAMENTAL PHYSICS*

PARAMETER	SYMBOL (UNIT)	EQUATION	Value for 6 km/s	Value for 10 km/s		COMMENTS
LAUNCHER LENGTH	S (M)	$V_T^2/2A_L$	180	500		
LAUNCH ENERGY	E_L (MJ)	$M_T V_T^2/2$	252	700		
LAUNCH TIME	T_L (S)	V_L/A_L	0.06	0.1		
AVERAGE POWER	P_L (GW)	E_L/T_L	4.2	7.0		
FORCE	F (MN)	$M_T A_L$	1.4	1.4		
ENERGY INPUT TO ACCELERATOR	E_{in} (MJ)	E_L/η	1010	2800	25%	Efficiency
			504	1400	50%	
			336	933	75%	
POWER INPUT TO ACCELERATOR	P_{in} (GW)	P_L/η	16.8	28	25%	Efficiency
			8.4	14	50%	
			6.0	9.3	75%	

*Constant acceleration assumed.

Fig. EML-3A

ELECTRICAL PARAMETERS*

PARAMETER	SYMBOL (UNIT)	EQUATION	VALUE FOR L' (u H/M) 0.4	0.8	1.2	COMMENTS	
CURRENT	I (MA)	$(2F/L'N)^{½}$	2.65	1.87	1.53	N=1	
			1.32	0.94	0.76	N=4	
BACK EMF	V (kv)	(IL'v)	6.4	9.0	11.0	N=1	6 km/s
			3.2	4.5	5.5	N=4	
			10.6	14.9	18.4	N=1	10 km/s
			5.3	7.5	9.2	N=4	

*Constant Current/acceleration assumed.

Fig. EML-3B

CONCEPT EVALUATION

ISSUE	RAIL GUN	COIL GUN	ELECTROTHERMAL
VELOCITY DEMONSTRATED (KM/S)*	>6	<1	~ 3
LIMITING TECHNOLOGY	ARMATURE	SWITCHING/VOLTAGE	SOUND SPEED
MASS DEMONSTRATED*	1 KG	100'S KG	1 KG
MASS CAPABILITY	HIGH	HIGH	CARTRIDGE SCALING
ACCELERATION CONTROL	0	+	-
DEMONSTRATED FORCE	1 MN	50 KN	600 KN
DEMONSTRATED EFFICIENCY	28%	-	-

* NOT AT SAME TIME

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Fig. EML-4

COMMON ISSUES

- VELOCITY DEMONSTRATION TO 10 + KM/S
  - AT "LOW" ACCELERATING PRESSURES
- "LOW" RELATIVE COST OF LAUNCHER PROVIDES OPPORTUNITY FOR SABOT/ACCELERATOR TRADE-OFFS
- RESTRICTIONS/OPPORTUNITIES FOR LAUNCHER CONFIGURATION OPTIONS
  - TRACK-GUIDED CONCEPTS
  - AVOID (HIGH VELOCITY) HYBRID/LGG CONCEPTS
  - CRITICALLY EVALUATE ARMATURE DECELERATION CONCEPTS
  - EMI ENVIRONMENT
  - ALIGNMENT ACCURACY

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Fig. EML-5

RAIL GUN ISSUES

- VELOCITY DEMONSTRATION TO 10 KM/S
  - NEW PHYSICS?
  - HYBRID ARMATURE
  - SLIDING FRICTION
- ARMATURE
  - HIGH PRESSURE / LOW PRESSURE OPERATION
  - SABOT / MODEL / ARMATURE INTERACTION
  - PLASMA OPERATION AND SEALING
  - MECHANICAL STRESSES

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Fig. EML-6

COIL GUN ISSUES

- VELOCITY DEMONSTRATION TO "HIGH" VELOCITY
  - VERIFICATION OF THEORETICAL CODES NEAR OPERATING LIMITS
- ARMATURE HEATING
  - STARTING CURRENTS
  - SKIN EFFECTS
- POWER CONDITIONING AND CONTROL AT HIGH VOLTAGE/CURRENT
  - HIGH FREQUENCY , TRAVELLING WAVE
  - SWITCHING
- SECTION-TO-SECTION TRANSITIONS
- OPERATING FLEXIBILITY FOR ACTIVE/PASSIVE STATORS

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Fig. EML-7

RELEVANT R & D FOR RAIL GUNS*

- LIMITED OPPORTUNITIES FOR HIGH VELOCITY "SMALL" BORE EXPERIMENTS - THUNDERBOLT; SNL; MLI; SUVAC; UT; AFATL
  - REDIRECTION NEEDED TO ADDRESS SPECIAL ISSUES RELEVANT TO NASA REQUIREMENTS
- SEVERAL LARGE POWER SUPPLIES AVAILABLE TO DO LOW VELOCITY LARGE-BORE EXPERIMENTS
  - EXPERIMENT DEFINITION/INTERFACES NEED DEFINITION

* READY FOR 1992 DECISION

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Fig. EML-8

RELEVANT R & D FOR COIL GUNS

- LARGE-SCALE EXPERIMENTS FOR STARTING SECTIONS
- DEMONSTRATE HIGH FREQUENCY POWER CONDITIONING (20 KHZ, 100KV) AT REASONABLE SCALE
- ARMATURE EXPERIMENTS UNDER CONDITIONS THAT ARE CLOSE TO FAILURE

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Fig. EML-9

PULSE POWER SUPPLY REQUIREMENTS

(Assumed 25% System Efficiency)

- AT 10 KM/SEC - STORED ENERGY = 200 MJ/KG

  AVERAGE POWER ~ 2 GW/KG

  PEAK POWER ~ 4 GW/KG

- PULSE FORMING EQUIPMENT IS REQUIRED

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Fig. EML-10

ON-GOING PULSE POWER PROGRAMS

• MAXWELL LABORATORY		
CAPACITOR	32 MJ	30 GW
• UNIV. OF TEXAS		
HPG/INDUCTOR	60 MJ	30 GW
COMPULSATOR	32 MJ	27 GW (1989)
• LLNL		
CAPACITOR	60 MJ	60 GW
• PPPL		
WATERWHEEL ALT.	3 GJ	1 GW
• WESTINGHOUSE		
CAPACITOR	60 MJ	6 GW (1989)
HPG/INDUCTOR	10 MJ	
PULSED ALT.	3 GJ	

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Fig. EML-11

ON-GOING PULSE-POWER PROGRAMS

- AFATL

BATTERY/INDUCTOR	160 MW 5-8 SEC
	350 MW (1990)
	65 μH, 2.5 MA
	200 MJ STORED
	10 KV, 20 GW
HPG	10 MJ
CAPACITOR	5 MJ

- ANU

HPG	500 MJ, 800V, 1.6 MA

- AEDC*

4 HPG	100 MJ EA., 500 KA

* MOTHBALLED

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Fig. EML-12

POWER SUPPLY RECOMMENDATIONS

- SEVERAL OPTIONS ARE TECHNICALLY FEASIBLE
- FINAL CHOICE WILL BE DRIVEN BY:

  CHOICE OF LAUNCHER

  COST

  RELIABILITY

- MODULAR DESIGN RECOMMENDED

6/13/88 WIS WKSHP12

Fig. EML-13

CONCLUSIONS

- EML TECHNOLOGY IS APPLICABLE TO THIS MISSION - JUDGED FEASIBLE
- VELOCITIES > 6 KM/S DEMONSTRATED WITH SMALL SCALE RAILGUNS -SCALING UP IS FAVORABLE
- BETTER REQUIREMENTS DEFINITION NEEDED
- POWER SUPPLY IS HIGH CAPITAL COST ITEM
  - DRIVEN BY LAUNCHER CONCEPT

6/13/88 WIS WKSHP13

Fig. EML-14

RECOMMENDATIONS

- DEFINE LAUNCH REQUIREMENTS
- PURSUE NEAR-TERM VALIDATION EXPERIMENTS
  - UTILIZE EXISTING AVAILABLE POWER SUPPLIES
- DO PARALLEL PRELIMINARY POINT DESIGNS
  - COST/SIZE TRADE-OFFS
- DO STUDY ON ENTIRE FACILITY
  - MODULAR POWER SUPPLY PREFERRED
- FORM ADVISORY COMMITTEE TO PROVIDE ACCESS TO EXISTING EML EXPERTISE/PROGRAMS

6/13/88 WIS WKSHP14

Fig. EML-15

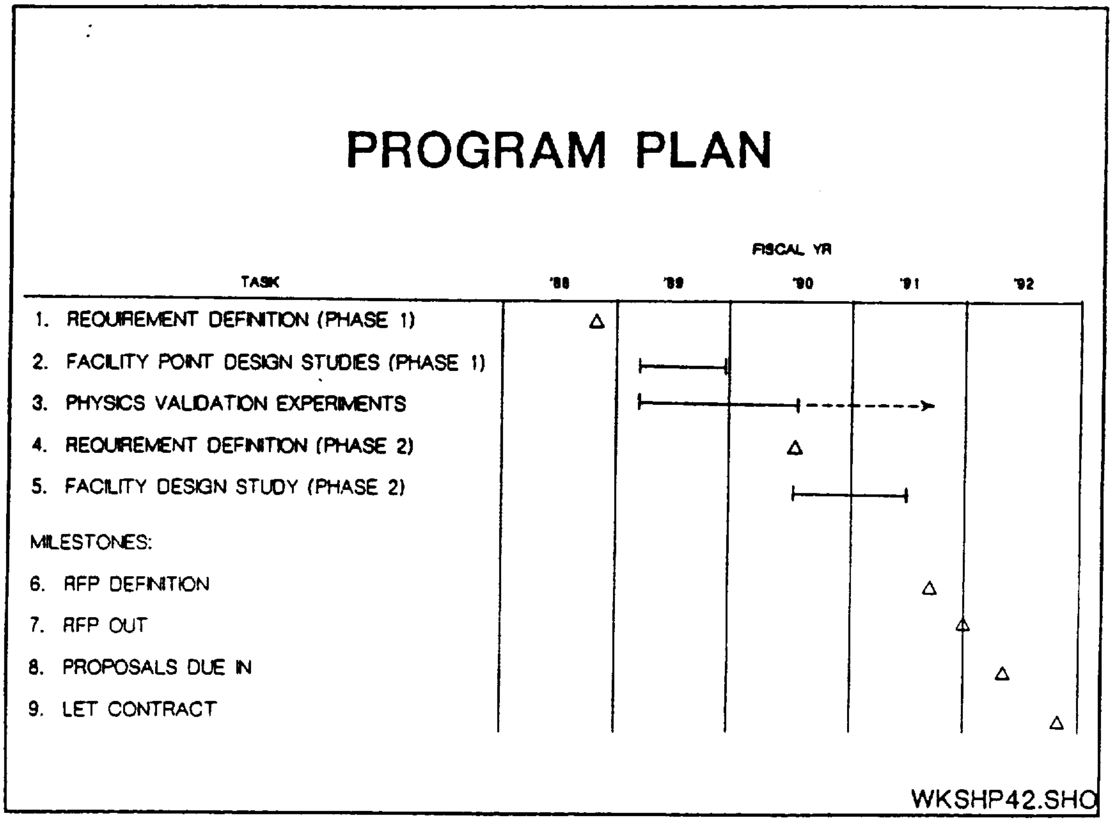
PROGRAM PLAN
FISCAL YR
TASK
'88
'89
'90
'91
'92
1. REQUIREMENT DEFINITION (PHASE 1)
2. FACILITY POINT DESIGN STUDIES (PHASE 1)
3. PHYSICS VALIDATION EXPERIMENTS
4. REQUIREMENT DEFINITION (PHASE 2)
5. FACILITY DESIGN STUDY (PHASE 2)
MILESTONES:
6. RFP DEFINITION
7. RFP OUT
8. PROPOSALS DUE IN
9. LET CONTRACT
WKSHP42.SHO

Fig. EML-16

RANGE TECHNOLOGY WORKING GROUP SUMMARY

(John Cable, Chairman)

(This is a transcript of Mr. Cable's oral summary)

As the Range Technology Group found out this morning there is a strong emphasis on free flight with nonsymmetric models. We decided to take a look at what the fly-off (trajectory of a model in the test section) might be for something like a shuttle model. We made a number of assumptions (Fig. R-1). We assumed that we would have a 25 cm long model, something like a shuttle so it is basically triangular in shape and at 40° angle of attack. We assumed a lift coefficient of 0.2 based on plan area. We said the average velocity was going to be 6 km/s. We picked a flight length, or tank length of 1 km and we picked a range pressure of 1 atmosphere. It is a pretty severe condition. So we did a quick calculation and we found that if you just allowed it fly off it will go off about 37 m straight (Figs. R-2 and R-3). This is proportional to range pressure so, if you go down to a 1000th of an atmosphere, you can get it under control. Also, if you roll the model so that the normal-force vector is always pointed inward, you eventually come up with a sort of maximum circle that it is flying in. We picked a pretty slow roll rate, one revolution in 300 m. That's about 3 times or so down the length of this range. And that gets down the dispersion to about 5 or 6 m, which is also proportional to range pressure.

So there is a way of getting dispersion under control. Now these were our straightforward equations, definition of lift coefficient and f = ma that type of thing. No complications or computer calculations. So that gives you an opportunity to do some nonsymmetric work and have a reasonable size facility. We then had a look at what needed to be done by this group or NASA or somebody if this test facility is going to go on any further. We suggested (Fig. R-4) four representative payloads or models be selected, and you subject these to a fairly rigorous design so that you can know that the model can be launched. You can then develop a sabot design from that knowing the model design. From that you can get a total package mass and thus determine the peak allowable acceleration. From that you can determine the size of the launcher and what energy is needed to deliver the package. The models that we thought about were suggested to us by Bill Isbell, and those we considered were a shuttle model, a very long slender cone, and one of these nonsymmetrical large diameter blunt bodies.

Addressing launcher technology, we came up with different ideas from the EML gun people. We are not prejudiced in favor of EML. So we said a conservative approach (Fig. R-5) might be to use a light gas gun launcher either by itself or as an injector for an EML velocity magnifier as a way of getting the test facility started. The light gas gun is pretty mature technology. Basically, all we have to do is to pull out the drawings and scale them up and get a cost estimate. We think the diameter, however, is limited to probably somewhat in the region of 25 cm. This would limit your model size to a 20 cm base diameter cone, some sort of blunt vehicle which is 20 cm or so in diameter, and a shuttle model which is say 56 cm long and about 20 cm across the wing span. This would require a range tank or flight chamber which would be comparable in size with current facilities. The aggressive approach is shown in Fig. R-6. We had trouble defining how to describe this approach. We did not want to say high risk and we did not want to say optimistic so we settled on the aggressive approach, which would be to go the whole way using the EML launcher 18 inches in diameter. In that case, we see the problem is that this whole facility is depending on a nondemonstrated EML capability and that the range tankage must be much greater than the current facilities. All that reflects in the cost of the facility. We thought of an intermediate approach (Fig. R-7) which was to design the range tank flight chamber for a 46 cm (18 in.) bore EML so that if the EML is developed quickly the range is available to complete the facility. In the meantime, you can install a light gas gun, and then when the 46 cm EML is perfected just take the light gas gun out and put in the EML gun.

Question: (Inaudible)

...but dealing with the velocity capability of light gas guns.

Response: (Cable)

I would be comfortable with around 8 km/s. I think that with a lot of effort you could probably squeeze it up to 10 km/s. But if you use it as an injector, you might well want to drop it down to 6 km/s; you'd have to do quite a few trade-off studies, to determine the best compromise.

Inaudible question.

Cable:

For those who are not sure what piezeometric ratio is, that's the ratio of the peak acceleration to the constant acceleration that's needed to launch the model.

Question:

What's your lower limit on acceleration on the system?

Response: (Cable)

It depends on the size of the gun. I would say 50,000 g just off the top of my head.

Inaudible comment from the audience but directed to the 18 inch launcher tube bore and a 22 pound model-sabot mass.

Cable:

That (22 lb model/sabot package) was based on a marshmallow model. It became clear again this morning that both track and free-flight configurations needed to be addressed. So we just put a couple of viewgraphs together showing the advantages and disadvantages. The advantages of the track (Fig. R-8) are (1) it produces an accurate model trajectory and you know where to place your instrumentation, (2) it permits recovery of the model if that's desirable, and (3) you can have a reduced diameter on your range tank. It's not going to fly off anywhere. The disadvantages are (1) that it's awful difficult to make wake measurements with that body flying behind it,

(2) aerodynamic coefficients that you get by free oscillatory motions are impossible, and (3) it will interfere with some of your flow-field studies. Now the other thing is that with the recovery tube length that we picked it about doubles the length of the facility. Now with free flight (Fig. R-9), of course, its advantages are that (1) you've got no flow-field interference, (2) you've got no constraints on your flight path, and (3) you can have relatively a short facility. In other words you don't have a 2 km long recovery section. The disadvantages are (1) your flight attitude is uncontrolled. The model is free to go where it wants. But where are you going to put your instrumentation to take those pictures of a hundred data points in one centimeter. (2) The models are probably not recoverable. There may be some way we can develop a recovery technique, but it's not very obvious. And because of the fly off you need that relatively large tank. As I mentioned earlier, if you roll the model you can cut the tank diameter down some. Rolling also reduces the large model dispersion.

We had just a couple of recommendations (Fig. R-10). One, we said that the formal study of representative model and sabot packages be performed. In other words, the experimenters pick three or four typical shapes they want to study and let somebody sit down and go through all the calculations necessary and come up with what launch mass you need and what acceleration the package is capable of withstanding. Then everybody has a basis to work from. The other thing we would like to do and it would not take that much effort, is to just run around the manufacturing community and try to see how big a forging they can make. Then we can see whether a 25 cm light gas gun is feasible or really the limit is 15 or 20 or 35 cm. Then you have a much better idea of whether any sort of hybrid or combination might work.

NONSYMMETRIC MODEL DISPERSION

- (A) ASSUMPTIONS:

  - 0.508 METER LONG SHUTTLE MODEL AT ANGLE OF

    ATTACK

  - LIFT COEFFICIENT ~ 0.2

  - AVERAGE VELOCITY ~ 6 KM/S

  - TANK LENGTH ~ 1 KM

  - RANGE PRESSURE ~ 1 ATMOSPHERE

6/16/88 WKSHP31

Fig. R-1

NONSYMMETRIC MODEL DISPERSION (CONTINUED)

- (B) IMPLICATIONS:

  - STRAIGHT FLY OFF ~ 120 FT

    (Proportional to Range Pressure)

  - MODEL ROLLS AT RATE OF 1 REV/1000FT

    MAXIMUM DISPERSION ~ 18 FT RADIUS

    (Proportional to Range Pressure)

6/16/88 WKSHP32

Fig. R-2

NONSYMMETRIC MODEL DISPERSION (CONCLUDED)

- LIFT FORCE

  $L = 1/2(\rho)(V)^2 C_L A$

- FLYOFF DISTANCE

  $X = 1/2(a)(t)^2 = 1/2(L/m)(l/V)^2$

- RADIUS OF FLYOFF

  $r = L/(m/\omega)^2 = L/(4(\pi)^2 m(R)^2 (V)^2$

  (R = Rifling Rate)

6/16/88 WKSHP33

Fig. R-3

MODEL DESIGN STUDY

- SUGGEST 4 REPRESENTATIVE PAYLOADS BE SELECTED:
  1. SUBJECT MODEL TO RIGOROUS DESIGN
  2. DEVELOP SABOT DESIGN
  3. DETERMINE LAUNCH CONDITIONS
     - PACKAGE MASS
     - PEAK ALLOWABLE ACCELERATION
- DETERMINE LAUNCHER SIZE/ENERGY DELIVERY REQUIREMENTS

6/16/88 WKSHP34

Fig. R-4

LAUNCHER TECHNOLOGY

- CONSERVATIVE APPROACH
  - LIGHT-GAS GUN LAUNCHER AND/OR INJECTOR FOR EML VELOCITY MAGNIFIER
    - DIAMETER IS LIMITED
      (~ 10 IN. BUT NOT YET DETERMINED)
    - MODEL SIZE LIMITS
      - 8 IN. BASE DIA CONE PROBABLY O.K.
      - BLUNT VEHICLE, 8-9 IN. DIA
      - STS MODEL, 14 IN. LONG @ 40° A.O.A.
    - RANGE TANKAGE SIMILAR SIZE TO CURRENT LARGE FACILITIES

6/16/88 WKSHP35

Fig. A-5

LAUNCHER TECHNOLOGY (Continued)

- AGGRESSIVE APPROACH
  - USE EML LAUNCHER W/18 IN. BORE DIA.
    - FACILITY DEPENDENT UPON UNDEMONSTRATED EML CAPABILITY
    - RANGE TANKAGE MUST BE MUCH LARGER THAN CURRENT FACILITIES

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Fig. A-6

LAUNCHER TECHNOLOGY (Concluded)

- INTERMEDIATE APPROACH
  - INSTALL TANKAGE FOR 18 IN. BORE E.M.L.
  - INSTALL LIGHT-GAS GUN WITH 10 IN. BORE
  - SUBSTITUTE 18 IN. E.M.L. WHEN/IF TECHNOLOGY BECOMES AVAILABLE

6/17/88 WKSHP37

Fig. R-7

TRACK CONFIGURATION

ADVANTAGES

- PRODUCES ACCURATE MODEL TRAJECTORY
- PERMITS RECOVERY OF MODEL
- ALLOWS SMALL DIAMETER RANGE TANKAGE

DISADVANTAGES

- INTERFERES WITH
  - WAKE MEASUREMENTS
  - AERODYNAMIC COEFFICIENT DETERMINATION
  - SOME FLOW-FIELD STUDIES
- RECOVERY SECTION APPROXIMATELY DOUBLES FACILITY LENGTH

6/17/88 WKSHP38

Fig. R-8

FREE FLIGHT CONFIGURATION

ADVANTAGES

- NO FLOW-FIELD INTERFERENCE
- NO CONSTRAINTS ON FLIGHT PATH
- FACILITY CAN BE MADE RELATIVELY SHORT

DISADVANTAGES

- FLIGHT ATTITUDE UNCONTROLLED
- MODELS PROBABLY NOT RECOVERABLE
- RELATIVELY LARGE DIAMETER RANGE TANKAGE IS REQUIRED
- LARGE MODEL DISPERSION
  - ROLL LAUNCH PACKAGE TO MINIMIZE DISPERSION

6/17/88 WKSHP39

Fig. R-9

RECOMMENDATIONS

- FORMAL STUDY OF REPRESENTATIVE MODEL/SABOT PACKAGES BE PERFORMED
- DETERMINE MANUFACTURING LIMITATIONS ON LIGHT-GAS GUN BORE DIAMETERS

6/17/88 WKSHP40

Fig. R-10

APPENDIX A

Presentation by Members of the
Experiment Definition Working Group

CFD/Real Gas Effects Subgroup

Chul Park/Desirable Hypersonic Experiments.- Five classes of experiments were proposed: (1) Trim angle determination in chemically reacting regime; (2) lift, drag, and moments determination for high-lift models; (3) ram-jet (inlets, combustion chamber, and nozzle) tests; (4) laminar-to-turbulent transition in boundary layers in chemically reacting regime; and (5) accurate radiation measurement. Difficulties associated with accomplishing these experiments expressed by Dr. Park were: (1) A long flight range is required to observe the slow-varying flight path and attitude for measuring trim angle and forces and moments and to actuate ram-jet fuel-injection mechanisms and (2) required telemetry for data transmission will be severely limited by high magnetic fields of EML. Additional concerns raised during the presentation were phenomena which could not be satisfactorily scaled on a model (such as real gas effects) and the extremely long range length required for observing the phenomena being investigated.

DESIRABLE HYPERSONIC EXPERIMENTS
Chul Park

(1) TRIM ANGLE DETERMINATION IN CHEMICALLY REACTING REGIME

(2) LIFT, DRAG, AND MOMENTS DETERMINATION FOR HIGH-LIFT MODELS

(3) RAM-JET (INLETS, COMBUSTION CHAMBER, AND NOZZLE) TESTS

(4) LAMINAR-TO-TURBULENT TRANSITION IN BOUNDARY LAYERS IN CHEMICALLY REACTING REGIME

(5) ACCURATE RADIATION MEASUREMENTS

DIFFICULTIES

SLOW ACCELERATION, LONG RANGE, AND AVOIDANCE OF STRONG MAGNETIC FIELDS.

(1) TRIM ANGLE DETERMINATION IN CHEMICALLY REACTING REGIME

Trim angle of attack issue has not been satisfactorily resolved though chemical reactions are suspected of being the cause (the interpretations on trim-point data for Apollo by Langley, AEDC, and Ames differ. Space Shuttle's trim angle data not fully explained.)

Trim angle measurement in a ballistic range for Mach numbers up to 25 by Ames for Apollo inconclusive due to poor resolution.

It is extremely difficult to predict the trim angle using CFD.

A large ballistic range is ideal for experimentally determining trim angles.

(2) LIFT, DRAG, AND MOMENTS FOR HIGH-LIFT VEHICLES

Lift, drag, and moments must be tested in reacting flow regime using a ballistic range because cold or vitiated wind tunnel flows lead to erroneous results.

Testing a high-lift model in a ballistic range requires a large size because of the complexity of the model. The large acceleration inherent with a small ballistic range destroys a complicated model.

(3) RAM-JET (INLET, COMBUSTOR, AND NOZZLE) TESTS

Realistic ram-jet testing requires simulation of enthalpy without vitiation of the test flow. This can be achieved only in a ballistic range.

To test a ram jet in a ballistic range, a large size is required for design of intricate details of the ram-jet engine and avoidance of large acceleration.

(4) LAMINAR-TO-TURBULENT TRANSITION

Laminar-to-turbulent flow transition point in a chemically reacting flow cannot be found in a cold-flow wind tunnel or a vitiated wind tunnel. Therefore, a ballistic range must be used.

A small ballistic range suffers from the surface roughness scale problem. Therefore, a large ballistic range is needed.

Many heat transfer gages must be put on the model, and the results must be telemetered.

(5) ACCURATE RADIATION MEASUREMENT

Radiative heat transfer rates to a blunt body are uncertain partly because their laboratory measurement is difficult. Only a ballistic range gives a fairly close simulation.

Even with a ballistic range, a small model usually leads to ablation caused by high convective heating. A large model is required.

Radiation measurement should be made at the model surface, not through a window of the range. The results must be telemetered.

DIFFICULTIES

(1) TRIM ANGLE AND (2) LIFT, DRAG, MOMENT MEASUREMENTS

A long flight range is required to observe the slow-varying flight path and attitude.

(3) RAM-JET TESTS

A low acceleration is required to preserve the intricate model.

A long flight range is required to actuate the fuel-injection mechanism.

Telemetry is required. This means that no high magnetic field is allowed.

(4) LAMINAR-TO-TURBULENT TRANSITION AND (5) RADIATION MEASUREMENT

Telemetry is required. This means that no high magnetic field is allowed.

Harris Hamilton/Summary for Experimental Definition Working Group.- Mr. Hamilton's presentation indicated that the proposed range offered the potential capability of significantly contributing to CFD code calibration/validation efforts. He also emphasized that the measurement of properties across a blunt body shock layer is necessary for code calibration/validation. He also said that large models are required to provide sufficiently thick shock layers to determine properties within the shock layer. He also emphasized the importance of high quality, accurate measurements (and improved instrumentation) to the success of code calibration/validation.

ADVANCED HYPERVELOCITY AEROPHYSICS FACILITY WORKSHOP

Summary for Experimental Definition Working Group

by

Harris Hamilton

QUESTIONS FOR DISCUSSION

- What are experimental capability requirements for the foreseeable future in hypersonics for which the Ballistic Range is well suited?

  Answer presented from view point of requirements to calibrate/validate CFD codes for flight.

- Do you see any practical impediments to achieving the capabilities you have outlined?

HHH/2

EXPERIMENTAL CAPABILITY REQUIREMENTS

- Advantages of Ballistic Range

  High velocities that produce real gas, radiating flow fields

  Clean, chemically inactive free stream with low disturbance level

  Base/wake flows without sting interference

  Wide range of free-stream conditions and gas compositions

  Potential for relatively large models

  Capable of simulating flow conditions that "stress" flow-field codes

HHH/3

EXPERIMENTAL CAPABILITY REQUIREMENTS

- Types of data required to calibrate/validate CFD codes for flight predictions (requires comparisons with large body of experimental data)

  Aerodynamic characteristics

  Shock and shear layer shapes and locations

  Surface pressure distributions

  Surface heat transfer distributions

  - Total, convective and radiative components

  Distribution of properties across shock layer

  - Density, velocity, and species profiles
  - Spatial and spectral distribution of radiation data

HHH/4

IMPEDIMENTS TO ACHIEVING CAPABILITIES

- Instrumentation (both on model and within range) must greatly improve to enable measurement of physical phenomena of interest.
  - Small size to allow onboard installation
  - Rugged to withstand accelerations
  - Improved methods of off loading data during test
  - Improved sensitivity and spatial resolution
- Model size must increase while maintaining high velocity
  - High velocities required for realistic flow simulation
  - Large models required to allow good data measurement
  - Shock layer profiles necessary to CFD code calibration/validation
- High model and instrumentation costs (unless reused)

HHH/5

SUMMARY

- Ballistic ranges are capable of simulating flow conditions that can severely "stress" physical models used in flow-field codes.
- Measurement of properties across shock layer is necessary for CFD code calibration/validation.
- Greatly improved instrumentation is necessary for making detailed high quality data measurements useful for CFD code calibration/validation.
- Large models are necessary to allow resolution of properties within shock layer.

HHH/6

Peter Gnoffo/Experimental Capability Required for Hypersonic CFD Validation.- Dr. Gnoffo's presentations indicated that a large-scale ballistic range could potentially provide flow measurements on blunt bodies which could significantly enhance CFD code validation efforts when compared to other ground test facilities. A major concern, however, was whether accurate profile measurements could be made through the shock layer on a blunt body. Unless this can be done, CFD code validation will not justify the proposed range.

Experimental Capability Required for Hypersonic CFD Validation
Peter A. Gnoffo May 10-11, 1988

- **Three issues:**
  - (1) **numerics - numerical viscosity influence on flow**
  - (2) **high temperature thermodynamic and transport properties** - available from theory but calculations and assumptions are complex and still need verification
  - (3) physical models - approximate in nature - need most help here
- **Physical models**
  - Multi-temperature environment (Boltzmann distribution at one temperature not good enough)
    - Chemical Kinetic Models
    - Energy Exchange Models - translational, rotational, vibrational, electronic, radiation
      - (1) define/refine model
      - (2) determine "critical" reactions - CSP procedure
      - (3) Compare prediction to experiment
  - Transitional Flows
    - Free molecular to continuum - nonlinear stress relations - need profile through shock
    - Laminar to turbulent - surface temperature and roughness must be documented
  - Base and near wake flows - issues are flow symmetry and steadiness
- **Ballistic Range Data Needed**
  - Integrated quantities - lift, drag, control surface effectiveness
  - Surface quantities - temperature, heating, roughness, shape change
  - Profile quantities - species number density, temperature(s), velocity, pressure, electric current
- **Desired experiment**
  - Blunt, sonic corner body with largest possible shock standoff distance in given facility - get profiles in plane of symmetry and normal to axis - opportunity to check repeatability a big plus here

SCALING CONCERNS IN NON-EQUILIBRIUM FLOWS

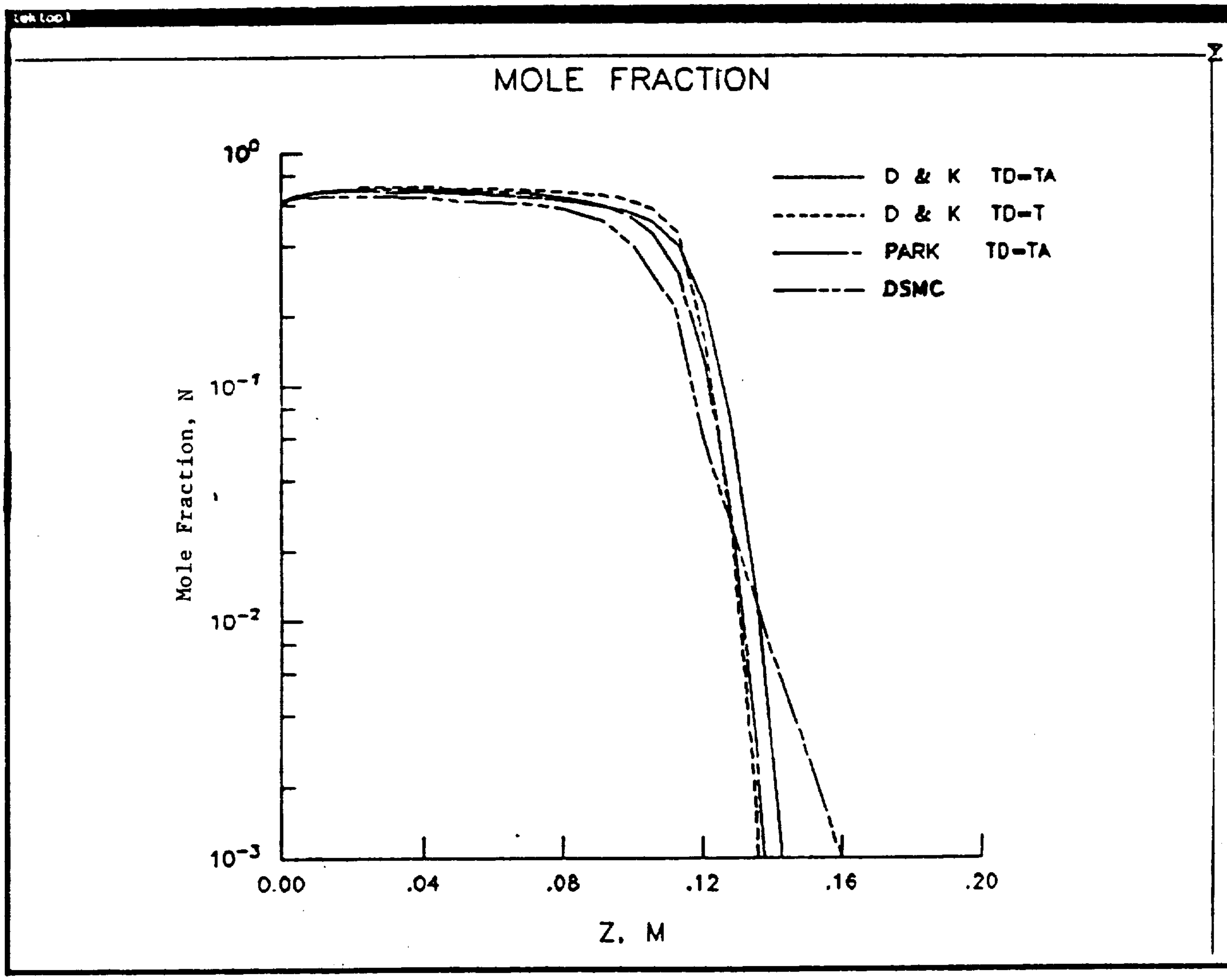
Peter Gnoffo

Figures (1a-c) compare the results of a continuum and non-continuum simulation on the shock layer profiles of atomic nitrogen mole fraction, electron mole fraction, and temperature across the shock layer of an axisymmetric approximation to the AFE. The free-stream conditions for this case correspond to a velocity of 8.917 km/sec at an altitude of 78 kilometers. Figures (1a-b) also highlight the effects of changes in the chemical kinetic model with respect to computed profiles across the shock layer. Results from the Dunn and Kang chemical kinetic model using dissociative rate controlling temperatures given by the translational temperature and by Parks's geometric mean temperature are compared to results using Park's chemical kinetic model. These comparisons give an indication of the errors arising from unknowns/uncertainties in the physical models alone. (Park's model represents the most recent analysis of data available for defining the chemical kinetic model. There are some empiricisms in the model which are calibrated with shock tube data and are not necessarily representative of flight conditions.)

Figures (2a-d) illustrate some of the scaling problems associated with real gas flows. The solid line in these figures represents a continuum simulation of the flow across the shock layer of the axisymmetric approximation to the AFE at a velocity of 9.863 km/sec at an altitude of 90 kilometers. The dotted line represents a simulation of a 1/15th scale AFE for the same free-stream condition. Note that the normal coordinate is scaled by a factor of 15 to facilitate direct comparison with the full scale simulation. The broken line represents a simulation of a 1/15th scale AFE at a density of 15 times the free stream in order to reproduce both Mach number and Reynolds number. Differences in the profiles, particularly the atomic nitrogen and electron profiles in Figures (2a-b), are primarily due to nonlinear scaling effects that arise from three-body reactions. Truncation error effects have not been defined in these tests but are believed to be approximately equal for the continuum cases because of their similar grid structure.

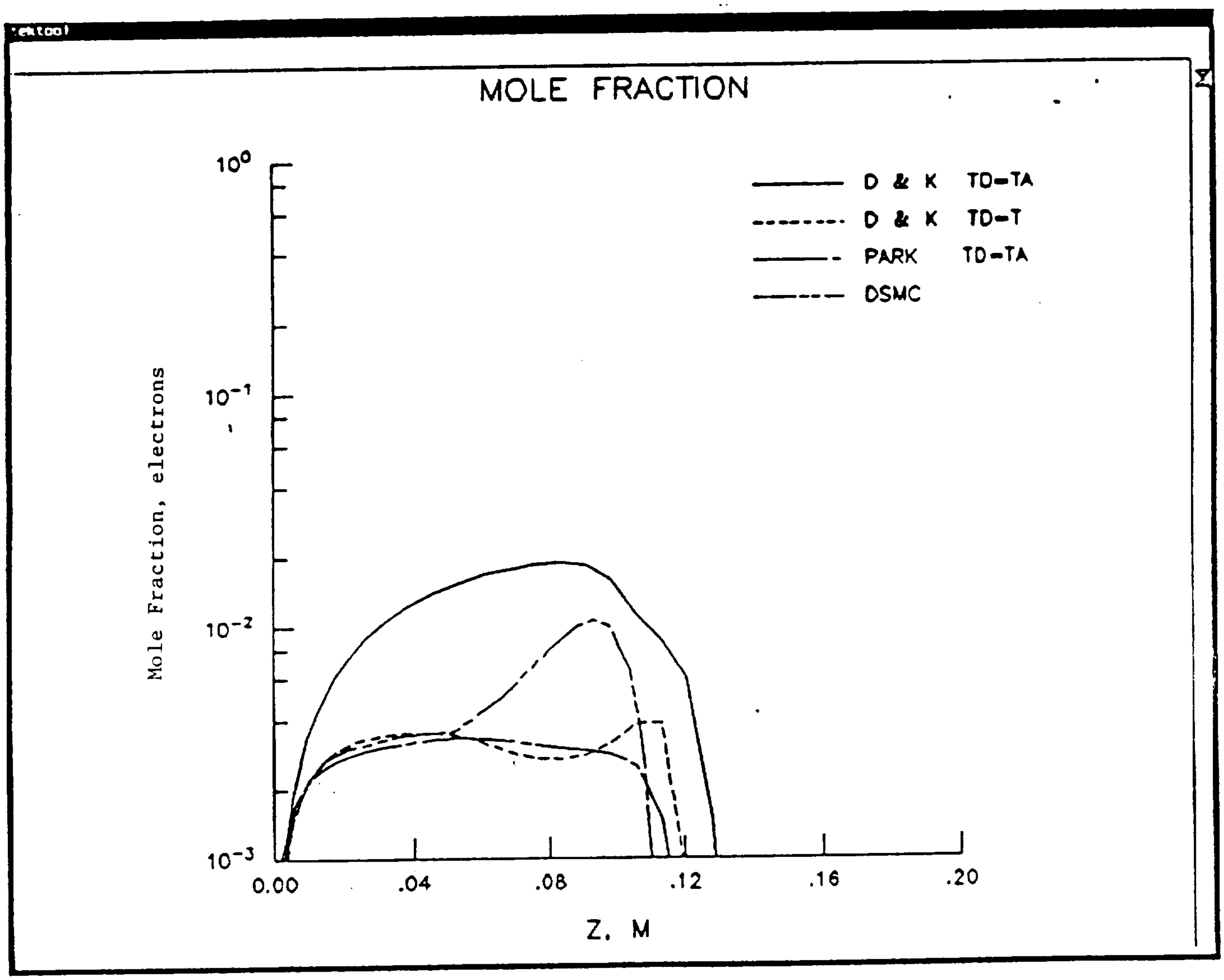
Symbols

AFE - Aeroassisted Flight Experiment
DSMC - Direct simulation Monte-Carlo
D & K - Chemical kinetic model of Dunn and Kang
L - Reference length (1 m for AFE, 1/15 m for 1/15 scale model)
N - Mole fraction
Park - Chemical model of Chul Park
T_d - Rate controlling temperature for dissociation
T_a - Average temperature defined by $T_a = (TT_v)^{1/2}$
T - Translational temperature
T_v - Vibrational-electronic temperature
T_r - Rotational temperature
Z - Distance from body surface through shock, m



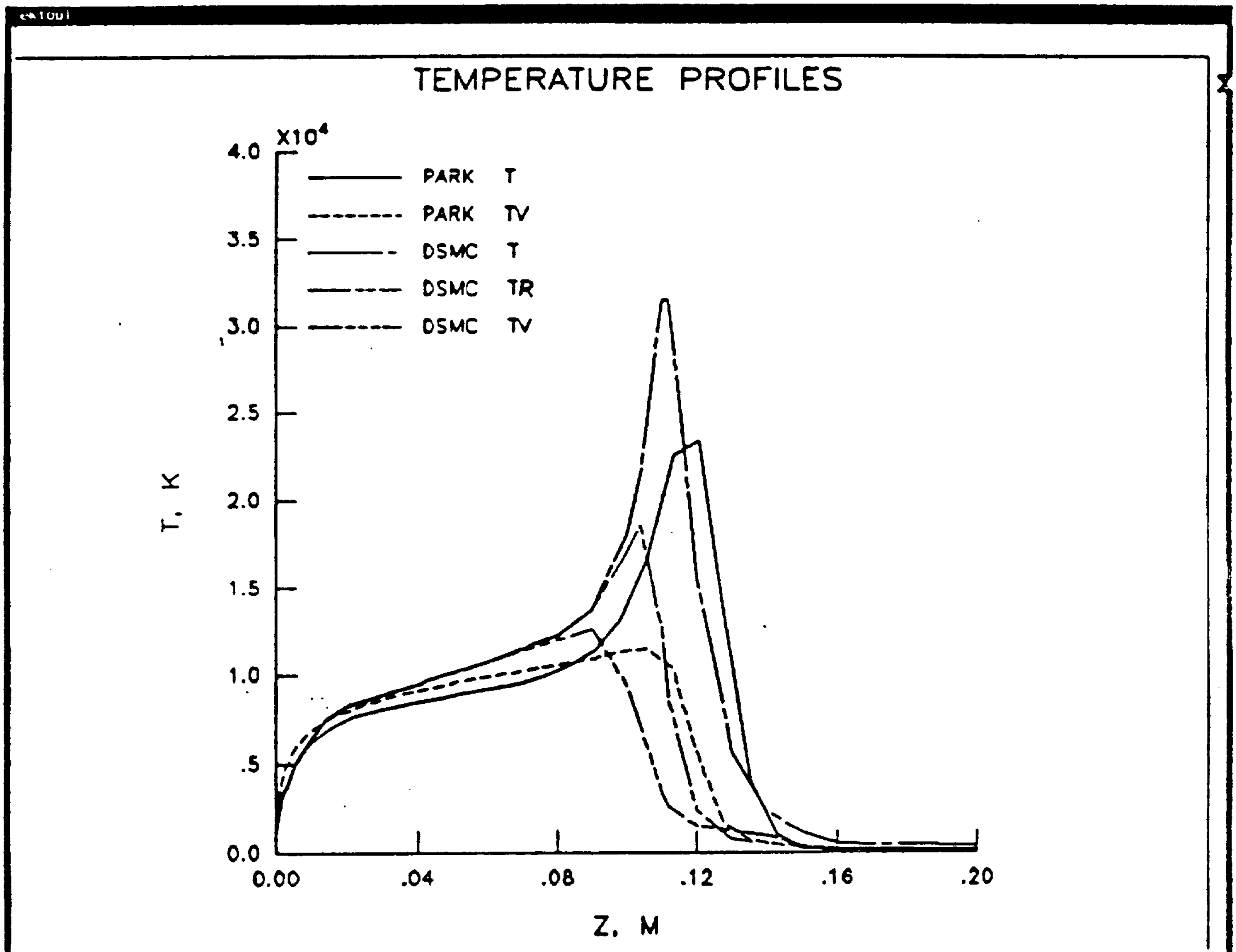
(a) N mole fraction

Figure 1. Comparison of profile predictions across the stagnation streamline with the non-continuum, Direct-Simulation Monte-Carlo algorithm.



(b) e^- mole fraction

Figure 1. contd.

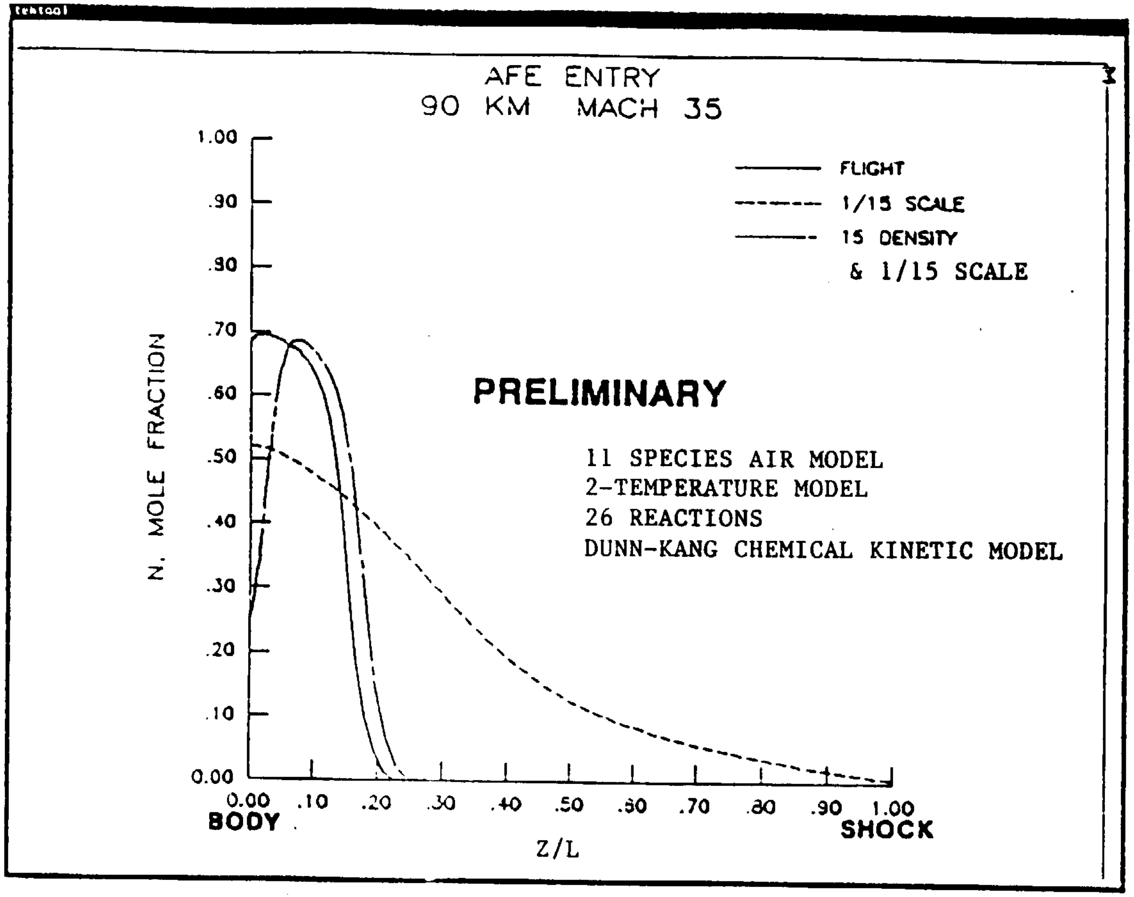


(c) T and T_v

Figure 1. concluded

USE OF CFD CODE TO EXAMINE SCALING EFFECTS

ATOMIC NITROGEN MOLE FRACTION



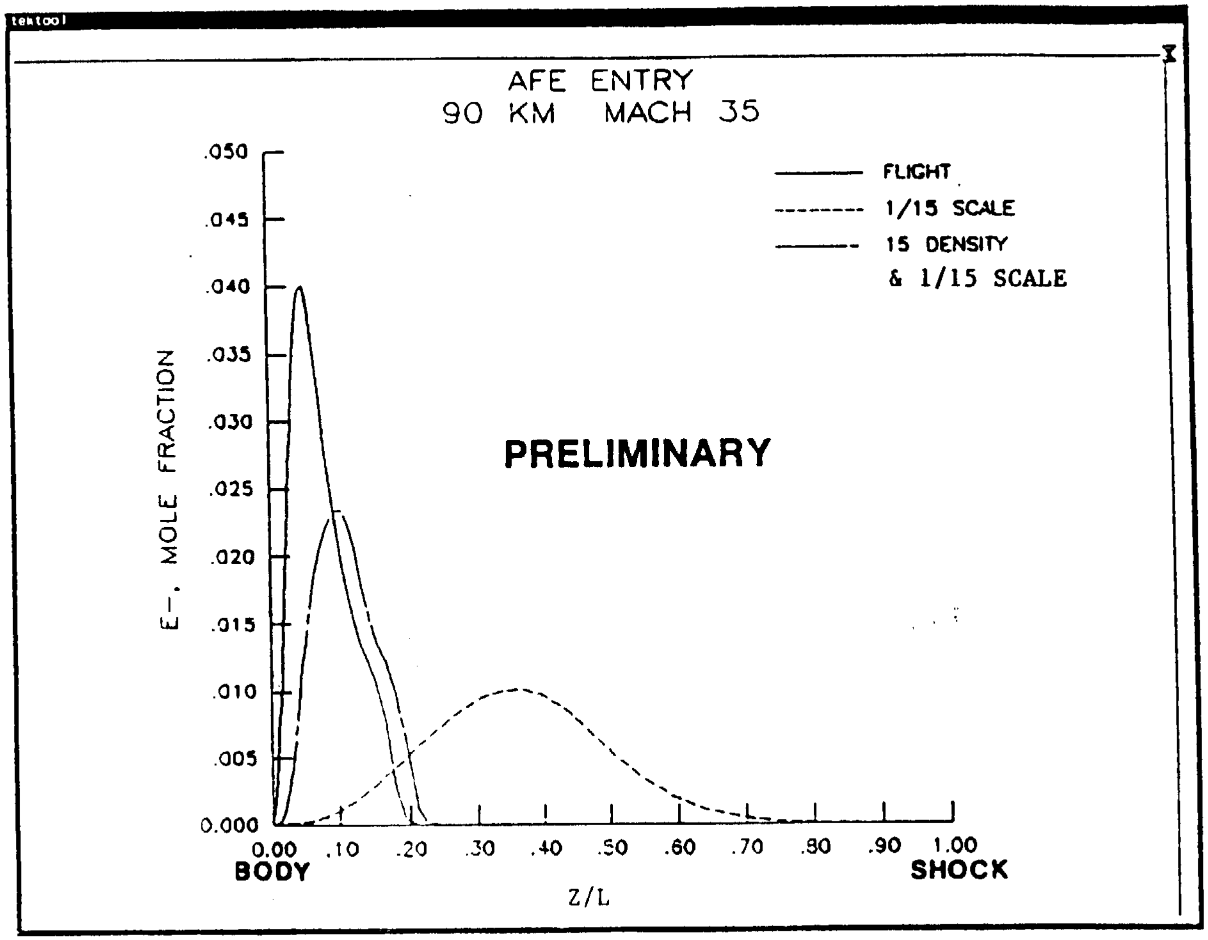
CODE: LAURA(LANGLEY AEROTHERMODYNAMIC UPWIND RELAXATION ALOGRITHM)

(a) N mole fraction

Figure 2. Scaling study for shock layer profiles over AFE at Mach 35 and 90 km.

USE OF CFD CODE TO EXAMINE SCALING EFFECTS - CONTINUED

ELECTRON MOLE FRACTION

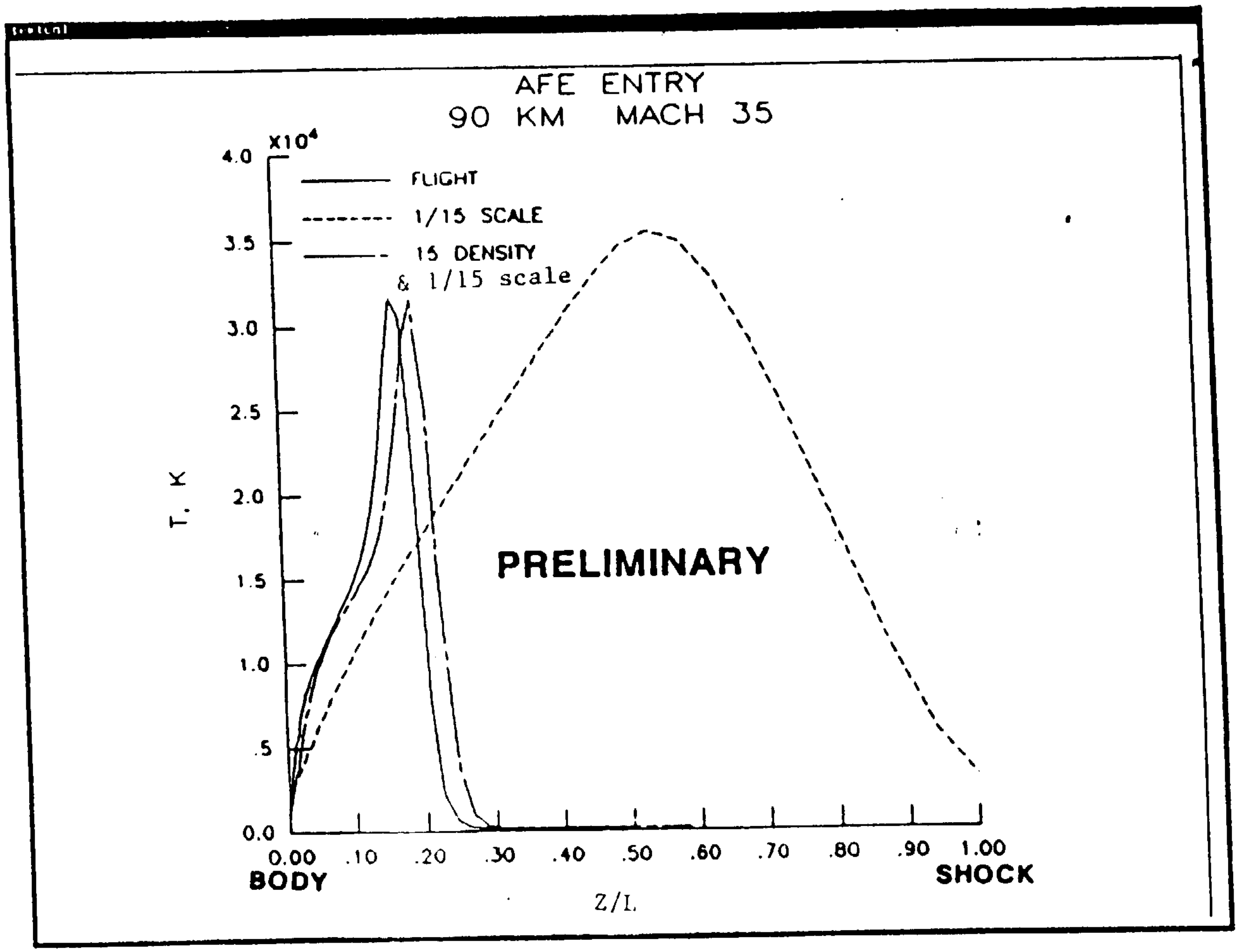


(b) Electron mole fraction

Figure 2. contd.

USE OF CFD CODE TO EXAMINE SCALING EFFECTS - CONTINUED

TEMPERATURE

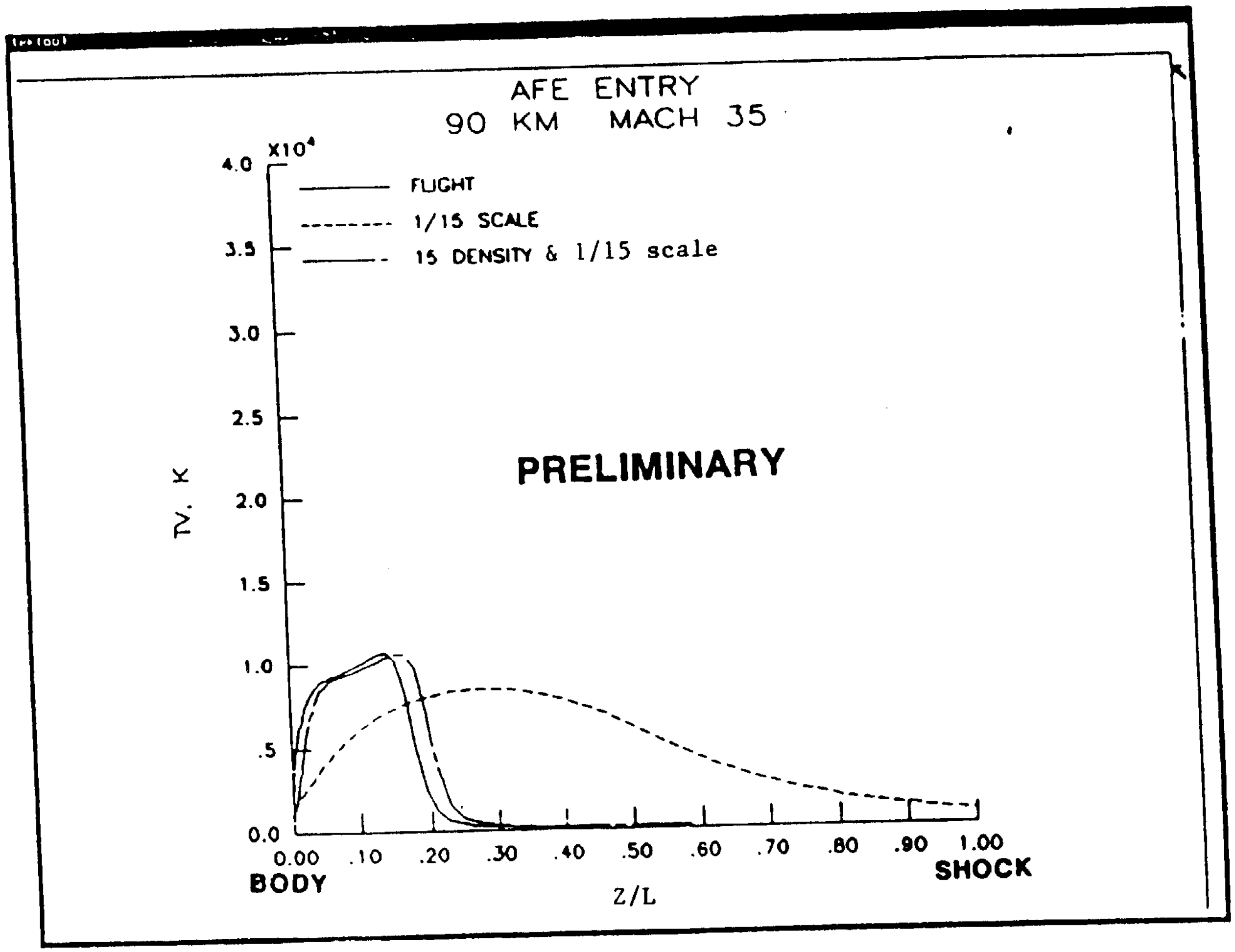


(c) Translational temperature

Figure 2. contd.

USE OF CFD CODE TO EXAMINE SCALING EFFECTS - CONCLUDED

VIBRATIONAL TEMPERATURE



(d) Vibrational temperature

Figure 2. concluded

Fluid Dynamics/Real Gas Effects Subgroup

Gary Chapman/Ballistic Range Experiments.- Mr. Chapman's presentation consisted of a very brief discussion of a number of potential experiments for the proposed range. Included were boundary layer transition and turbulence modeling studies on cones in air and helium/argon mixtures; control effectiveness studies on cones with various flap and flow geometries; afterbody flow-field studies on AOTV-like forebodies; and various basic fluid phenomena studies examining non-equilibrium chemistry, radiative flux, viscous-inviscid interaction, etc. Real gas effects were emphasized for all of these proposed studies although caution was expressed that many of the real-gas effects were dependent on real times and lengths in flight and are not readily amenable to scaling for facility investigations. Mr. Chapman concluded by recognizing that full duplication of all real gas effects would not be possible, that model size requirements would be driven by flow chemistry and instrumentation packaging requirements, and that the proposed range would provide sufficient operational simulation capability to validate computational aerodynamic/aerothermodynamic codes.

BALLISTIC RANGE EXPERIMENTS AND ISSUES
Gary Chapman

BALLISTIC RANGE EXPERIMENTS

- Boundary layer transition (V = 15,000 - 25,000 ft/s)
    - Effect of Real Gas
        - Cones in air and in He/Ar mixture
    - Effect of pressure grad.
        - Tri-Cones or continuous comp - in air and He/Ar mix.

- Turbulence Modeling (V = 10,000 - 25,000 ft/s)
    - Effect of Real Gas
        - Cones in air and in He/Ar mixtures measure total drag, heat, transfer, and mean velocity profiles

- Afterbody flow fields (V = 15,000 - 30,000 ft/s)
    - Effect of Real Gas and Geometry
        - AOTV-like forebodies, various corner and afterbody shapes measure heat transfer, base pressure, flow field, wake st. flow resident time.

- Control Effectiveness (V = 15,000 - 25,000 ft/s)
    - Effect of Real Gas
        - Cones with various flap, flare geometries measure pitching moment, pressure distribution, heat transfer, flow field.

- Nonequilibrium Chemistry in Expanding Flows (V = 15,000 - 25,000 ft/s)
    - Blunt cones with various boattail angles. Measure forces and moments, pressure distribution, heat transfer, and flow fields in boattail region.

BALLISTIC RANGE EXPERIMENTS, Continued

- Radiative Flux from Blunt Body ($V = 20{,}000 - 30{,}000$ ft/s)
  Measure spectrum at several spacial points on blunt forebody, total radiation distribution over the front face.

- Viscous - Inviscid Interaction ($V = 10{,}000 - 25{,}000$ ft/s)
  Test blunt shapes (spheres from $Re = 10^2 - 10^5$) in air and in Ar/He (to separate chemistry effects); measure total drag, shock stand-off, and heat transfer (similar test for cones).

- Turbulent Mixing and Burning ($V = 10{,}000 - 20{,}000$ ft/s)
  Test cones with H_2 injection (normal or slot); measure drag, spreading ratios, and species distributions.

SOME ISSUES

- Full duplication not possible for all real gas effects.

- Range of simulation sufficient to validate computational aerothermodynamic (CAT) codes.

- Model size requirements driven by
  Chemistry (2-Body vs 3-Body)
  Instrumentation - this is a trade off. Smaller and/or better instrumentation can allow the use of smaller models.

Ivan Beckwith/EML Workshop Experiments Definition.- Mr. Beckwith discussed the kind of aerodynamic/aerothermodynamic data required in a data base to develop an understanding of hypersonic flight and the potential contributions of a large-scale ballistic range facility to that understanding. The various kinds of data included aerodynamic forces and moments, heat transfer, and CFD codes and their development and calibration/validation. The major emphasis of the presentation was heat transfer and related topics including real-gas effects, boundary-layer transition and turbulence, local flow structures, etc. Mr. Beckwith is especially interested in boundary-layer transition phenomena. His presentation indicated that this proposed range facility could probably not be justified on the basis of investigating these transition phenomena. His opinion is that for near-term applications (3 to 10 years from now), these phenomena can be investigated more successfully in existing and proposed wind tunnels and existing ranges if the ranges are utilized properly. Major impediments to successful development and utilization of the proposed large-scale range in Mr. Beckwith's view are the large estimated cost and length of time to construct the facility, its high operational and model costs, the large anticipated g-loads on complex models and instrumentation, the difficulties associated with data acquisition and storage or transmission, and model/instrumentation survival and retrieval.

EXPERIMENTS DEFINITION GROUP

I. E. BECKWITH. LARC

VFB, HSAD

AEROTHERMO REQUIREMENTS FOR HYPERSONIC FLIGHT

- AERODYNAMIC FORCES AND MOMENTS
- HEAT TRANSFER
  - REAL-GAS CHEMICAL EFFECTS
  - BOUNDARY-LAYER TRANSITION AND TURBULENCE
  - COMBUSTION PROCESSES FOR AIRBREATHERS: MIXING, ETC.
  - LOCAL FLOW STRUCTURES:

    SHOCK WAVES
    SEPARATION
    VORTEX FLOWS
    WAKES } INCLUDES
    SHEAR LAYERS } TRANSITION
- DEVELOPMENT OF CFD CODES
- CALIBRATION/VALIDATION OF CFD CODES

Figure 1.

TRANSITION

- NEAR-TERM LIMITS (THROUGH 1998 ?) ON CFD CODES
  - TRANSITION LOCATION AND EXTENT REQUIRED AS INPUTS
  - CORRELATIONS FROM FLIGHT DATA
  - e^N METHOD FOR ONSET:

    NOT YET APPLICABLE FOR WALL ROUGHNESS/WAVINESS, VIBRATION, ARBITRARY FLUCTUATION ENVIRONMENTS, AND PARTICULATES (RAIN, ICE, ETC.)

- DATA FROM CONVENTIONAL WIND TUNNELS NOT RELIABLE FOR ONSET, EXTENT, OR TRENDS

Figure 2.

e^N METHOD FOR TRANSITION PREDICTION (Smith, 1952)

- Calculate mean boundary layer profiles
- Calculate linear amplification rate by using "appropriate stability model"
- Transition occurs when disturbances in the boundary layer are first amplified by a factor e^N, where

$$N = \ell n(A/A_0) = \int_{x_0}^{x_T} (\text{linear amplification rate})\, dx$$

Figure 3.

CALIBRATION OF e^N METHODS FOR TRANSITION PREDICTION/LFC DESIGN

- HIGH SPEED (TO $M \sim 3.5$, PILOT QUIET TUNNEL AT LaRC)
  - AXIS (FLIGHT AND W.T.)
  - FLAT PLATE
  - GORTLER
  - BLUNT CONES, CONES AT α
  - SWEPT-LEADING EDGE
  - SHEAR LAYER
- CONCLUSIONS FROM THESE APPLICATIONS:
  - WHEN LINEAR THEORY HAS CORRECT PHYSICS, THEN $N \sim O(9\text{-}12)$ FOR BACKGROUND DISTURBANCES OF O(.05%)
  - FLIGHT AND WIND TUNNEL
  - LOW-SPEED, SUPERSONIC
  - CROSSFLOW, TOLLMIEN-SCHLICHTING, GORTLER

Figure 4.

HYPERSONIC TRANSITION - LaRC NASP-RELATED RESEARCH PROGRAM EXPERIMENTAL VERIFICATION/CALIBRATION

- FABRICATION/UTILIZATION OF $M \sim 6$ PILOT QUIET TUNNEL (1988 -)
  - THREE-DIMENSIONAL AND DP/DX TRANSITION DATA FOR e^N
  - EXTENT OF TRANSITION; 3-D AND DP/DX
  - ALLOWABLE ROUGHNESS/WAVINESS
  - DETAILED DATA FOR FULL SIMULATION VERIFICATION
- UTILIZATION OF EXISTING FLIGHT EXPERIMENTAL DATA BASE TO DETERMINE HYPERSONIC N VALUES (1988 -)
  - TWO- AND THREE-DIMENSIONAL
  - $DP/DX = 0$, $DP/DX \neq 0$
  - REACTING GAS AND IMPERFECT GAS
  - SURFACE FINISH
- $M \sim 8$ PILOT QUIET TUNNEL (1990 -)
- $M \sim 20$ HELIUM QUIET TUNNEL (CONICAL NOZZLE, 1988 -)
- RANGE TESTS OF CONE-FLARE MODELS. AEDC RANGE G (1988 -)
- $M \sim 3$ - 6 CoF LARGE-SCALE QUIET TUNNEL (1991 -)

Figure 5.

MACH 6 LOW-DISTURBANCE PILOT NOZZLE

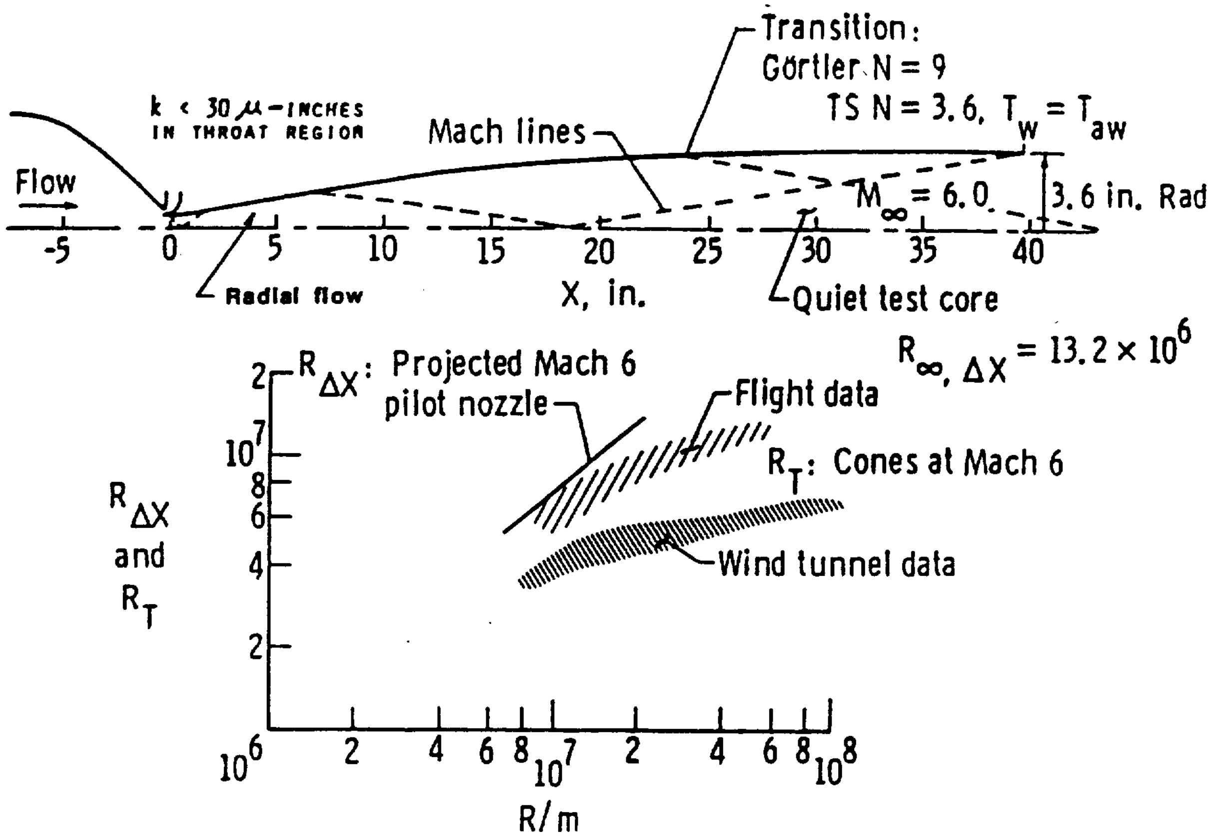


Figure 6.

Figure 6 shows the nozzle contour and predicted quiet test core for N - 9 of a new type of quiet nozzle. The new design feature used for this axisymmetric nozzle is the region of radial flow which moves the nozzle inflection point far downstream. The onset of the Görtler instability is then delayed and the amplification rates are reduced due to the thicker boundary layers as compared with the two-dimensional rapid-expansion nozzle. The quiet test core is therefore about five times longer than in the Mach 3.5 two-dimensional nozzle. However, the integrated amplification of the Tollmien-Schlichting (TS) waves is now much larger and results in a calculated value of N - 3.6 for the TS waves at the predicted location of transition caused by the Görtler instability. The possibility of interaction between the two instability modes is therefore of some concern. Also, the maximum peak-to-valley wall defects must be maintained in the range of k < 30μ-inch.

The lower part of the figure compares the predicted values of $R_{\Delta X}$ with R_T on cones in flight and in conventional wind tunnels. The implication of the relatively large values of $R_{\Delta X}$ compared with the R_T data is that sufficiently long regions of low-noise conditions will be present on test models to insure the proper simulation of low-disturbance flight conditions.

TRANSITION ON SHARP CONES

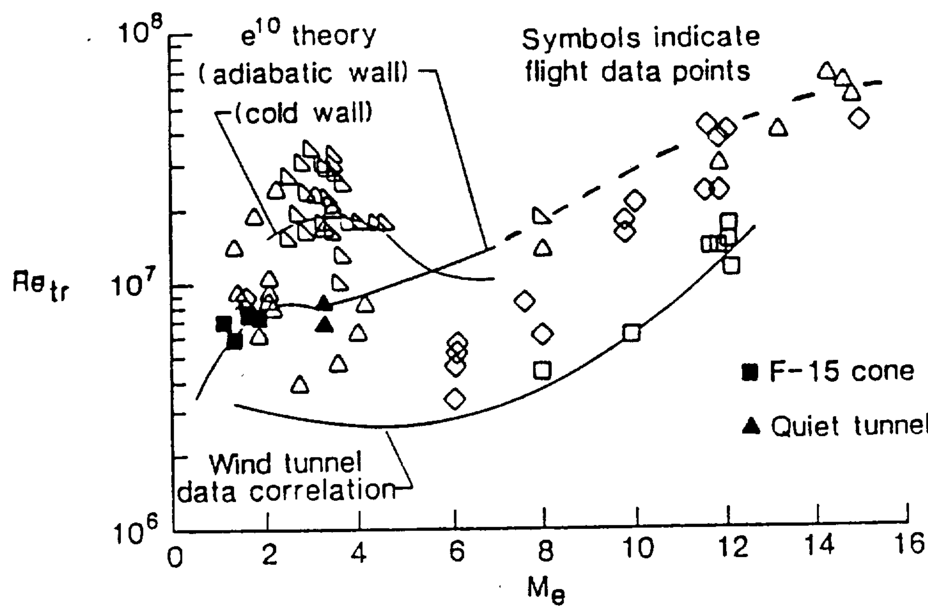
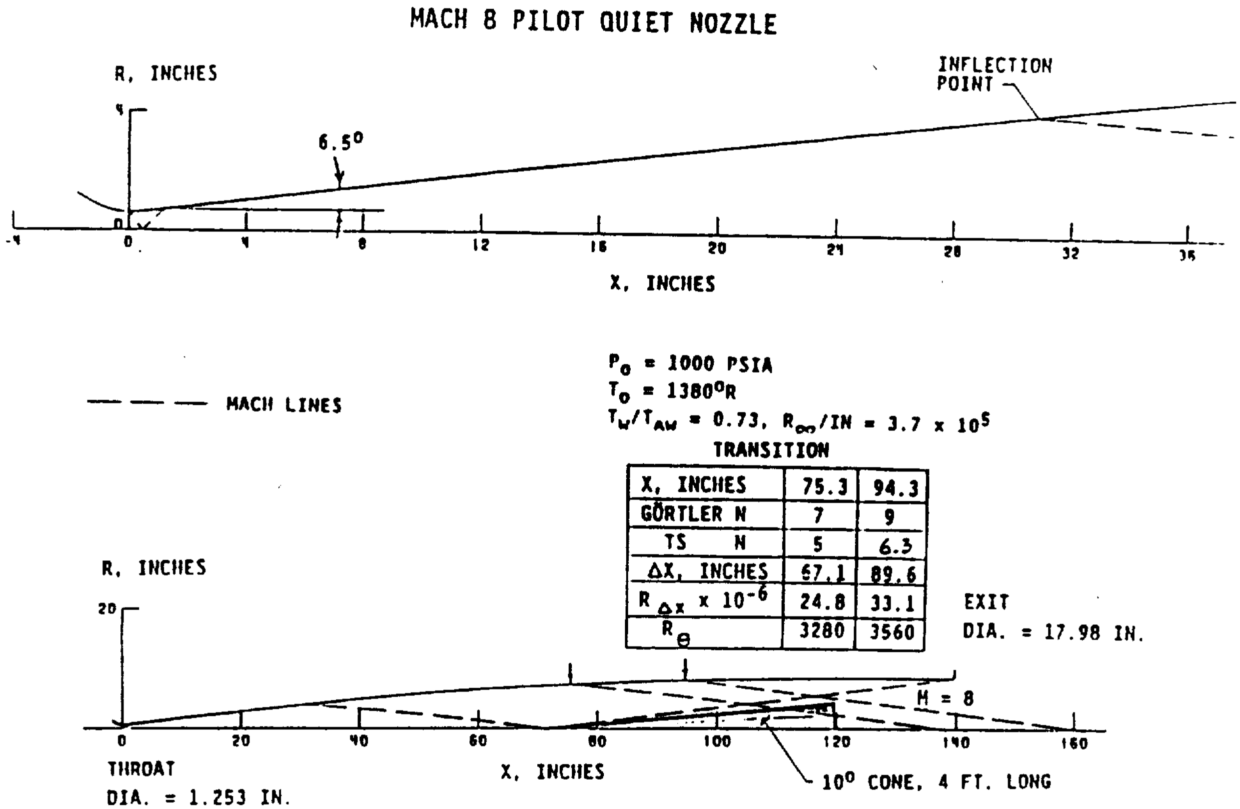


Figure 7.

Figure 7.- This figure is a plot of local transition onset Reynolds number, Re_{tr}, against local Mach number, M_e, on sharp tip cones at zero angle of attack. The flight data points and wind tunnel data correlation are from Fig. 4, AIAA Journal, Vol. 13, No. 3, March 1975. The filled symbols are data for adiabatic wall temperatures from the F-15 cone flight and the Mach 3.5 Quiet Tunnel (Langley Research Center). The lines are faired through calculations from linear stability theory with the e^N method for $N = 10$. The flight data are at cold wall conditions, so the curves show how wall temperature affects the predictions where the first mode instability dominates for $M > 5$. Agreement with data trends is good.



X, INCHES	75.3	94.3
GÖRTLER N	7	9
TS N	5	6.3
ΔX, INCHES	67.1	89.6
$R_{\Delta x} \times 10^{-6}$	24.8	33.1
R_θ	3280	3560

Figure 8.

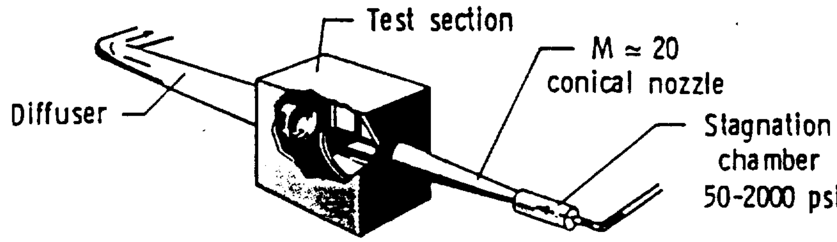
Shown in Figure 8 are the contour and predicted quiet test core regions for a Mach 8 nozzle that will tested in the Mach 8 Variable Density Tunnel at LaRC. The upper part of the figure shows the upstream radial flow region and the throat region up to the leading edge of the subsonic boundary layer removal slot. Note that the roughness requirement of $k < 20 \times 10^{-6}$ in., corresponding again to $R_k \sim 10$, will be very difficult to achieve and maintain in this high-temperature environment

The lower part of the figure lists the conditions for the stability calculations and the resulting values of the Gortler N and the Tollmien-Schlichting (TS) N at two locations along the wall. The predicted values of X are now about 90 in. for a Gortler N ~ 9. The corresponding large value of the TS N ~ 6.3 indicates that non-linear interaction between the two instability modes is likely. However, even if transition occurred at a value of Gortler N ~ 7, the quiet test core is long enough to provide valid test results on a 4-ft long cone as indicated in the figure.

HYPERSONIC HELIUM QUIET TUNNEL

Mods to Open-Jet Leg Tunnel

- Objective - Laminarize nozzle wall boundary layer at high M to create low P'_∞ stream for transition research



- To obtain transition data in adverse pressure gradient, etc
  - M ~ 20 nozzle
    - Scoop inlet (re-initializes nozzle boundary layer)
    - Conical nozzle (obviates Görtler instability)
    - Design +dp/dx models to account for -dp/dx nozzle flow
- Backup approach: Design, manufacture and test slotted (suction) throat nozzle (M ~ 20 helium version of M ~ 3.5 and 6 tunnels)

Note: P' refers to RMS pressure fluctuations.

Figure 9.

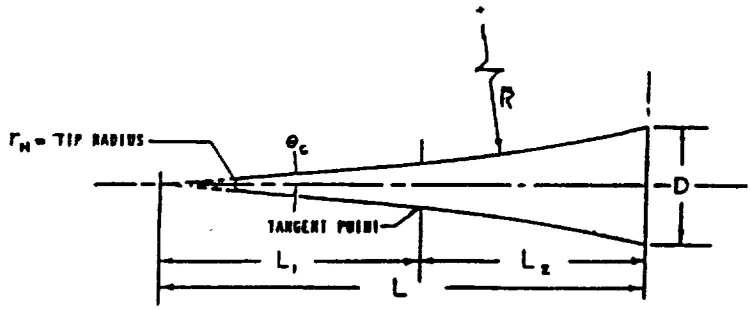
Figure 9 shows the helium tunnel with a conical nozzle which is expected to provide some quiet test flow for the purpose of evaluating the e^N method at Mach numbers from 14 to 17. From the present linear stability theory as applied to nozzle wall boundary layers, this straight-wall conical expansion nozzle would not develop the Görtler instability, since no concave wall curvature is used. The uncertainties at this time are: (1) the actual streamlines may have some slight concave curvature due to the rapid boundary-layer growth in this type of nozzle, and (2) the TS growth rates may still be appreciable because of the long runs of laminar boundary layers and high local Mach numbers.

Modification to an existing conical nozzle at NASA Langley will consist of a new throat section and boundary-layer bleed from the settling chamber. The new throat section is designed to provide conical flow by utilizing the Hopkins-Hill subsonic-transonic contour and the method of characteristics to provide an accurate transition from the sonic flow region to supersonic radial flow.

CALIBRATION OF HYPERSONIC e^N THEORY

CONE FOREBODY, TANGENT FLARE AFTERBODY

LaRC PROGRAM



WIND TUNNEL TEST MODELS (TYPICAL)

GAS	M_∞	θ_c	L	L_1	L_2	r_N INCH	$\bar{R}$	D INCHES	EST. $Re_T \times 10^{-6}$ CONE	FLARE
HELIUM	14 TO 18	5°	4.4D	2.4D	2D	0	17.82D	10	60	20
AIR	6.0	5°	4.34D	2.17D	2.17D	"	20.23D	4.6	12	6
FREE FLIGHT RANGE TEST MODELS										
EQUIL.	14 TO 16	7°	2.94D	1.76D	1.18D	.1	5.31D	1.70	30	10
AIR	"	"	"	1.18D	1.76D	"	11.76D	1.70	30	20

Figure 10.

Figure 10 illustrates two typical range models that will be launched at the approximate conditions listed in the AEDC Ballistic Range G. The afterbody-flare radius will be varied to provide different adverse-pressure gradients. The 0.1-in. radius nose is made of a tantalum-tungsten alloy. This is followed by a beryllium-copper section and an aluminum afterbody. A focused shadowgraph system with schlieren-quality optics is used to determine the location of transition. The combined effects of nose bluntness, adverse-pressure gradients, angle of attack, and real-air properties will be included in the stability theory and evaluated with the e^N method as applied to the experimental transition data.

Similar type models consisting of the conical forebody and tangent-flare afterbody will be tested in the quiet nozzles from Mach numbers of 3.5 to 20.

PRACTICAL IMPEDIMENTS FOR LARGE EML

- LARGE ACCELERATION FORCES ON COMPLEX MODELS
  (10 TO 30 KG COMPARED WITH 150 TO 500 KG IN EXISTING RANGES)

- DATA TRANSMISSION IN FLIGHT
  - PLASMA SHEATH BLACKOUT AT HIGHER VELOCITIES
  - DEVELOPMENT OF CIRCUIT COMPONENTS

- RETRIEVE MODELS ?

- DEVELOPMENT AND CONSTRUCTION TIME
  - 10 TO 20 YEARS ?

- DESIGN AND FABRICATION COST
  - $100 TO $200 M ?

- HIGH OPERATIONAL AND MODEL COSTS

Figure 11.

CONCLUSIONS

- TRANSITION NOT YET PREDICTABLE FOR HYPERSONIC VEHICLES

- NASP TRANSITION PROGRAM AT LaRC FOR NEAR-TERM REQUIREMENTS
  - DEVELOPMENT OF STABILITY THEORY
    - LINEAR, e^N METHOD
    - NON-LINEAR
    - 2-D, 3-D, EQUILIBRIUM REAL GAS, SHEAR LAYERS, TS, CROSSFLOW, GORTLER, ARBITRARY T_w AND DP/DX
  - VALIDATION IN QUIET TUNNELS, $M \sim 3.5$ TO 20
  - RANGE TESTS FOR EFFECTS OF REAL GAS, TIP BLUNTNESS, DP/DX, AND SMALL α

- VERY SIGNIFICANT PROBLEMS SEEN FOR LARGE EML

Figure 12.

Jerry Walberg/Potential Experiments for a Hypervelocity Ballistic Facility.- Dr. Walberg briefly reviewed several possible areas of interest for launch vehicles or hypersonic aircraft that could be investigated in the proposed range such as geometry-related phenomena (complex geometry/vortex flows/separated flows/viscous effects/shock-boundary-layer interaction), rarefied flows, and boundary layer phenomena/transition. He stated that the range would offer simultaneous velocity/altitude duplication, a capability not available in existing ground-test facilities. He was also of the opinion that some real-gas effects and flow phenomena could not be adequately scaled and would be a problem for any ground test facility. He also presented a list of potential planetary/Earth return vehicle experiments for consideration for the proposed range; included were boundary layer/shock layer interaction-phenomena, convective heating with wall catalysis, afterbodies/wake flows, and vehicle aerodynamics. Other phenomena associated with such vehicles in flight and suggested and suggested as potential candidates for experiments in the proposed range must approached very carefully for their practicality; these include vehicle trim characteristics, ablation effects, and radiation phenomena. Non-scalable real gas effects may predominate in these phenomena.

POTENTIAL EXPERIMENTS FOR A HYPERVELOCITY BALLISTIC FACILITY

GERALD WALBERG

POTENTIAL RESEARCH AREAS

PLANETARY ENTRY/EARTH RETURN VEHICLES

- BOUNDARY LAYER/SHOCK LAYER PHENOMENA
- CONVECTIVE HEATING WITH WALL CATALYSIS (NON-ABLATING)
- AFTERBODY/WAKE FLOWS (NON-ABLATING)
- VEHICLE AERODYNAMICS (NON-ABLATING)
- VEHICLE TRIM ?
- ABLATION EFFECTS ??
- RADIATIVE PHENOMENA ???

LAUNCH VEHICLES/HYPERSONIC AIRCRAFT

- COMPLEX GEOMETRY/VORTEX FLOWS/SEPATATED FLOWS/ VISCOUS EFFECTS/SHOCK BOUNDARY LAYER INTERACTION
- RAREFIED FLOWS
- BOUNDARY LAYER PHENOMENA/TRANSITION
- VEHICLE TRIM ?
- REAL GAS EFFECTS ?

NOTE: QUESTION MARKS INDICATE AREAS WHERE SCALING PROBLEMS MAY PREVENT MEANINGFUL RESEARCH IN THE PROPOSED FACILITY

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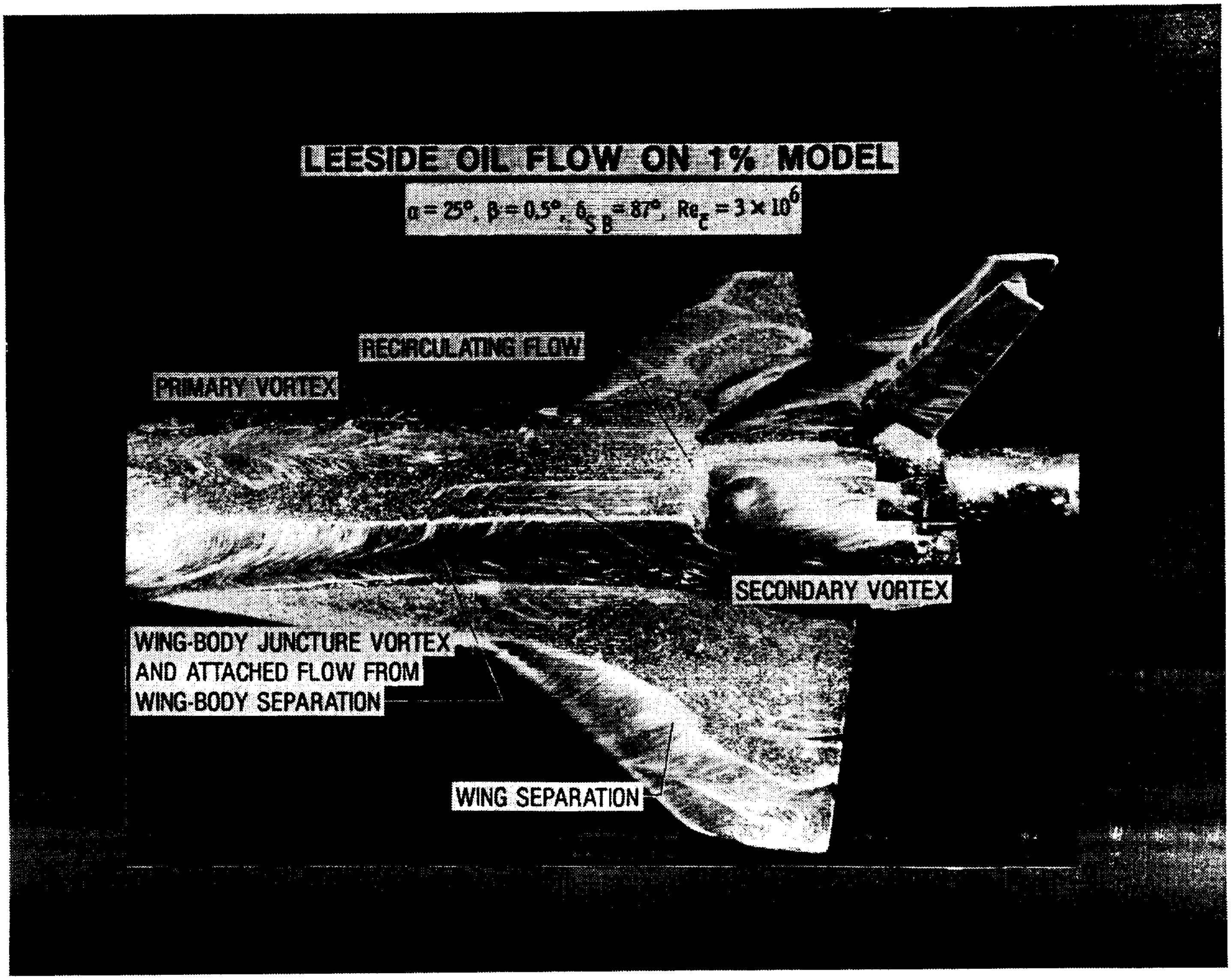

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Figure 1.

Oil flow pattern illustrating complex separated, viscous-dominated flows that can influence significantly the aerodynamic characteristics of winged vehicles like the Shuttle orbiter.

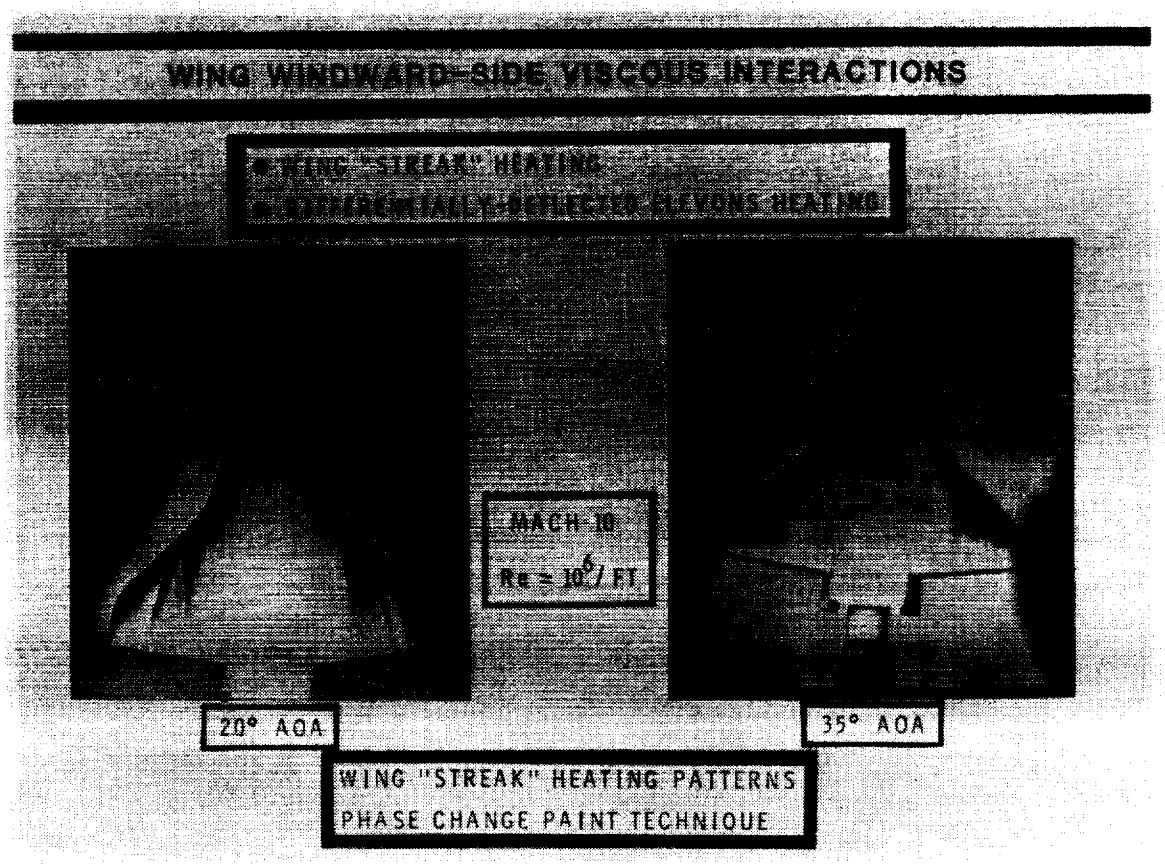


Figure 2

Phase change paint patterns illustrating streak heating on the windward surface of the Shuttle orbiter. Theoretical models have not yet satisfactorily predicted these phenomena which may result from strong entropy gradients in the flow. Unexpectedly high local heating can result.

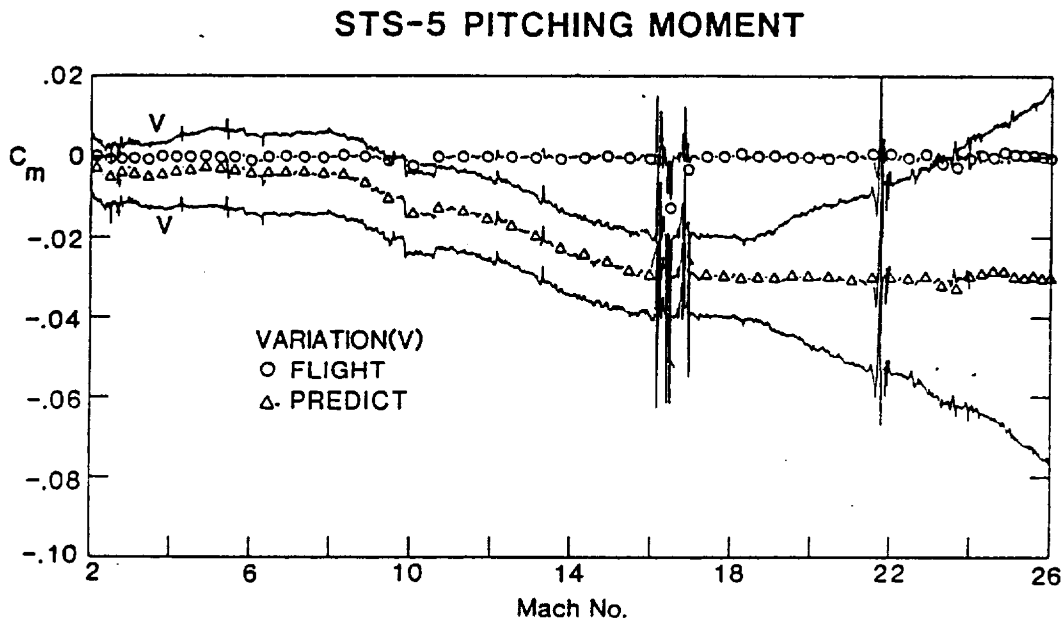


Figure 3

Shuttle orbiter flight data compared with predictions, illustrating the importance of real-gas effects on longitudinal trim for winged vehicles. Such phenomena may not be suitable for investigation in the proposed facility because of scaling problems.

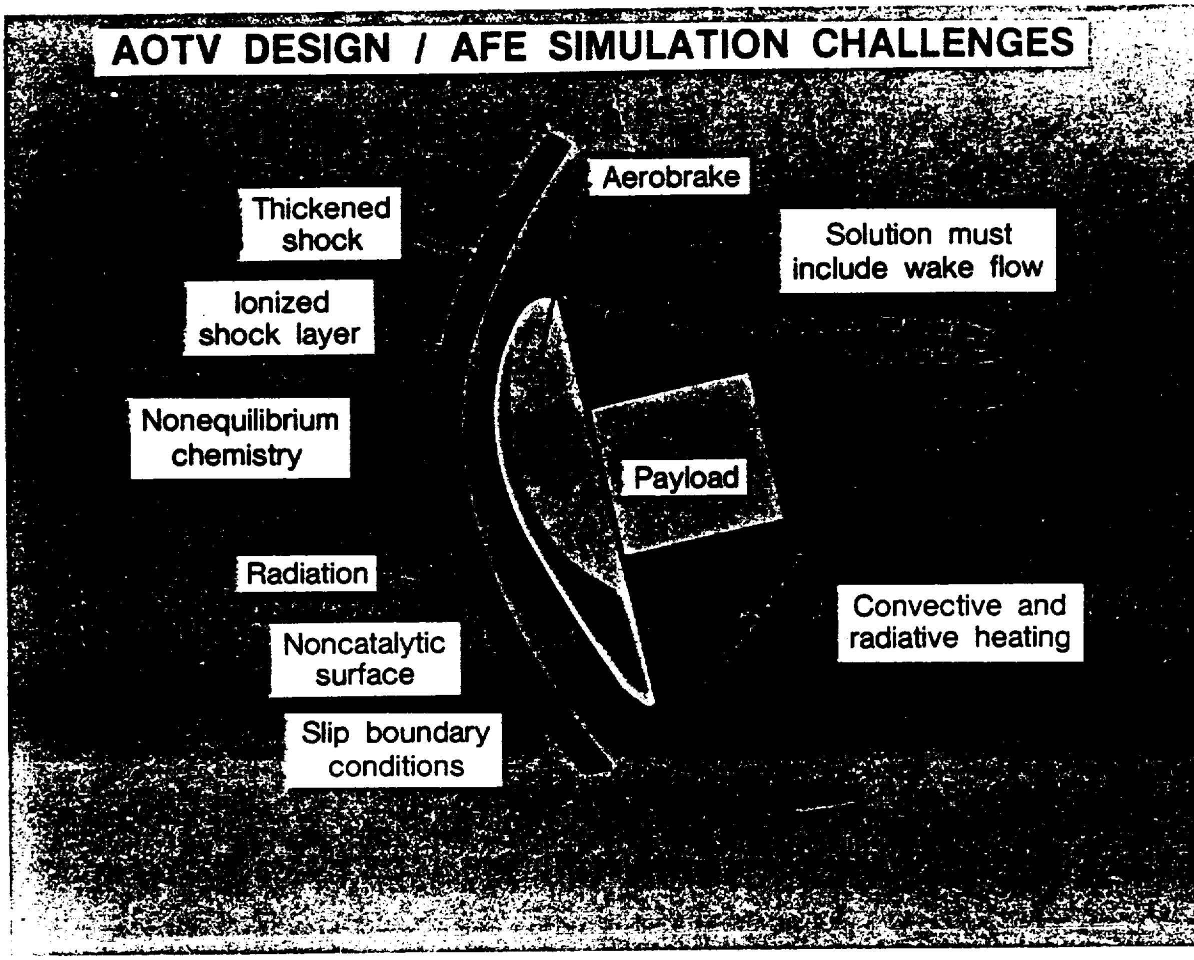


Figure 4

Important forebody and afterbody flow phenomena for an aeroassisted orbital transfer vehicle, some of which may be addressed in the proposed facility. Radiative heating is significant for such vehicles but does not dominate flow field processes at entry velocities less than those typical of lunar return (11 km/sec).

GALILEO FLOW FIELD

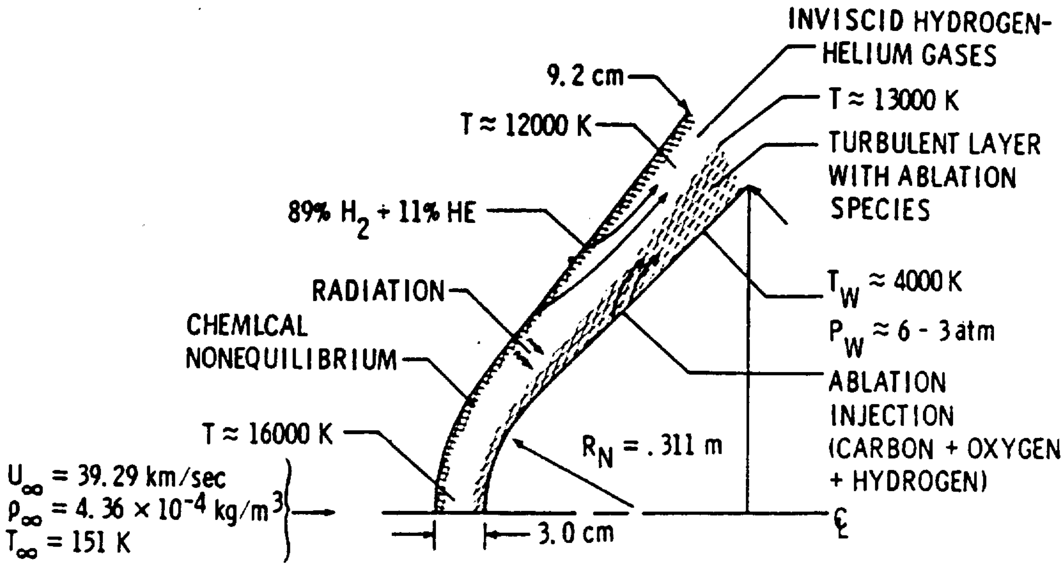


Figure 5

Flow-field characteristics and phenomena for the Project Galileo Jovian entry probe. This is a radiatively dominated flow field and, because of scaling problems, it may not be addressable in the proposed facility even if the very high velocities typical of the mission could be achieved.

Carl D. Scott/Review of Scaling Laws and Ballistic Range Experiment Possibilities.- Dr. Scott presented a brief review of scaling parameters for various flow phenomena and regimes and indicated those that would be amenable to study in the proposed range and those that would be very difficult. He stated that base flow studies would be very attractive for the free flight range because of the lack of sting interference. He also cautioned against expecting such a range to provide capabilities to investigate real gas phenomena which would not be scaled. Many things about base flows could be investigated assuming measurement techniques and instrumentation (on-board or remote) can be provided. He briefly reviewed some of the difficulties which would be encountered in the range regarding model design, utilization, and survival and regarding instrumentation and measurement technique requirements.

FLUID DYNAMICS/REAL GAS EFFECTS

Dr. Carl D. Scott

The ballistic range has certain advantages over the conventional wind tunnel. The main two characteristics are the correct velocity simulation and the lack of sting effects in the ballistic range. The correct velocity leads to more adequate simulation of chemical effects. Although the chemistry cannot be simulated exactly, the binary scaling law does allow one to determine the approximate model size and ambient pressure to be used to simulate a particular altitude of flight.

BALLISTIC RANGE ADVANTAGES FOR AEROTHERMO AND AERO

- BASE FLOW STUDIES - NO STING INTERFERENCE

- BASE HEATING DISTRIBUTIONS
  - DESIGN OF BLUNT AEROASSISTED VEHICLES & THEIR PAYLOADS
  - VERIFICATION OF FLOW-FIELD SIMULATIONS (CFD)
- BASE PRESSURE DISTRIBUTIONS
  - EFFECTS ON AERODYNAMICS
  - VERIFICATION OF CFD
- WAKE/BASE FLOW CLOSURE
  - CHEMICAL RELAXATION EFFECTS
  - GAS MODEL AND RELAXATION RATES
    - AIR & PLANETARY ATMOSPHERES
  - TURBULENCE
- FLOW SEPARATION
- BASE FLOW RADIATION
- SURFACE CATALYSIS & BASE HEATING
- ELECTRON CONCENTRATIONS & COMMUNICATION
- GEOMETRICAL/CONFIGURATION STUDIES
  - TURBULENCE & TRANSITION
- UNSYMMETRICAL GEOMETRY & ANGLE OF ATTACK
  - DOWNWASH
  - FLOW IMPINGEMENT
- TRANSIENT & OSCILLATING FLOWS
- PLUME/BASE FLOW INTERACTIONS
  - PROPULSION
  - RCS
  - JET EFFECTIVENESS
  - GLOBAL EFFECTS
    - HEATING
    - PRESSURES
    - CONTAMINATION & BASE FLOW PURGING
- PROTUBERANCES
  - TURBULENCE & FLOW DISTURBANCES
  - WAKE CLOSURE EFFECT
  - LOCAL HEATING

Base Flow - No sting effects

Stings or other supporting hardware for models in conventional wind tunnels often disturb the flow in base regions such that the pressure and heating distributions are not simulated well. The Ballistic range gets around this problem in an obvious way. The main difficulty of ballistic range simulation is instrumentation. Provided suitable instrumentation can be employed, many important phenomena listed in the chart can be measured without the disturbing effect of a sting.

ADVANTAGES OF BALLISTIC RANGES

- CORRECT SPEED/ENERGY
  - CHEMISTRY EFFECTS MODELED WHERE BINARY SCALING IS VALID
  - SPECIES DISTRIBUTIONS & MAGNITUDES
  - TEMPERATURES
  - TRANSPORT & THERMODYNAMIC PROPERTIES
  - GAS/SURFACE INTERACTIONS
    - CATALYTIC RECOMBINATION HEATING DISTRIBUTIONS
  - ABLATION EFFECTS
  - TRANSPIRATION EFFECTS & BLOWING
  - ENERGY MODES IN GAS CORRECTLY SIMULATED VIBRATION, TRANSLATION, ELECTRONIC, ETC.
  - SHOCK LAYER RADIATION

Correct Speed/Energy

Conventional wind tunnels do not match the velocity or energy of the flow around the vehicle in flight. This leads to quite different density ratios across the shock and shock shapes and thus to different pressure and heating distributions. Catalytic atom recombination effects on the heating are also not modeled. Since the velocity in a ballistic range can equal the flight velocity, these chemical effects can be approximately simulated. Thus the thermodynamics and transport properties of the gas are similar and diffusion is better simulated. Shock layer radiation is thus possible due to the high temperature shock layer, and simulation of certain radiation characteristics is possible. Chemistry effects can be modeled approximately on the basis of the binary scaling law which is derived in the next charts.

SCALING LAWS

- VISCOUS EFFECTS

  Reynold's No. $= \frac{\rho U R}{\mu}$

- NONEQUILIBRIUM FLOW

  Damkohler No. $= \frac{\text{FLOW TIME}}{\text{REACTION TIME}} \propto \rho R$

  BOTH DISSOCIATIVE IN SHOCK LAYER AND BOUNDARY LAYER
  RECOMBINATION IN BOTTOM LAYER

BINARY SCALING ρR

- RADIATIVE HEATING

  $\dot{q}_{RAD} \propto \rho R$

- CONVECTIVE HEATING

  $\dot{q}_{conv} \propto \sqrt{\frac{P}{R}}$

- DYNAMIC PRESSURE

  $P_{T_2} \propto \rho$

SCALING LAWS

This chart summarizes the principal scaling laws associated with aeroheating and chemical effects, such as the density ratio and the shock shape, hence the pressure distribution. Assuming the velocity of the projectile (model) is the same as the flight vehicle, then one must match the tunnel density to the free-stream flight density to achieve the same dynamic pressure. One is not usually interested in dynamic pressure simulation, however, because other parameters are of more interest and because the dynamic pressure would be pertinent for loads simulation on full-scale vehicles. However, one could scale loads if they were of some interest.

SCALING LAWS/NONEQUILIBRIUM FLOWS

$$\frac{1}{\tau_R} = \frac{\partial \alpha}{\partial t} = k_f \rho (1 - \alpha) - k_b \rho^2 \alpha^2$$

SHOCK LAYER - DISSOCIATION NONEQUILIBRIUM

$$\tau_F = \text{FLOW TIME} = \frac{\Delta}{U_2} \propto \frac{R_N}{U_\infty} \frac{\rho_2}{\rho_\infty}$$

$$\tau_R \simeq k_f \, \rho_2 (1 - \alpha)$$

DAMKOHLER NO

$$\frac{\tau_F}{\tau_R} \simeq \frac{R_N \rho_2}{\rho_\infty U_\infty} \frac{\rho_2 k_f (1 - \alpha)}{1}$$

$$\propto R_N \rho_\infty$$

BINARY SCALING

SCALING LAWS/NONEQUILIBRIUM FLOWS

The simple chemical rate equation for the production of atomic species is used to obtain a scaling relation for the dissociation nonequilibrium in a shock layer. By requiring the ratio of the reaction times to flow times (same Damkohler number) to be the same for the simulation as for flight, one obtains the Binary Scaling relation $R_n \rho$.

SCALING LAW/NONEQUILIBRIUM FLOW

BOUNDARY LAYER - RECOMBINATION NONEQUILIBRIUM

τ_F = FLOW TIME = DIFFUSION TIME

$$= \frac{\text{BOUNDARY LAYER THICKNESS}}{\text{DIFFUSION VELOCITY}}$$

$$\tau_F = \frac{\delta}{V_D} = \frac{\delta}{D\frac{\partial\alpha}{\partial y}} \propto \frac{\delta}{D\frac{\alpha}{\delta}}$$

NOW $\quad \delta^2 \propto \frac{R_N}{\rho}$

THEN $\quad \tau_F \simeq \frac{R_N}{\rho D\alpha}$

τ_R = RECOMBINATION TIME = $\frac{1}{-k_b\rho^2\alpha^2}$

$$\frac{\tau_F}{\tau_R} \simeq \frac{R_N k_b \rho^2 \alpha^2}{\rho D\alpha} \propto R_N\rho \qquad \text{BINARY SCALING}$$

SCALING LAW/NONEQUILIBRIUM FLOW

Recombination usually occurs in boundary layers of stagnation regions. Since the dominant transport mechanism in boundary layers is diffusion, the diffusion velocity governs the time for species transport; and thus using simple relations for the diffusion velocity and the reaction rate equation for recombination, which depends on the density squared, we again obtain the Binary Scaling relation $R_N\rho$ for recombination in stagnation point boundary layers. This relation may not apply in the boundary layers of sharp slender vehicles where the dominant reaction is dissociation. Likewise, it may not apply in the base flow region which is not diffusion controlled.

BALLISTIC RANGE EXPERIMENT IMPEDIMENTS, DIFFICULTIES AND DEVELOPMENT

- MODEL DESIGN
  - ONE SHOT PER MODEL (UNLESS CAPTURE TECHNIQUES ARE PERFECTED)
  - HIGH-G'S & MODEL STRUCTURAL INTEGRITY
  - SHORT TEST TIMES
  - DATA STORAGE ON MODELS
  - MAINTAINING CENTRAL FLIGHT PATH WITH LIFTING SHAPES

- INSTRUMENTATION
  - EM DISTURBANCE & INTERFERENCE
  - REQUIRES MICRO MINIATURIZATION
  - IN-FLIGHT TELEMETRY
  - HIGH g LEVELS or HIGH ACCELERATIONS

- NEW TECHNIQUES POSSIBLE
  - HIGH SPEED (CCD/CID) VIDEO: THERMAL MAPPING
  - HIGH SPEED SPECTROMETERS
  - LASER DIAGNOSTIC TECHNIQUES
    - TEMPERATURES - RAMAN, LIF, DOPPLER BROADENING
    - VELOCITIES - DOPPLER
    - SPECIES - RAMAN, LIF
    - DENSITIES - SHADOWGRAPH, SCHLIEREN, INTERFEROMETERS

- LARGER MODELS DESIRABLE
  - LOWER CONVECTIVE HEATING ALTHOUGH SHORT TIMES MAY MAKE LESS IMPORTANT
  - GREATER RADIATIVE HEATING - MEASUREMENTS LESS SENSITIVE TO ERRORS
  - EASIER TO GET GOOD DISTRIBUTION MEASUREMENTS
  - ESPECIALLY SHARP LEADING EDGES

BALLISTIC RANGE EXPERIMENT IMPEDIMENTS & DIFFICULTIES & DEVELOPMENT

Many problems arise in the use of ballistic ranges for aerothermodynamic and aerodynamic testing. A model is used only once, since it is destroyed at the end of its trajectory. Otherwise, some sophisticated apparatus must be devised to restrain and decelerate the model "slowly". Instrumentation and data storage are very difficult and will require much development and miniaturization. The onboard instrumentation must be able to withstand the very severe launch acceleration loads.

New techniques are possible. High speed video systems and even infrared video are possible to measure position and even surface temperature as a function of time and space. High speed spectrometers and laser techniques are available to diagnose the temperature of the flow around the models and also may obtain information about the chemical state of the gas as well as the radiation heating characteristics.

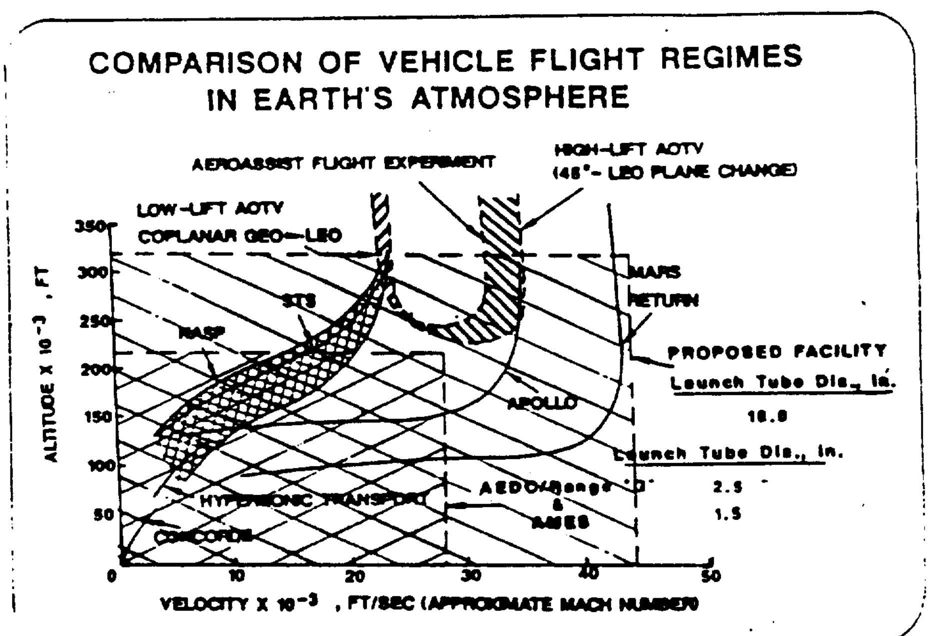
Large models are desirable from an instrumentation and resolution standpoint. Larger models will permit greater accuracy in the measurements and allow finer resolution around sharp leading edges, corners, etc.

Hypersonic Propulsion Subgroup

Ernest Mackley/Capabilities Required for Hypersonic Propulsion Experiments.- Mr. Mackley stated that the range could potentially duplicate some flight conditions such as velocity, Mach number, Reynolds numbers, etc., which can only be simulated in other hypersonic ground-test facilities for propulsion type experiments. He also stated that hypersonic propulsion studies would require basic aerophysics data also required by other disciplines; examples are boundary layer transition, CFD turbulence modeling data, leading edge viscous interactions, and shock/boundary layer interaction. These data may or may not be supplied by the range. NASP-like experiments are likely to require larger, heavier models than even the ones being proposed for this large-scale range.

CAPABILITIES REQUIRED FOR HYPERSONIC PROPULSION

Ernie Mackley



EXPERIMENTAL CAPABILITIES REQUIRED

- 0 DUPLICATION OF FLIGHT VELOCITIES TO 25,000 FT/SEC
- 0 DUPLICATION OF FLIGHT REYNOLDS NUMBERS
- 0 DUPLICATION OF FLIGHT CONDITIONS SIMULATED BY OTHER FACILITIES--I.E. SHOCK TUNNELS AND EXPANSION TUBES (M = 10 TO 20) AND "STEADY-STATE" (M = 10 TO 14 AIR OR N_2 AND M = 18 TO 20 He) FACILITIES
- 0 FOR HYPERSONIC PROPULSION: BASIC AEROPHYSICS DATA NEEDED ARE ALSO REQUIRED BY OTHER DISCIPLINES
    - o BOUNDARY LAYER TRANSITION
    - o TURBULENCE MODELLING DATA FOR CFD
    - o LEADING EDGE VISCOUS INTERACTIONS
    - o SHOCK BOUNDARY LAYER INTERACTION
- 0 FOR HYPERSONIC PROPULSION: SUPERSONIC COMBUSTION EXPERIMENTS
    - o MODEL SIZE REQUIREMENTS LARGER THAN PLANNED FOR VELOCITIES GREATER THAN 16,000 FT/SEC
    - o EXPERIMENT MIGHT BE POSSIBLE AT 11,000 FT/SEC FOR MODELS WEIGHING 50 LB AND 14-IN. DIAMETER
    - o H_2 TANKAGE AND VALVES NECESSARY EXPOSURE TO HIGH "G" FORCES
    - o MODEL DIRECTIONAL STABILITY LIKELY TO CHANGE WITH COMBUSTION
    - o MODEL COST HIGHER BECAUSE OF COMPLEXITY

PRACTICAL LIMITATIONS

- 0 MODEL SIZE
- 0 LIMITED MEASUREMENTS
- 0 SHORT TEST TIMES
- 0 MODEL COST AND LIMITED, OR NO, RETEST CAPABILITY
- 0 DIRECTIONALLY STABLE MODELS PREFERRED (AXIAL SYMMETRY)

INNOVATIONS ARE NECESSARY

- 0 CONSIDER HIGH PRESSURE AND CRYOGENIC TEMPERATURE TEST GAS
- 0 PRECOOLED MODELS
- 0 DECELERATION SABOT

SUMMARY

- THE EXPERIMENTAL CAPABILITIES REQUIRED GENERALLY CAN BE STATED AS DUPLICATION OF FLIGHT WITH VELOCITY GIVING THE CORRECT TOTAL ENTHALPY AND HIGHER THAN ACTUAL DENSITY MAKING UP FOR REDUCED SCALE
- DUPLICATION OF OTHER FACILITY TEST CONDITIONS WOULD BE DESIRABLE TO PROVIDE COMPARISONS
- FOR HYPERSONIC PROPULSION RESEARCH BASIC AEROPHYSICS DATA WILL BE OF HIGH VALUE AT SPEEDS ABOVE $M = 8$
- FOR HYPERSONIC PROPULSION SUPERSONIC COMBUSTION EXPERIMENTS CURRENT SIZING WOULD LIMIT POSSIBILITIES TO ABOUT 11,000 FT/SEC WITH VERY DIFFICULT AND COSTLY MODELS AND WITH SUCCESS AT VERY HIGH RISK
- THERE ARE OBVIOUS PRACTICAL LIMITATIONS BUT INNOVATIONS SHOULD BE EXPECTED

Joe Gladden/Advanced Hypervelocity Facility Experiments.- Mr. Gladden described 3 classes ofpotential experiments for the proposed range: (1) AOTV heat transfer experiments, (2) propulsion system experiments/Mach numbers 10-25, and (3) simulation versus duplication experiments (to study and verify similarity principles).

The range would potentially supply much of the required capability to perform these experiments although concerns were expressed with regard to facility characteristics such as model size, test duration, and model acceleration and deceleration loads; instrumentation accuracies, capabilities, and resolution; and computational capability.

SUMMARY OF ACTIVITIES
Hebert J. Gladden

- HOST (Hot Section Technology) Turbine Heat Transfer Program Manager
  Improve the durability and life of the turbine hot section through enhanced computational techniques that are based on good experimental data.

- AOTV Verification Experiment
  Develop an AFE-complementary experiment to verify the guidance, control, and material capabilities for GEO/LEO multiple missions.

- NASP Thermal Management Team/Cowl Leading Edge Technology
  Participate in the propulsion system review and technology development for the NASP program. Conduct thermostructural support program to define aerothermal load capability of lightweight, high strength hot structures. A high heat flux experiment has been developed to verify the analytical capability.

- High Temperature Heat Flux Measurements
  Develop method to measure heat flux in high temperature turbine environment using time resolved temperature measurements.

ADVANCED HYPERVELOCITY FACILITY
Experiments

- AOTV Heat Transfer Experiments
  - Nonequilibrium Radiative and Convective Heat Flux
  - Bow Shock Stand-Off Distance and Thickness
  - Real Gas Effects
  - Boundary Layer Flow and Transition
  - Edge Effects on Heat Flux
  - Wake Effects on Afterbody
  - Wall Catalysis

- Propulsion Systems - Mach No. of 10 to 25
  - Stagnation Heat Flux
  - Shock/Boundary Layer Interaction Heat Flux Augmentation
  - Boundary Layer Transition
  - Skin Friction/Drag Reduction with Mass Addition
  - Real Gas Effects
  - Thermal/Structural Effects

- Simulation vs Duplication
  - Well Defined and Conducted Experiments to Study and Verify Similarity Principles.

ADVANCED HYPERVELOCITY FACILITY
Requirements

- SIMILITUDE
  - Aerodynamic Similarity - Reynolds/Mach/Ratio of Specific Heats
  - Thermodynamic Similarity - Prandtl/Lewis/Stanton/Enthalpy
  - Stress/Strain Similarity -

- INSTRUMENTATION
  - Surface Heat Flux - Total/Radiative/Nonequilibrium
  - Surface Temperature - Local Distribution
  - Gas Properties - Real Gas Effects
  - Structural Strain - High Temp Strain Gage

- COMPUTATIONAL
  - Increased Speed & Accuracy to Model/Control Experiment.
  - Interaction of Analyst & Experimentalist to Verify or Calibrate Codes.
  - Develop/Verify Scaling Laws Between Simulation & Duplication Experiments.

- EXPERIMENTS
  - AOTV Heat Flux Modeling
  - Thermal/Structural Modeling
  - Propulsion System Modeling

Rod Burton/Research Facility Workshop Experiments Definition.- Mr. Burton's presentation consisted primariy of a description of a new concept for an arc heater for a hypersonic facility, Liquid Air Arc Heater, along with brief comments about operational EML range experience. We summarized his presentation as follows: (1) velocity of 15 km/sec still to be achieved by accelerators; (2) compared with accelerators, the wind-tunnel approach results in significantly less expensive (factor of 10?) facility and models; and (3) the proposed arc heater facility requires analysis of nozzle flow for speeds to 15 km/sec and of the resulting species and their effect on the experiments.

APPENDIX B

PRESENTATIONS BY MEMBERS OF THE INSTRUMENTATION WORKING GROUP

ONBOARD PRESSURE SENSING WITH TELEMETRY

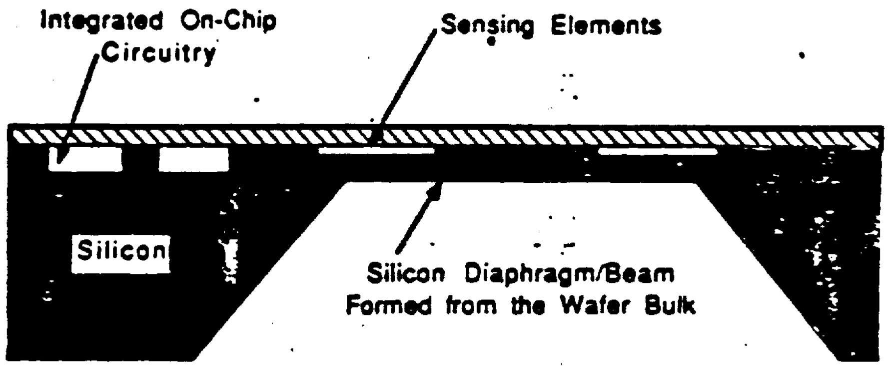
John J. Chapman - NASA Langley

Vu-Graph "A" shows a silicon die pressure sensor. This device has a thin etched-silicon membrane within which is a diffused piezoresistive bridge. The bridge elements are strain gauges that convert deflections in the membrane to voltage output signals. The use of silicon-on-sapphire technology with this type of geometry should result in a device capable of functioning from -196°C to +700°C. Unfortunately, these sensors also have some unwanted sensitivities and will also respond to accelerations and are photosensitive. These types of problems must be solved for each application. Miniaturization of the pressure sensing substrate will eventually invoke "on chip" signal conditioning and switching. There are important considerations as to how these devices are to be implemented, particularly in the hypersonic model launch environment of 50,000 G. Research of the technique used to bond the device to the substrate and type of lead attachment and component potting to use will determine if the final instrument will survive the launch environment.

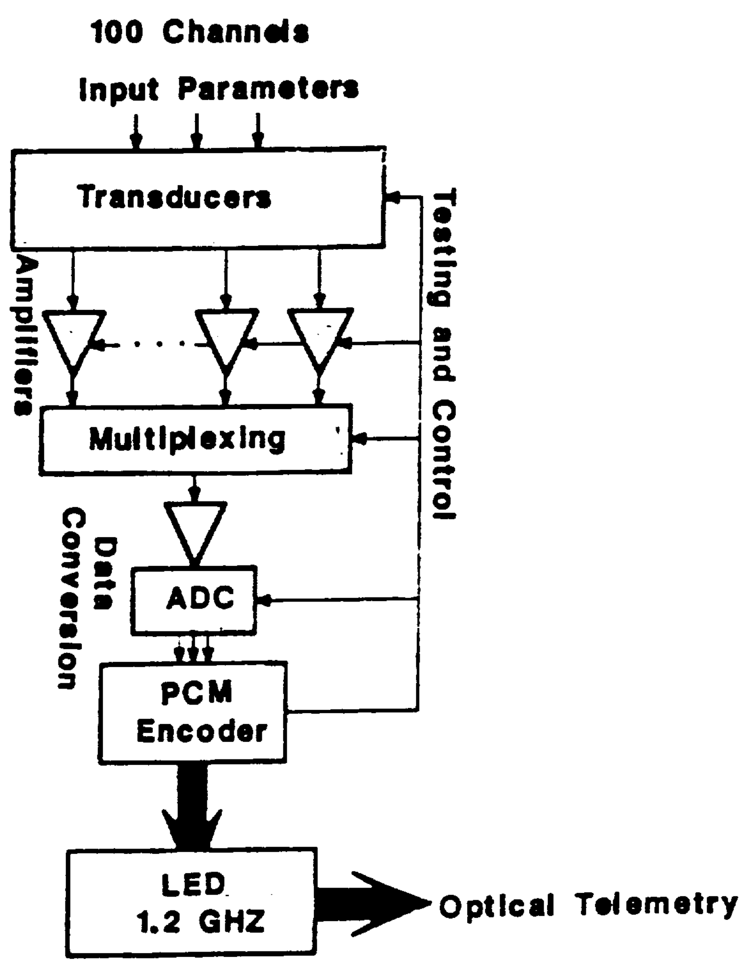
Vu-Graph "B" shows a module with an array of 100 transducers such as the ones just described at the top with the input parameters to be measured. A line of signal conditioning amplifiers is shown for the next stage with the outputs feeding a multiplexing switch. The next stage is an analog-to-digital converter which feeds serial data words to a PCM (Pulse Code Modulation) encoder. The PCM output data stream modulates an aft-mounted L.E.D. at 1.2 GHz. This will allow a 1 MHZ sampling rate per input channel with 12-bit resolution. If more channels are necessary, then additional encoding units of 100-channel modules can be added. Each module of 100 channels will have its own L.E.D. wavelength.

Vu-Graph "C" is a NASA LaRC photograph L-87-8791. This is a partial view showing 8 solid state pressure sensors on a substrate with 8 adjacent temperature sensors and the 4 CMOS (complementary metal oxide semiconductor) die switching circuitry to multiplex. As shown, this will not tolerate the high g launch environment, but this is a current state-of-the-art pressure sensing substrate.

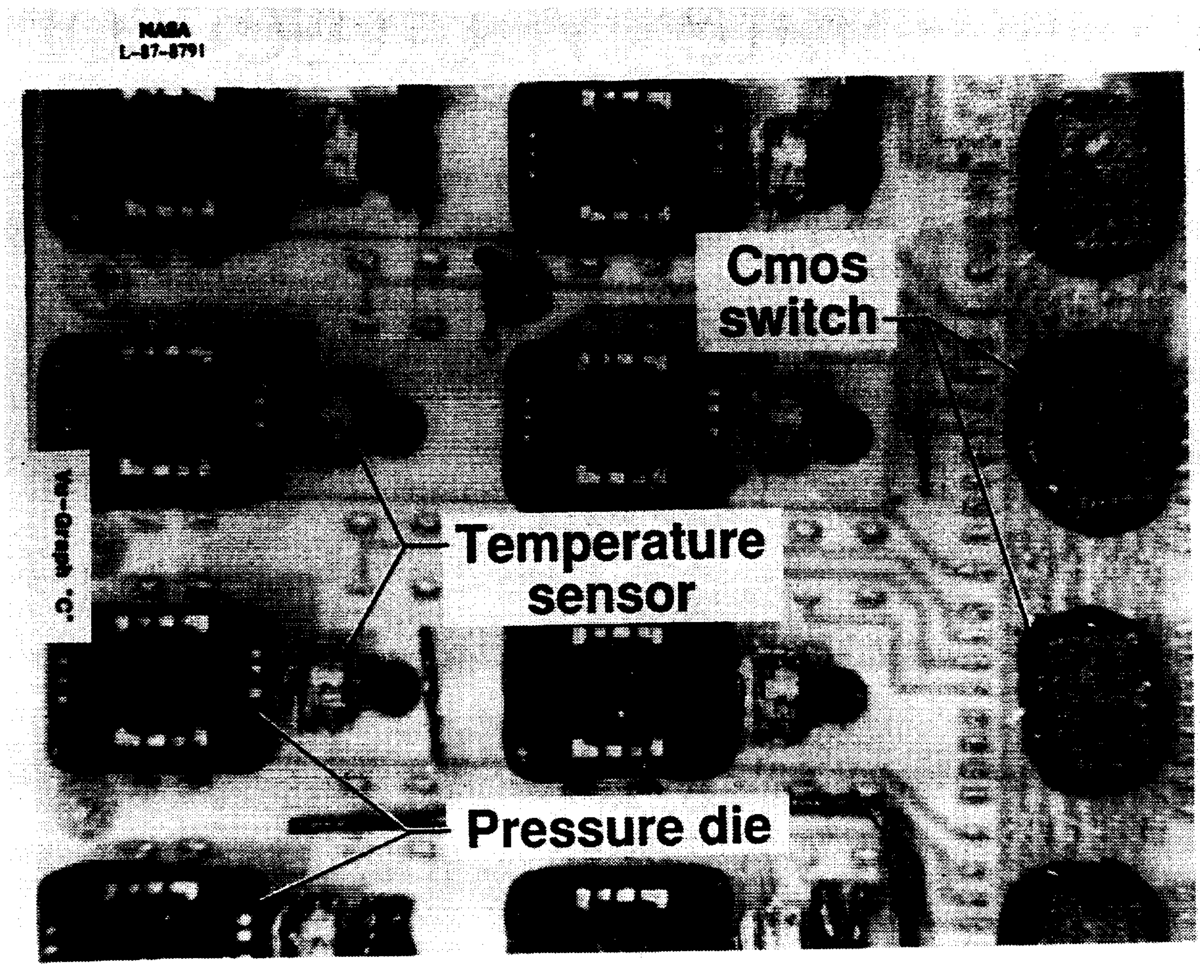
Solid-State Microsensor



Vu-Graph "A": Silicon pressure die



Vu-Graph "B": Modular data encoder



Vu-Graph "C"

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

NONINTRUSIVE DIAGNOSTICS FOR PROPOSED

HYPERSONIC BALLISTIC RANGE

R. J. Exton - NASA Langley

There are a number of established techniques that can be employed to remotely diagnose the flowfield about a free-flight model. There has also been an explosion of new, laser-based diagnostic techniques developed during the last 5-10 years which may be applicable to this type of environment. The following lists some of these techniques along with comments on their availability and applicability.

I. ESTABLISHED TECHNIQUES

1. Shadowgraph/Schlieren/Holographic Interferometry - Probably the most useful and easiest to implement techniques for obtaining shock shape and line-of-sight integrated densities. Extension of these techniques to the low density regime will require further development--possibly including atomic resonance techniques. Exposure times in the 5-10 ηsec range are required.

2. Broad-Band Radiometry - Filter/PMT radiometers can be especially useful to gain a cursory view of gaseous radiation and also to obtain model surface temperatures (ref. 1).

3. Time-of-Flight Scanning Spectrometer - A higher resolution view of the gas cap radiation can be provided by this spectrometer in which the model's motion is used to generate a scanned spectrum (ref. 2).

4. Absorption/Emission Spectroscopy - Broadband absorption or resonance absorption may be useful for species concentration (e.g., N_2, O_2, NO). Excimer lasers have recently been shown to have overlap with many gases of interest.

5. Rayleigh (molecular) Scattering - Density measurements can be made in principle, but Mie (particle) scattering will probably limit its usefulness in a ballistic range.

The first three techniques listed above have a particular advantage in that they do not require any prior knowledge of the model position in the test section, either radially or azimuthally.

II. PROMISING NEW TECHNIQUES

1. Laser Induced Fluorescence (LIF) - LIF may be the most promising new diagnostic technique applicable to ballistic ranges. This results from the ability to tune into resonance with particular species (ref. 3) or in the case of Excimer laser--to overlap with many species directly (ref. 4). Furthermore, the ability to generate a 2-D laser sheet and to capture the fluorescence using high speed, gated cameras also circumvents the requirement to know model position beforehand. The lower wavelengths employed by these lasers may also be helpful in improving the sensitivity of holographic interferometry. LaRC already has an active LIF program, but would need to be augmented with Excimer laser capability.

2. Coherent Anti-Stokes Raman Spectroscopy (CARS) - LaRC has developed a dedicated CARS system for monitoring $[N_2]$, $[O_2]$, and temperature in combustion environments (ref. 5). This system is capable of single laser pulse (10 ηsec) measurements at a single, spatial point. This technique could be useful, particularly in the wake region, if model positioning can be controlled.

3. Mode-locked (p sec) laser techniques should be explored for ultrafast photography and LIF imaging.

4. Two photon absorption/fluorescence of O and N should be explored for ascertaining the degree of dissociation.

III. REFERENCES

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3. Chang, A. Y., Rea, E. C., and Hanson, R. K., "Temperature Measurements in Shock Tubes Using a Laser-Based Absorption Technique," Applied Optics, Vol. 26, No. 5, March 1987, pp. 885-891.

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APPENDIX C

PRESENTATIONS AND SUBMISSIONS BY MEMBERS OF THE ELECTROMAGNETIC LAUNCHER TECHNOLOGY WORKING GROUP

The following contributions by members of the EML Technology Working Group have been selected for inclusion in the proceedings.

* A transcript of comments delivered by John Barber during the plenary session held at the opening of the workshop.

* Written responses by Miles Palmer and Jerry Parker to the questions (presented in Appendix E) posed to the workshop.

Comments delivered to the
NASA-Langley EML Workshop
by
JOHN BARBER

Exactly 20 years ago this month, as a naive young graduate student in Australia, I was seduced by the concept of electromagnetic launch of projectiles. I acquired the EML habit as a graduate student there, and I have been unable to kick it since.

About a week ago I found out what the launch requirement was for this project. I concluded that the facilities we have at IAP are irrelevant. This task is so much bigger and so much different. I'm not going to talk about our facilities. I thought what I should do today is give you my impressions of what this launch task is, how it differs from what has been done, and what the critical issues are from a launcher point of view.

Let me begin with the launch requirement. The projectile is large (maybe 10 kg), and it has a high velocity (maybe 6 to 10 km/s). That means very high energy, something like 180 to 200 MJ of muzzle kinetic energy.

How does that compare to what's been done? The largest program being done to my knowledge, has a goal of 9 MJ of muzzle kinetic energy. They have achieved, as far as I know, about 4.5 MJ of muzzle kinetic energy. This goal is 20 times lower than what is required here, and the demonstrated muzzle energy is more like 40 times lower. We have a big energy difference.

What about velocity? Six to ten km/s is what I believe you want. Six km/s has been achieved by a number of people. Over 5 km/s was obtained back in 1963 (under NASA's sponsorship with an electric railgun powered with a capacitor drive). Six km/s seems to be quite achievable. Claims of 8 to 10 km/s have been made (but not always with great vigor). The velocity probably is not a great problem.

The factor in this project that is quite different from our experience is that the gun is very large -- about a half a meter bore size. The largest electric railgun, which I know of that has been fired, is a 100 mm gun fired at Los Alamos a few years back. There is a 90-mm railgun operating now at Maxwell. These are five times smaller than what we need here.

The large bore means something else. We don't require high acceleration, and that implies low pressure. In fact, we are talking about a gun that operates with a base pressure of 1000 psi (6.9 MPa) or less. Now this is exactly the opposite of what the EM gun community has been working on for weapons systems. We have been battling to get pressures up. Typical gun pressures are 50 kpsi (345 MPa) or higher, but now you want a gun that operates at 1000 psi (6.9 MPa)! That certainly changes some of the technology and the design thrust.

Can the launch be done? Do we have any unsurmountable problems? To answer these questions we need to ask three more. Do we have physics problems? (Do we have unresolved physics questions that might prevent us from doing what we want to do?) Are there technology or engineering issues which are unresolved? Are there programmatic issues? I will try to answer each of these questions.

Are there physics issues? Well, my first impression was no, but that generally gets you into trouble. So I backed up and asked "If I was required to identify at least one physics issue what would it be?" I think it would be armatures. For armatures there are physical issues that we don't understand. (I understand them, but Jerry (Parker) doesn't!) The way I look at it, until I can convince Jerry, these are still unresolved physical issues. Bill (Weldon) identified that all of the problems we have encountered have been in small bore guns. We don't have enough energy to drive large bore guns. Some of the theoretical developments indicate that the critical armature physical issues will be alleviated in large bore guns. However, we are considering very large bore guns and much much lower pressure, so I conclude that there will be physical issues that need to be resolved, and they probably have to do with armatures.

Are there technology issues? Given that we understand all the physics, do we have the engineering skills to engineer those physical concepts into a system that will do our job? The answer is no, we don't have the engineerng skills to do it. (At least it's not clear to me that we do.) What are the critical issues? There are only two components in the electromagnetic launch system, the power supply and barrel. I think they both have engineering and technical issues that are not clear and should be resolved.

Let me start with the power system. We are dealing with a very large power system if we need 200 MJ of muzzle kinetic energy. Given the efficiency which we have demonstrated, that means that the order of 1 GJ of stored energy must be stored. Is that large? Yes, it is large. I brought along one viewgraph (and only one) and it is a picture of the homopolar generator at the Australian National University. It was built in the 1960's when big things were undertaken all around the world. This generator stored 560 MJ of energy and could deliver that energy at about the current level required for this job. You can see the man down here in the corner to indicate the scale. Technology has advanced and Ian (McNab) showed an artist concept of a machine that stores twice as much energy but is much smaller. However, I wantd to show you something that exists (or existed -- It's in mothballs now and I understand that it is for sale. If anybody wants to buy it, I can probably arrange it for you.)

What other technical issues are there in the power supply? Well, I think there are tradeoffs involved between performance and risks. In a program like this, I think you would make the tradeoff in favor of reducing the risk and taking lower performance capability. You don't mind if it is big and uses old technology, what you really want is for it to work. Finally, you want to develop a practical system concept -- one that you can see how to engineer. If you can't see how to engineer it at the beginning, it will probably disappear into a myriad of overruns and schedule slips, and will never operate. I think a lot of effort at the beginning must go into selecting a concept that makes sense, is practical, and reduces the risk.

What about the barrel technology? The main factor that comes across to me is the very low pressure at which you would be operating. That means that containment is not a problem. Massive containment members, large bolts, and high prestress are not going to be necessary. Usability, life, and precision are probably the principal issues. There are substantial engineering problems in making such a large barrel so long, with the precision and straightness required, and making it usable. It is going to be damaged occasionally during the launch -- you can't avoid that -- so the barrel must be easy to maintain, service, and refurbish.

Are there program issues? Yes, and they may be the most serious. They involve time and money. The system cannot be built with off-the-shelf components. It takes time to develop the components and to do the testing and verification that is required. I hate to say it, but the EM gun community has not demonstrated particularly good skills in predicting how long and how much money it will take to do things. (I am sure that this is not unique to the EM gun community!) It does rate a red flag. Whatever we say we will do, it will probably take longer and cost more!

Time is money and we must avoid technology push. This program should not be the one to push technology. It is going to cost enough without trying to advance launcher technology. However, I think the EM gun will be a low cost part of this system. Instrumentation, range facilities, and support facilities will be very expensive. My estimate is that the launcher system will cost less than $1/J of muzzle kinetic energy.

In summary, the launch task is large -- well beyond the range of our immediate experience. The critical issues are probably different from those experienced in the weapons development programs. Physical issues will be relatively less important. Engineering and programmatic issues will be more important.

Question: (Kolm)

Among the various considerations in the rationale for selecting an approach, if one has to make a decision in the beginning, is whether you will consider the inevitability of electromagnetic launch technology sometime down stream. It may not be rational to use electromagnetic launch technology for this facility, in terms of the other competing ways of doing it, but it might make sense, just simply because sooner or later we are going to launch space vehicles electromagnetically. Inasmuch as we don't spend a large amount of money on far downstream research, this could be a vehicle for allowing us to do it, and particularly with the advent of even better super conductors, it could be inexcusable to turn our back on that entire field of technology. I am just saying that because you have heard from all of us a pessimistic assessment as to whether this is really the practical way of doing it.

Answer: (Barber)

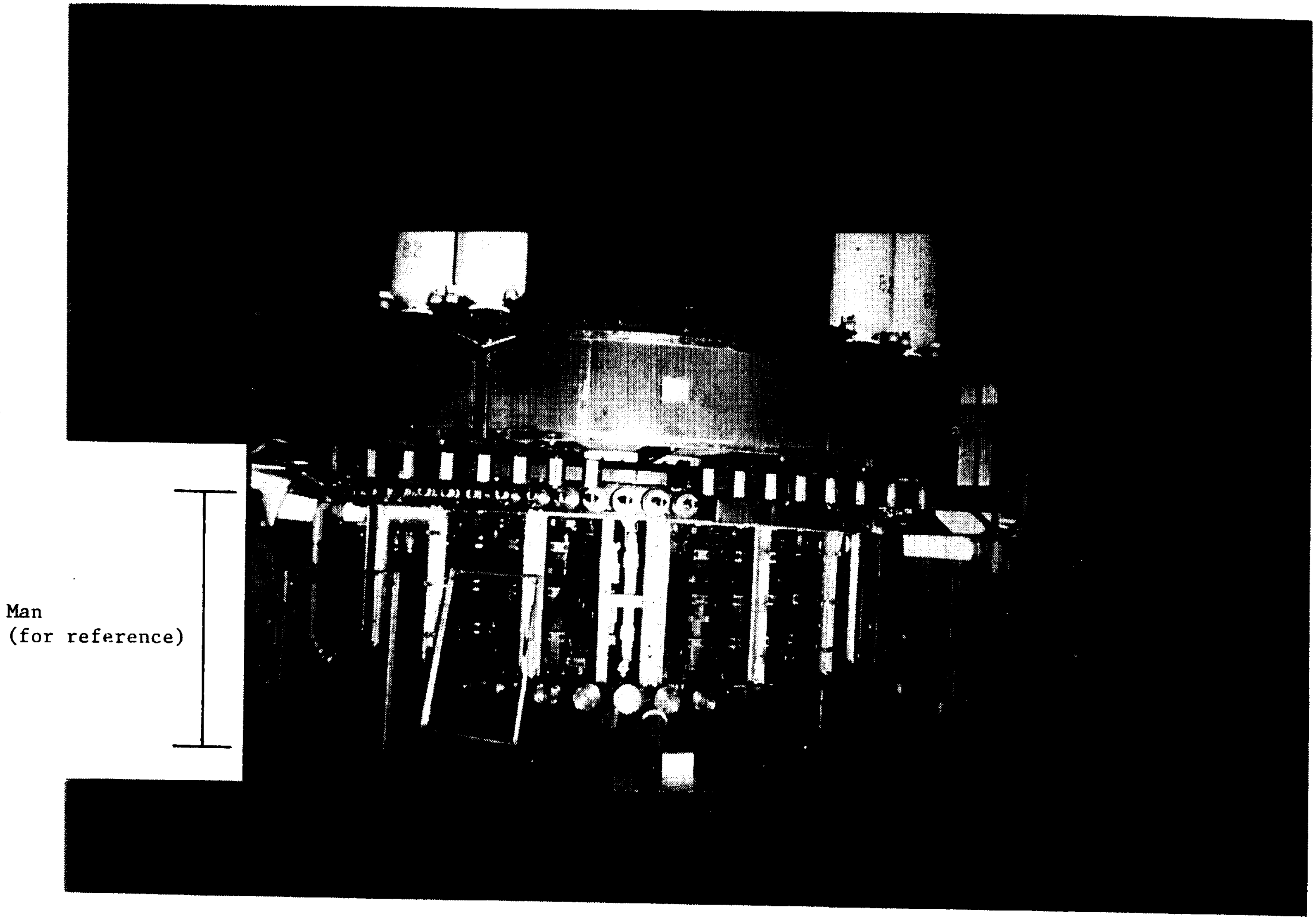
I didn't mean to imply pessimism about electromagnetic launching for this project. I am not sure there are other ways of doing it.

Question: (Swift)

In Bill Weldon's report he docked the issue that you brought up about the arc by suggesting using smaller arcs in guns that are very doable and are widely in use today. Could you comment on the notion of driving this thing with four small guns within the current technology as opposed to a large gun which breaks new technological ground?

Answer: (Barber)

I have not had a chance to talk to Bill Weldon about this concept, but it seems that what he is doing is trying to reduce the launch problem to one that he knows more about, that is high pressure guns. I am not convinced about that approach. Low pressure guns don't scare me. I built and operated a railgun that plugged into the wall and operated at a couple of psi.



John Barber's Figure - Australian National University Homopolar Generator (560 MJ Energy Storage)

WRITTEN RESPONSE TO QUESTIONS POSED BY NASA LaRC

Dr. Miles Palmer
Science Applications International Corporation

1. Consensus at workshop indicated large models are desired at high velocity. Sabot and model mass for 18 in. (46 cm) diameters will probably be at least 20-50 kg. Accelerations could probably be up to 50-125,000 g at this size if high strength ceramics are used with proper design. Larger models up to 200-500 kg could be accommodated in an 18 in. (46 cm) bore ("Electromagnetic Space Launch: A Re-Evaluation in Light of Current Technology and Launch Needs and Feasibility of a Near Term Demonstration" by Palmer, M. R. and Dabiri, A., 4th Symposium on Electromagnetic Launch Technology, Austin, Texas, April 12-14, 1988). In this case, G limits would be ten fold lower, or 5-10,000 g. Models this large could accommodate more complex instrumentation.

2. Armature and payload design must be integrated, but they may be physically separated as a result of this design process. The B and BDOT fields should not be a problem in simple rail launchers, since fields in the model region are relatively low. Augmented or coil launchers may present problems due to the high fields in the model region. Keeping the model somewhat ahead of the armature would be an advantage.

3. Model declaration is currently done by gas compression and drag forces. Electromagnetic deceleration would be more flexible and controllable, but more complex and probably less reliable. It should be possible to design an electromagnetic "funnel" which would guide free flying models into a catcher which would decelerate the model by EM or gas forces.

4. Depends on which of many coaxial designs are chosen. Primary problems in most designs are hoop stresses and high voltages on drive coils, not payload coils.

5. Yes. Maxwell labs is one of the best test sites due to large bore (9 cm), high mass (1-5 kg), high current (3MA+), high energy (30MJ+), experience level, and the routine operational level which has been achieved.

6. Not my field. Large models at high velocity are very difficult to stop reliably except with very massive shielding. Free flight on open test ranges or in suborbital trajectories might be desirable. This would allow electro-magnetic Earth-to-space launch to be demonstrated. These considerations would argue for siting at an existing free flight range such as White Sands.

7. See previous section.

8. Probably.

9. A crucial and very difficult question. Coil launchers have failed to work at hypervelocities, possibly due to lack of adequate funds for detailed de-sign. Induction launchers do not appear to be suitable for high velocities at high accelerations due to the voltage problems. At lower accelerations or at high velocity, the energy transfer efficiency is quite low for most coil

launchers. This implies terajoules rather than gigajoules of stored energy. This dictates a superconducting design. I feel that coil launcher development will be much longer term, higher cost, and higher risk than rail launcher development. Demonstration of a superconducting coil launcher could change this, but probably requires a minimum of $20M per year for 5 years to achieve useful results. Ultimately, a superconducting coil launcher might offer higher performance than rail launchers, but at much lower g levels. With a 100 kg model, g levels of 500-1000 g might be expected, resulting in launcher lengths of several kilometers.

10. Probably. Plasma blowby might require a gas stripper section of a few hundred feet.

11. Large masses at high velocities require very high stored energies and pulsed powers. This requires careful attention to cost reduction, since costs can rise to the billions of dollars for power supplies alone. A battery charged inductor is probably the cheapest option. (See paper referenced in response to question 1.)

12. This may require a guide rail track range unless magnetic "funneling" as in 3 above can be achieved.

13. B and BDOT will probably make data collection during acceleration very noisy and poor quality. A few hundred foot section of free flight between the launcher and the data acquisition section is recommended to get away from region of magnetic fields.

14. Testing at Maxwell Labs (near term) or AFATL (longer term).

15. Further battery charged inductor development should be pursued if Eglin AFATL battery system works as expected. No other options appear cost effective at this time. Solid state opening switches would be a desirable development to replace the presently available explosive opening switches. Pulsed superconducting power supplies might be developed for high currents. High frequency high energy drivers for coil launchers are probably exorbitantly expensive due to the very low energy transfer efficiencies. These are all being pursued by DARPA/SDIO, etc. Total funding is woefully inadequate. Another $100M per year is needed to maximize rates of progress.

16. Major safety issue is unplanned escape of the projectile. This may dictate siting at White Sands or a similar remote area.

17. See 16.

18. There are a lot of unknowns here. See 16.

19. Would be a useful capability to have.

20. Armature can be thermally isolated.

21. Small problem in simple rail launchers. Potentially a problem in augmented rail or coil launchers.

22. Single stage system to achieve 500-1500 m/s injection velocity is desirable for arcing launcher designs to minimize damage in breech section of launcher. Two stage or higher velocity injection probably causes more problems than it solves.

23. An interesting question. More data are needed, but the viewgraphs which I presented at the workshop are attached. They indicate that the larger the bore size, the better. Model mass and power supply size and cost scale as the cube of bore size, however.

24. Probably, the requirements to study complex shock kinetics and radiation transport set a minimum model size of interest which is larger than the minimum size required for instrumentation purposes.

Written Response to Questions Posed by NASA LaRC

J. V. Parker

Los Alamos National Laboratory

With only one day to study the CEM-UT report and to analyze rail-gun requirements, these comments are very preliminary. In some cases the questions concerned areas outside my expertise. These are denoted "NA".

1. Model size - the cost of the energy system to drive the EML is the primary issue - a secondary issue is structural integrity during launch (this tends to limit length/diameter of model).

Velocity.- Up to 5-6 km/sec propulsion should not be a major issue. Sliding contact with wall must be considered an uncertainty in this range of velocity. Above 5-6 km/s there is no demonstrated technology, particularly at low acceleration. Required armature mass to avoid melting is a serious concern. Simple calculations tend to underestimate armature mass, particularly at high velocity. Sliding contact is a major uncertainty at $V > 6$ km/s, particularly if balloting occurs during launch. Induction launchers have not been demonstrated above 1 km/s. Armature heating will be a serious concern.

Design.- Structural integrity during launch is a primary issue. How accelerating force can be transmitted from armature to model must be determined early in launcher design. Important question is whether all force must be applied to the model base or whether shear forces can be applied to the body of the model. Magnetic shielding will be a serious issue if it is required. A major effort is required to eliminate the sensitivity of electronics and to reduce B.

2. From EML considerations, the armature should be far from the model (presumably behind). This requires additional sabot mass, however, and cannot be carried too far. Railgun geometries which reduce the field in the model should be examined for their practicability. For reliable model separation, it would be desirable to place the armature behind the sabot so that the current carrying elements do not have to avoid separation planes in the sabot.

Evidence from tests on electronic components shows them to be highly resistant to high B fields. There are no data yet on complete systems with peripheral sensors and bus connections. Careful wiring with twisted pairs and extensive use of LSI components should make electronic package feasible at multi-Tesla fields. Must stress importance of controlling dB/dt. Need smooth current waveforms.

3. NA

4. Transverse pressure loads are typically 1 to 3 times the axial pressure. The local force acting on the armature is $\dot{J}x\dot{B}$. JxB is the drive force, while JxBz is radial compressive force. Typically $Bz \geq Br$ for coils without iron cores to control the field geometry. This can be very important because a thin shell armature has very little strength against collapse, particularly

when it gets hot at the end of launch. A significant extra mass is needed to support the cylinder. This mass has been neglected (or not discussed) in the CEM report.

5. Yes. Some work has been done as part of Sagittar and Gremlin programs. Straightforward to do more, but only a few current facilities have large bore capability for testing complete systems (90mm Maxwell SSG, CEM 90mm when complete, ARDEC 50mm, AFATL battery system with suitable barrel).

Magnetic effects can be evaluated in a static tester (no acceleration). Only requirement is sufficient current (~MA) and relevant waveforms (probably a capacitor bank to provide flexibility).

6. NA. But, vertical orientation was considered for space launch system by LANL team advising Virginia Tech. Costs and operational complexity are enormous. No safety consideration could justify this alternative. Trench & fill is a relatively cheap technique which provides additional safety on flat ground. A good size hill is the cheapest insurance.

7. This is a complex question whose answer is critically dependent on the type of launcher system planned. For any system an in-depth technology assessment should be performed after concept selection and prior to preliminary engineering design. This assessment should focus on determining what is demonstrated technology vs. design concepts, one shot demo's, extrapolation, etc.

8. NA.

9. Assuming both concepts are technically feasible and have similar costs, the key questions are operational reliability and equipment maintenance costs.

For example: The CEM coaxial induction launcher has only four large machines. Recent history suggests that long down-times can result from a single machine failure (~ 1 year). Several machines have experienced such failures in recent years.

Similarly, the coil structure of a coax launcher is very vulnerable to an in-bore failure of the model/sabot structure. A glancing collision at 6 km/s could require a complete rebuild of many meters of accelerator. Simple, railguns are generally less costly to rebuild.

Pivotal issues exist for all EML approaches. The technology base is not adequate for a "go-ahead" decision at this time. For example: (1) There are no demonstrations of a coaxial induction launcher at velocities in excess of 1-2 km/s; (2) A railgun of 18 in. (46 cm) bore should utilize a hybrid-solid armature to reduce losses and rail damage. No adequate demonstration of hybrid armature operation has been conducted at this time.

10. NA.

11. NA.

12. NA.

13. NA.

14. NA

15. There is substantial development work to be done before the advanced compulsator devices proposed by CEM-UT can be considered reliable enough for a Hypersonic Research Facility. Conventional homopolar machines of 10-20 MJ capacity are available, but there are no simple opening switches available at this time for distributed operation of a homopolar system. (Explosive switches are the current technology of choice, but they could be very labor intensive for such a large system.)

The same switching issue exists for battery powered, distributed systems.

Despite the large energy requirements, the alternative of capacitor bank storage should be given a thorough evaluation. New capacitors with 250-500 kJ/can storage capacity are expected to be available within 2-3 years. This work is supported by DNA via the Mile Run program. The advantage of a large number of capacitor banks (~100-200) is a very smooth current waveform. Distributed energy storage on this scale has not yet been demonstrated.

16-20. NA.

21. The key to protecting instrumentation is controlling dB/dt. An ideal system would have a smooth current rise at the beginning, constant current during launch, and a smooth decrease at the end. All systems with periodic fluctuations (switching transients in distributed inductive stores, etc.) will require extra care in electronics design and shielding. Principal thrust in electronic instrumentation should be toward use of LSI technology to reduce interconnections, design of smaller sensors with decreased magnetic field sensitivity, and experimental evaluation of new interconnection techniques (transposed conductor buses, optical fiber, etc.). I do not believe this issue will be a "show-stopper."

22. A single-stage gas injector using helium would be very desirable for any railgun EML. A two-stage gun of 18 in. caliber is too expensive and represents too much of a safety hazard to consider for this application. An injection velocity of 500-1000 m/s would be adequate to reduce rail damage in a hybrid armature railgun. A single-stage helium gun operating at 400 psi (2.8 MPa) would provide an acceleration of 10,000 g and reach 500 m/s in less than 5 m. This type of pre-acceleration requires a sabot/model design compatible with base-pressure-only drive.

23. This comes back to energy again. The launch mass must eventually scale as D^3 for a stable sabot ($L/D > 0.7$). Since system cost is generally proportioned to stored energy, a large bore places a great strain on the financial bottom line. Every effort should be utilized to miniaturize the model and instrumentation. Current model/instrumentation technology should not be allowed to drive the EML design to excessive bore diameter. A balanced expenditure of resources between launcher and model/instrumentation development is needed.

24. NA.

APPENDIX D

TRANSCRIPT OF THE RANGE TECHNOLOGY WORKING GROUP MEETING

The following is a transcript of the Range Technology Working Group Meeting. This group chose to address the questions (presented in the Appendix E) posed to the workshop, responding to those questions which were applicable to their discipline. The questions which they addressed are noted in the transcript. The charts, which reflect their response to particular questions are presented at the end of the transcript. The charts can be identified by the number of the question being addressed, the question number being identified by the number at the right of the chart title.

RANGE TECHNOLOGY WORKING GROUP MEETING TRANSCRIPT

QUESTION 1

Cable:

Regarding question number 1, 10 kilograms is too light a mass for an 18 in. (46 cm) launcher model/sabot package. A model/sabot package with a length-to-diameter ratio of one and a mass of 14 kg (i.e. including Bill Weldon's 4 kilogram sabot) corresponds to an average density of 186 kg/m^3, about that of balsa-wood. Lexan, commonly used for sabots in light gas guns has a density of 1246 kg/m^3. A more likely mass for a 46 cm launcher is 100 kg. 10 to 14 kg correspond to a 23 to 25 cm launcher.

An average acceleration of 10,000 g to give a velocity of 6 km/s implies a launch tube 183 m long. Scaling the AEDC launcher would imply about 20,000 g peak (but they have never measured their peak acceleration). AEDC has.

Note: Model acceleration for similar models is inversely proportional to bore diameter. So increasing bore size automatically reduces acceleration. But, base pressure on the package to produce this acceleration is independent of size. So, if 40,000 psi (276 MPa) is needed to launch a 2.5 in. (6.4 cm) bore model to 4.5 km/s, 40,000 psi (276 MPa) is needed to launch a 46 cm bore model to the same velocity. Do not be misled by the reduced acceleration.

Model size is limited by the items listed in viewgraph 2.

Velocity limits depend on "real" effects on propulsion means. Examples, for light gas guns are real gas effects and ablation/erosion of bore material into the propelling gas. For EML I am not sure, but I am sure there are similar loss producers.

QUESTION 2

Question 2 we won't address because we consider that an EML problem.

QUESTION 3

Cable:

Question number 3, what are feasible methods for decelerating models? I guess I just gave a few possibilities. One method is a pressure tube followed by tapered rails, which is the way we do it at AEDC. Shooting into a fluid or shooting into a foam is another possibility

Swift:

I almost think of all of those, the only really feasible one is the gas dynamic catch, which is your compression-tube method. The reason is that shooting into a fluid or foams at these kind of speeds will do horrible damage to the model, and we have a technique that is pre-built, it works at several speeds and there is no reason that you shouldn't expect it to work here. The only thing is that it needs real estate because it has to be long. It has to be in the order 10 times the length of the launch tube. But it is so powerful that I think it should be used everywhere that there is not some all-encompassing reason why it shouldn't be used.

Cable:

The only thing I have to say about that is that I think in order to use a compressed gas type of technique you have to guide it, which means you probably have to guide the model the whole way.

Swift:

One thing, we don't get a discarding sabot so we don't have to worry about discarding a sabot, but the model itself will either have to form a front of the sabot or be supported on a sting. One thing that this prevents is doing any wake studies around the model. If they want to study wakes, then I think they are going to be left with, as you would do in range "G", moving all that paraphernalia out of the way, free flying the model down the range, and studying your wakes. I really think you might as well catch the model against the thin metal plate and destroy it.

Cable:

The other thing you can't do is aerodynamic testing which relies on motion of the model in flight.

Swift:

But I would think that you can do one thing, with these sizes you can build a model that is articulated somewhat where we would launch the model at one angle of attack and during the flight path the model angle of attack would change. If we had onboard instrumentation we could take wind-tunnel-type measurements on the model while it was in flight.

Piekotowski:

JPL is doing some work with foams to capture material from meteoroids and that is working pretty well I understand. That could be an alternate recovery technique. They are recovering materials from comets tails or that's their plan. I don't know how well it is working.

Cable:

They have been working with the gun range at Ames, and what they are doing is shooting like 1/8th or 1/16 in. aluminum or glass spheres into foam and recovering some that are undamaged from I believe, about 12,000 ft/s. Now that is, to me, a very hard model. The sort of models that they may be talking about here are not very hard. It may be a combination of gas to get initial deceleration, then perhaps foam afterwards.

Swift:

The only trouble I see with the gas is that you may need the foam to serve as a rag bag. If you don't let the model off the rails or let the model out of the tube going at a finite speed, then the model will turn around or reverse directions, and I understand you guys often recover the models in your pump tube.

Cable:

Well it can be. I see the gas and the foam as being a possibility for where there is a free flight model involved. What we have done to avoid the model going back into the launcher again is not to try to slow it down to zero velocity, to slow it down to maybe 200 or 300 ft/s and then use a tapered rail as a braking system and then you know where it is. Our problem is if it reverses, it can be anywhere in 1500 ft that you're going to have to look for it, and 500 ft of that you can't see into either.

Swift:

At what rate does the model decelerate?

Cable:

We try to do it at about 1/10th of the g loading of the launch values. We've got a 68-ft launch tube and we've got a 500-ft recovery tube. So it is not quite 10 to 1, 8 to 1, something like that.

Piekotowski:

But your peak deceleration occurs when it first enters?

Cable:

Yes, but what we do to ease that is we use helium as the initial gas and then we use nitrogen as the gas later on. We have those two at the same pressure and there is a valve in between which we can open just before the shot so we don't have to worry about it not opening.

Swift:

With 500 ft, if you get 10 ft of mixing in the gas back and forth it probably helps you.

Cable:

The other thing we have is 50 ft of the tube ahead of the quick opening valve so you get sort of a ramp pressure going into it; you don't get a sudden increase in pressure. That seems to work.

Swift:

We are marketing, by the way, a sabot separator that works on that same principle, and it is doing very well for itself.

Cable:

That recovery tube doesn't require too hard a model, but it does require a model that is capable of absorbing loads in both directions.

Swift:

There is one other thing, by the way, about foam. If you are going to use foam or use any atmospheric stopper without restraint you have to use what we call the weak center concept. We started decelerating steel disks in foam and we discovered that this steel disk turned 30 degrees and went out through the side of the range. We built a cardboard deceleration system which was weak in the center where the deceleration occurs and radially it became progressively tougher and tougher until finally there was full density cardboard at the inside edge of the steel pipe. So what happened was the thing went into the s-bend as it stopped and would wander off into the heavy going and, being flexible, back into the easy going.

Cable:

If you had an aerodynamic type of vehicle rather than a disk, I think you'll find it will tend to turn broad-side. That is what shells do when they enter water and cause a fuzing problem for attacking ships. I think the technique, for disks, makes the model design rather constrained if you're going to be able to do that. Now people have done it, decelerated ones in similar fashion by having foam with a taper hole in it. So you start to pick up on the sides.

Swift:

I think the name of the game though is that it is questionable whether a lot of money should be spent on this facility to build a foam capture. That ought to be thought about long and hard. Are you going to want to soft catch aerodynamic models where you are operating without a sting or can you afford to catch with a pressure system with possibly some little adjuncts on the rear end.

Cable:

Another thing that Chul Park suggested today was that, if you have an asymmetric model that is lifting, why not make a mirror image of it, so as far as going down a track or recovery tube or something like that is concerned, it is a symmetrical model. Then you make your measurements by pressure transducers or accelerometers or whatever.

Swift:

Of course you halve the size of your model, or you have one dimension that way.

Cable:

You can also have interference with those too. I think what we need to do is ask the experimental group how important it is for them to recover a model which has to be in the free flight.

Piekotowski:

How often do we want to do that?

Swift:

Is that one of their major adjuncts? If it is, we're going to have to bear down and figure out some way to do that, but it is not going to be easy and it is going to be expensive and it is not going to be terribly successful or terrible effective.

Cable:

The other thought I had was, one of the things we were asked to look at somewhere is should the thing (facility) be shaped horizontal or vertical. Now the one thought I had with the vertical one was that we could just shoot it up in the air and wait for it to slow down and then parachute it back. That way we don't have to worry about its dispersion. But you may need a fairly wide area to do this in and a telemetry package to locate it again afterwards.

Swift:

Beyond that, you are going to have to have an extremely quick-opening valve at the end of your range.

Piekotowski:

You'll have to slow it up or burn it up.

Swift:

Yes, that is a good point. Then it is going to have to negotiate hypersonic travel at essentially sea level unless we build a really long range.

Cable:

It could be a vertical one, above ground. I think that we have hashed that around awhile now. We may not have come to any conclusion except that track and pressure tube seems to be the most likely.

QUESTION 4

Cable:

Question number 4 is what are the magnitudes and implications of the pressure loads acting on the model-sabot for the coaxial concept? Now the coaxial concept, if I remember, is this thing where there are a series of coils that are spaced.

Swift:

The coils can be one tube like, for instance, if you make an aluminum sabot, the aluminum sabot can serve as the accelerator tube itself.

Cable:

Now one thing that I noticed is that they had a size given in their report for this aluminum armature, kind of an outside sabot there, and from the numbers they gave me in the report, I calculated out that it weighed 6 1/2 kilograms not the 4 they have been quoting. So there is some discrepancy there. I was going to say maybe it's lighter aluminum than what I'm used to. I'm not sure about this coaxial gun, I know on the rail gun you generate pressures which try to blow the gun apart.

Swift:

You have the same thing with a coaxial gun, but it is in the coils themselves. So what you can do then is to put contiguous belts around the coil. Typically, when they make these things, they make the coil, and then they wrap it thickly with fiberglass so the area between the coil has no force on it.

Cable:

The sabot is essentially being pushed, so if you are going to get the same velocity and the same average acceleration load, the pressures are going to be much the same.

Piekotowski:

Don't you have a lot of heating in that loading too?

Swift:

That is an interesting point. Supposedly, you get much less heating than you get in the DC rail gun because of the mutual inductance, the efficiency goes as the mutual inductance. Mutual inductances are far higher than the L-prime out of the rail gun so the efficiency of thing goes high. Now we heard very indirectly that by the time you get to a kilometer per second, you have melted the model, and that seems to go in the opposite direction. So it appears that is a question, and I guess that is not a question that has an answer.

Cable:

There was a calculation in their report that said that they wanted to pre-cool that aluminum sabot with liquid nitrogen because it was going to heat up to about 287°C. If a sabot is cooled in liquid nitrogen, what does that do to the model structure underneath and what do you do when you put it into the gun? If it warms up at all, you probably have a shrink-fitted model in there by the time you turn on the power. You load it in a cooled section somewhere which is matched to the uncooled bore. If you don't get the heating quite right, you have a step in your gun which will probably tear bits off the model.

Swift:

Again, is this something the range people should worry about?

Cable:

Only from the viewpoint that I claim that models and sabots are part of range technology. It is also part of the launcher technology as well.

Swift:

You mentioned bending the barrel straight and putting lots of little bends in it that have steep variations. One opportunity that comes with this great big thing is to make the sabot follow the bore of the gun and put a fairly generous pad of foam laterally into your model. Now this sabot can go back and forth as it goes down the tube, and the model can go down the tube straight and just jiggle around inside of its foam.

Cable:

At the speed you need, to match those imperfections, I'm not sure you can tailor that.

Swift:

I'm not either, but it does represent a possiblility.

Cable:

The other thing I mentioned this morning is that there seems to be a lot of concentration on reducing the g-loading, but essentially what happens to the model is the same base pressure is going to be transferred through the sabot into the model somehow. It was suggested that you could support the model on pins. My experience is that if you don't hold a model pretty securely something is going to give way. Again that relates to question number one.

Mouring:

Has anyone mentioned any of the weights of some of the models that they have currently tested? The ones that we saw this morning, does anyone know what those things weighed?

Swift:

They probably weren't optimized for weight in any way because they were optimized for cost of construction and things of that sort to go into a wind tunnel. Stainless steel, for instance, is the handiest thing to make the model of, even though you perfectly well could make it out of magnesium.

Cable:

What you're after is to get the highest strength for the minimum weight. We have been looking for the infinite strength, zero weight material for many years.

Swift:

We came pretty close to it but it was beryllium. (Toxic material.)

Cable:

I guess the implications are that they (coaxial launcher) will affect the model and sabot design in a similar manner as the rail gun. With that 4-rail gun, around the side where everything is pushing forward on four little lugs which they wrapped with kevlar tape to keep them together, I think somebody needs to look at a stress analysis of that. It seems that although it may be pulling you have still got a pretty hefty force on those lugs. My experience is that if you have any gaps and things and you have got hot gases around, they will find the means to cut through the model parts.

Swift:

How about that labyrinth that is going to cool the gas down to the point where it doesn't strike an arc behind the model?

QUESTION 5

Cable:

Question 5, is it possible to conduct meaningful instrumented model tests with current existing facilities, the purpose being to determine whether instrumentation can withstand the g-forces and electromagnetic environment? What applicable investigations have already been done? Now at AEDC we have done quite a bit of work on high g-loading on instrumented models.

Swift:

An interesting experiment to suggest, it would seem to me, is to go to AEDC and fire a very low velocity shot where you are going for the acceleration levels that NASA is talking about here. Build a generic instrument package, particularly the recorder, go down and catch the recorder in your decelerator, and play the recording back. But it seems to me that some tests at AEDC will be very apropos. You may not want to go to hypervelocities because you need to go 20 times the g-loading to get what is needed, and it is not the velocity that you are interested in, it is the acceleration.

Cable:

A lot of our work is done with single stage guns on getting high g-loading.

Swift:

By the way, the other one that is very good at that is Diamond Ordinznce Fuse Lab. They have that extremely low acceleration gun, and then they come in and crush honeycomb to generate elegant deceleration profiles. What you get is what you pay for.

Cable:

Essentially, what they do is the reverse process. They decelerate the projectile to get the g-loading so they fire it backwards.

Swift:

They have a very, very low g-launcher that doesn't go very fast at all, but it is extremely gentle. They launch this thing up, and then they hit these cones. They machine these cones of aluminum honeycomb to get the profile that they want, and they come in and crush up this cone. They have gotten to the point where they can predict what the profile is going to be. They generate the cone and that is the profile they really hit.

Cable:

The thing you need to do in addition to g-loading is to create an electromagnetic environment.

Swift:

Well there was that one gun, the locked gun which is a standard technique for getting an electromagnetic pulse, that is reminiscent of a gun pulse.

Piekotowski:

I don't know what you get out of the 7-in. air gun, is that the right kind acceleration on that?

Cable:

It may be a little low, but we could make it go faster. We only use about 150 psi in it, and the driver chamber is good for 30,000. The driver is an 8-in. gun barrel. So what we would need is to add an electromagnetic pulse to the tests.

Swift:

I guess the question is that do you need to simultaneously do them, or can you send the package off and get it electromagnetically pulsed (EMP) and then bring it to AEDC and get it accelerated, and if it survives both, say its great?

Cable:

I was thinking about putting the EMP on the muzzle of our gun.

Swift:

If it turns out that there was any danger of coupling of the problems while it is undergoing g's and it's also being EMPed, then you clearly don't want to do that. Separate acceleration and EMP.

Cable:

We have got the 100 megajoules on a homopolar generator in the next door building, and surely there is someway we can pulse that over to the gun barrel. That certainly can be done.

QUESTION 6

Cable:

Question 6. What are the operational, safety, and cost implications of constructing such a facility below ground level, in the ground vertically, or above the ground horizontally?

Swift:

I would like to make a comment on that, that came up at lunch time. We talked about the possibility of doing this whole thing with a 2 stage light gas gun, and the point that came up was that the "beast" for the 4 in. gun at GM Delco was the largest forging that a great big forging shop had ever made. The beast is a great clamp that encloses the high pressure section. I said, you don't need to enclose the high pressure section. They do it there to simplify the high pressure section and to protect the surrounding environment and to also to transmit the acceleration loads from the gun.

What we do typically these days, with a bigger gun, is we have a collar which threads the pump tube to the back of the high pressure section and a collar that threads the launch tube to the front of the high pressure section, and we transmit the tensile loads right through the high pressure section itself. If the high pressure section bursts, we have no protection. However, its getting to be extraordinarily rare that those high pressure sections burst. This gun is certainly going to have to have a high pressure section that is made up of concentric collars, and all we need to do is go to an outside collar and put a mild steel one on or a maximum toughness steel one on.

Cable:

But we are talking about light gas guns. I guess I say on the safety aspects that the main thing you're going to be concerned with is, what does it do if your launcher fails? That is, the big components fail, the power supply or the launcher, and can you get much damage from model impact? I think we can take care of that easily enough. My own feeling, and it may be just through natural habit, is it ought to be horizontal. It ought to be, probably below ground. Whether you dig a trench and put it in or whether you dig a tunnel and put it in, do make it accessible.

Swift:

You want it in a large underground structure, and it is the cheapest way to prevent particles from flying over and hitting your neighbor.

Mouring:

This is exactly the point, you know, my interest here as master planner for Langley. Fairly early on we have to find a place to put it, if we are serious about whether it can be physically located here at this center or some neighboring federal facility.

Swift:

What's your ground water here?

Mouring:

We have water level problems here that would add to the cost of construction of such a facility. I am not saying it can't be put here, maybe it can, depending on the total length, but I'm interested in the environmental safety zone.

Cable:

At AEDC, for instance, we have 40,000 acres of which 2000 is the built up site. The rocket motor people go up to something in the range of 50,000 lbs of rocket propellant and we do have cleared areas for that. They are just putting up a new facility there for these more energetic explosives which will be a couple of miles away from the rest of us, I'm glad to say. So I think AEDC is a possibility, it has gun range people as well. What you need is just a lot of space around you.

Swift:

I thought you were going to say something else, and that is your facilities which are flea-sized compared to this, but are still substantial, are in a built-up area with parking lots and other groups around you. In fact the one thing that has always surprised me is right out in front of you is a very high pressure gas line, above ground. It is a very lightly built building.

Cable:

No, parts of it are but we have 12 in. reinforced concrete walls on the launcher area.

Swift:

The point I'm saying you can build this thing next door to people without creating a safety issue if you plan it properly.

Cable:

Or you can operate on a third shift. There are not many other people around if you want to do it that way.

Mouring:

Your rocket motor test facilities aren't really all that far away.

Cable:

No, in fact that is what they do with the tests of big motors, they do it around 11 to 12:00 at night and they evacuate very big areas of the base, and say don't come in this area.

Swift:

I guess I don't think we need to worry about this. Remember, one thing about explosives, explosives come in 2 megajoules per pound. So even if you build a gigajoule system you are talking about 500 lb. of explosives.

Cable:

If you've got rotating machinery, if they get loose, they can be a problem.

Swift:

That is what I was thinking, dirt is the cheapest way of protecting people. But even rotating machinery, if you put it in an area where there is 20 to 30 ft of dirt to get through, it is not going to get through. Now you can wreck your facility if a big piece of rotating machinery goes bad, or if we should blow the center piece out of the high pressure section of a 2 stage light gas gun, you can just tear the facility up. But you keep people out of the facility when it is a danger state. You can build it so the facility next door will hardly notice that something is going on.

Mouring:

Does that mean dirt coverage?

Cable:

Yes, concrete wall and then dirt coverage, somewhere for the gases to vent out where they won't do anybody harm or equipment harm.

Swift:

Around here it is going to be a little bit more expensive, because you can't go down because you'll get water problems so you might want to go up and make a mound but 100 dump truck loads of dirt makes a big pile of dirt.

Mouring:

I think you want to stay horizontal though just for servicing.

Cable:

Servicing a vertical gun, which is going to be of the length we're talking about, could be a problem.

Swift:

By the way, there is one ten stories deep at the University of Texas, and the facility we are considering is going to be longer than that. This whole facility is probably going to be on the order 2000 ft long. So imagine a 2000-ft pit with enough width so we can work in it.

Cable:

When you work on something and you drop your hammer, you might have to go 1000 ft to pick it up. You have to watch out for the guy down below you all the time.

Mouring:

What is the best thinking of the size of this footprint?

Swift:

We have talked about 200 m for the gun, and no one is going to beat Bill Weldon's calculation there (i.e. shorter length). So you have 200 m for the gun. I can't imagine building a facility like this to do external ballistics, flight testing, of one form or another, without making it a kilometer long. Already you have a 1000 ft and you don't have a lot of excess distance for one of your tests.

Cable:

With the size of the model that we use, we usually like 3 oscillations down the range for aerodynamic tests.

Swift:

And that length is going right back up.

Cable:

It is going back up with a bigger model.

I would think that a kilometer is a minimum. Now, if you're going to recover the model, we would want 10 times the launch tube length. The launch tube length is 180 m so that is 1.8 km to catch the model. So we are talking about 3 km plus. To my way of thinking, anything but horizontal is nonsense. This would be one of the deepest holes that has ever been dug and by far the biggest in diameter, if we try to put this thing underground. It would mean that it would exceed the Empire State building by a great deal if we try to go up.

Mouring:

I think we settled on the horizontal idea.

You're talking in range of 3 to 4 km for overall length.

Swift:

At the very minimum, don't point this at something that is not going to be convenient to move.

Cable:

There is no reason that the recovery part could not be out over the water.

Swift:

Well, that would be a pain. The recovery will need a tube with portions that have to be at least pretty straight. So you're going to have under water piles to support it, etc.

Cable:

That may be a problem with setting it as close to the ocean as you are, maintaining the stability of the range itself.

Swift:

Oh, that is a good point, the geological stability of where you go. But, the reason I'm thinking about this is that the world's largest strain gage is on the campus of Stanford University and it is called Stanford Linear Accelerator. It is 3-miles long, an eighth of an inch in diameter, and it has to maintain a clear line of sight down it. It goes across the San Andreas fault, and that has created some very severe engineering problems.

Mouring:

So we can go on record, I can start looking for a place 3 or 4 km long and probably 100 m wide or something like that.

Swift:

The guns and ranges tend to go into very long slender buildings. Huge aspect ratio buildings.

Cable:

Yes, and they are a problem to keep aligned too.

Swift:

By the way, this becomes very, very serious.

For open air ranges, we came up with a very neat method of keeping beautiful atmospheric and dimensional control. You build a cheap building and put a cheap air conditioner in it, and you build inside the cheap building a second building and put a good air conditioner in that. In the two buildings, maintain a $5^\circ \pm 1^\circ$ temperature differential.

Cable:

I have got to think the cost of tunneling vertically has got to be higher than everything else. Probably the cheapest to put it above ground and put some banks around it.

Swift:

Well you might want to make a little mountain or a hill to cover critical areas, electric guns and 2-stage light gas guns. Critical areas should be massively protected, and the design criterion should be that no particle leaves the building under any circumstance.

Mouring:

With these kinds of velocities, if there is any kind of material with any substance in it at all and it should get loose, it's going to be a terribly lethal thing.

Swift:

We have some design criteria for ranges which pretty well guarantee keeping the model in the range.

QUESTION 7

Cable:

The next question I would prefer to address is number 7 which is what prototype or subscale tests/R&D should be done prior to any commitment to design and construct such facility? I think a whole lot. Certainly, the electro-magnetic launcher needs to be proven to be able to do what this facility is supposed to do.

Swift:

The launcher in general, I would think a scale prototype of the launcher demonstrated and exercised to the point where you become really convinced that it really works. For any size here, it is going to at least one scaled prototype before you attempt to build a full scale one.

Cable:

I guess I had some concern about one of the items, I think it was the distributed energy gun. They were saying what they wanted to do was to make it in a series of segments with a little space between them. Now, my experience with joints in launch tubes is that anything at high speeds can be a real pain.

Swift:

We learned a lot about making joints but we've learned making joints in homogeneous steel which is both very stiff and very tough. Now my hat has always been off to the electric gun field in that they have been able to accomplish much of anything with the structure that they have for a barrel. We have a hard enough time in homogeneous steel making barrels that are effective, and they have to do it with this complicated mix of conductors and insulators.

Cable:

So we think there ought to be subscale tests of these two launcher concepts.

Swift:

Whatever concept is chosen, there ought to be at least one subscale test. That can be a very, very useful facility in itself.

Cable:

What I would like to say is that if you're having a launcher where you're going to have, say 10 segments in it, it isn't going to be enough just to test the 2 lowest speed segments. You need to really test the higher speed ones. Maybe you need to stick it on the end of a light gas gun to do that unless you want to build the whole facility.

One thought I had on handling the aerodynamic fly off was to curve your track, and I think that concept ought to be checked out. What I was going to do was try to predict what the flight path would be and make the track follow that flight path.

Swift:

Isn't that specific for every model?

Cable:

Yes, that is why I say you need to have a steerable track. I'm going to predict it in advance. I'm not going to try to steer it as you go into motion like a captive trajectory test. I think you could maybe get within 50 percent and it would be still working. You don't have to match it exactly.

Swift:

Have you looked into the ramification of this, like how far you would have to turn, because you're probably going to want to also steer the tankage. Now we might run the track down the middle of the tankage and steer the tankage and put articulated joints in the tanks.

Cable:

It is either that way or you have a bell shaped tank.

Swift:

On the steering of the tankage, if you did it strictly horizontally, the tanks can be mounted on cross rails, and at first it is going to have a large radius of curvature without much in the way of an articulation in the joint in between each tank. Tanks always come in segments. We build an articulating seal between each tank and mount these things on cross joints. I have never heard of that before but it sounds absolutely intriguing. We are probably talking about a turn of 50 ft or so in the length of the range. Like I said, we can't be talking about the model making a U-turn in this facility, so we're talking about a displacement of 50 or 60 ft, and that fits well within our 100 m wide footprint.

Cable:

So that concept ought to be checked out.

Swift:

You always turn in one direction and it will always turn horizontally.

Piekotowski:

What about some experiments where models were mounted in sabots and then flown and try to recover them? Is that a feasible concept for the kind of models we're talking about?

Swift:

That would go well with the G-range at AEDC.

Piekotowski:

That's something you could do right away without much modification. I think that we will find that the package weights being talked about are way out of line.

Swift:

We've already assumed that we would build an 8-in. gun or a 9-in. gun, as opposed to an 18-in. gun. I think we can scale the size of the overall experiment to that, and we have to do that for a range because if we have an 18-in.

gun range, then we probably ought to be talking about 12,000 to 15,000 ft of free flight.

Cable:

The model and sabot is certainly an item, especially for these things where you are trying to pull them along by lugs sticking out of the side and the problems associated with gas going down passages.

Swift:

Do we feel strongly enough to state as a committee that, unless other groups deem the 11 km/s to be a vital requirement for this facility, they consider dropping EML and consider replacing it with 2 stage light gas gun technology from the point of view of managing risk?

Cable:

I think we can certainly do that, I was going to get to that a little later.

Swift:

We can't do quite as well as an electric gun because an electric gun can get down around a piezometric ratio of about 2, and we are probably going to work up around 3. But we are only going to be like 3 halfs the acceleration of an EML.

Piekotowski:

To get velocities on the order of 6 km/s, I'm not sure that we are providing enough push.

Swift:

The point here is that by the time we get to the size that they are talking about, we're down in the ball park of the acceleration that they are talking about.

Cable:

We would be down to 50,000 g, or something like that.

Swift:

One thing that was very interesting, when Weldon pushed them about the 11 km/s, about going up in g's so we can use the same length facility, he said he encountered little or no resistance. He pushed and they said O.K., they didn't resist him at all.

Piekotowski:

I think there is a feeling in NASA that they would like to have some place that they could test at 11 km/s so that they can test for orbital debris.

QUESTION 8

Cable:

Question number 8. Is it possible or practical to have a tracked and possibly compression tube deceleration and/or recovery system for nonsymmetrical models such as winged bodies?

It is, I think, going to be real difficult.

Swift:

I think it is yes, if you are willing to sting them to a slug. I think it is definitely possible.

You can launch them out of the sabot and then have an aerodynamic separator on the sabot. That's done all the time.

Cable:

This is another item for question 7. Should recovery methods be a subject for subscale tests?

Piekotowski:

Because of the different gases, you almost have to have a spring sabot. Some of these gases are going to be very light, aerodynamically, and they are not going to do much to assist sabot separation.

Swift:

He has a point. When we have a mean free path of 4 in., we are not going to rely on aerodynamic separation. I was going to make another suggestion. We are now doing progressively more and more by putting very, very light rifling in tubes with extremely low pitch. It was started years ago, I understand, at AEDC for rotating models so they wouldn't fly away, even when they have aerodynamic lift. We are using it for centripetal sabot separation, and it's been working like a champ. So where you can allow the model to roll, I would roll the model and use centripetal separation. If you have air in the tank, you can use air too. But your point is well taken, you are not going to be able to do it with aerodynamic separation.

Cable:

I think Andy Piekotowski said something about the need to check out launcher and model-sabot separation. The other I guess is the possibility of using the curved track concept. So you can curve the track to try to keep it under control and then at the entrance to the recovery tube, and as long as you've got enough piston at the back, you'll bring it to rest. If not, you may have to have something that flips it over to a non-lifting position.

Swift:

Now I guess that is a question. Do we kill the pressure recovery system if we curve the track?

Cable:

No, I don't think so.

Swift:

Maybe you can swing the recovery tube back.

So a recovery tube and the last few sections stay pointing parallel, and they simply displace. Then we would put the curve in the test section where we're putting the model.

Cable:

You have to ask yourself how much do you really want to recover these non-symmetrical models because it will really cost you.

Swift:

The other thing of course is we may be able to simply sting the model sufficiently sturdily and put a limitation on the pressure they operate in the range and we sting the model and fly the model at angle of attack. If they want angle of attack, we set angle of attack in, and we fly the model at that angle of attack.

Cable:

If you have a high pressure and a high angle of attack, I don't think there is anyway you're going to hold it on the sting.

Swift:

But again, what you do is you put on the range a product of angle of attack and pressure and velocity which is not to be exceeded.

Piekotowski:

Well, that is going to be a big factor for angle of attack. It is going to be a majority of time.

Swift:

If you support the model at the center of gravity with a sting, then the angle of attack becomes a secondary issue.

Cable:

Yes, but it is going to want to oscillate if it is lifting. It is still going to need to try to accelerate in order to move.

Question nine I left out of our consideration, it was to do with both concepts of the rail gun.

QUESTION 10

Cable:

Question ten. Can a model/sabot combination for perhaps a boundary layer/transition experiment be released in a manner such that the model (optically smooth for experimental purposes) will not be damaged such as to preclude valid data acquisition?

I think the answer to that is if we plan a tracked mode, you don't have to release it. We have been able to maintain smooth surfaces at AEDC in a track mode, so I think the answer to that is yes.

QUESTION 11

Cable:

Question eleven. Are there experiments which place constraints or demands upon such a facility which could or would make it impractical from the standpoints of physical size or operation aspects?

Yes, that is the high lift bodies at angle of attack and high pressure.

Swift:

There is a famous story that they tell up at the very first of the spark ranges at BRL where they flew a model with a canard and they set max lift on the canard and fired it out of the gun. In the pictures, it got higher and higher in the field of view until it was half way down the range, and it passed out of the pictures. They went down and looked at the roof of the range and there was a hole. When they fired the model, it turned and went out through the hole in the roof. They don't know where it went after that.

Cable:

They were shooting lifting bodies at Ames so they tried to get their boss to sign off on shooting through the windows of the range.

Swift:

How powerful is this technique of rolling the model so it flies towards the center?

Cable:

It is quite powerful. That is another technique that could be done.

QUESTION 16

Cable:

I'm dropping off to question 16 now. What are the major safety concerns of such a facility and how can they be best addressed? To what degree will safety concerns adversely affect the cost of such a facility?

Swift:

If safety can be limited to flying particles, then we almost covered that.

Cable:

Yes, we have covered that before with the launcher power supply failure. I think if you put up a big enough barricade you are alright.

Swift:

There are all sorts of electrical problems that I think the EML people talk about. You've got multi tens of kilovolts, multi-mega ampere pulses running around loose, and you can fry somebody a long way off.

Cable:

Launcher and power supply failure can be contained. Electrical pulses were not addressed.

Swift:

We would recommend concrete and dirt as good methods for containing these.

Cable:

I know when I visited UT/Austin they were concerned about the pulses that get into the conduits and things, and pulling nails out of walls, and things like that so this facility can probably do it. You would have to watch it if you had false steel teeth or maybe even gold teeth would be even worse.

Swift:

I always heard it was a hot electromagnetic environment when your wedding ring heats up. When you feel your wedding ring heating up you are probably getting more electromagnetic environment than you want to be in.

QUESTION 17

Cable:

Question 17. What are the major concerns regarding siting such a facility? I guess I would say you need a fairly remote site. Access to finding electricity.

Swift:

Close access to rail because a lot of this stuff is going to have to come in by rail.

Cable:

Yes, to rail or large transport.

Swift:

Ability to achieve geological stability. I hadn't thought about AEDC but that area has a lot going for it.

Cable:

They have got a bid for the super collider to be sited just a little bit to the north of AEDC.

O.K. the other thought is the availability of the right sort of manpower.

Mouring:

Going back to this electrical thing, we will not have that much of a demand. Isn't it stored?

Swift:

You probably will not have much of a demand. Let's say this, there are places where you might have real problems with electric power because there are places you couldn't get a megawatt. Now if you store a gigajoule at a megawatt, it is going to take you 1000 seconds, now that is 20 minutes. So you probably want several megawatts. As long as don't pick a notably bad spot for electricity, you are probably O.K. Conventional main power, as long you are able to have your sub-station you are home free. It will probably need a small sub-station.

Mouring:

What are the electrical characteristics of that sub-station?

Swift:

Four-forty volts at a good many 100 amps. You might use 880 volts, but I think 440 will probably be it.

Mouring:

From an operational standpoint, I think that you're talking about a 3- or 4-km long facility. You want to make sure that you have very easy access to a paved road.

Swift:

That would be part of the facility. Just build that right into it.

QUESTION 18

Cable:

Question eighteen is, what if any, are the pitfalls associated with model launch, model release methodology, model oscillation, and divergence from the flight corridor?

Swift:

One thing about the track, if it works it will not diverge from the flight corridor.

Cable:

To me there are center-of-gravity and inertia constraints.

Swift:

I think one of the questions we have to answer before we leave here tomorrow is do we recommend that we build a single purpose track facility, or do we build a facility like range-G, where the track folds out the way and that is also free flight, because it is going to be of a gigantic diameter if you have to accommodate free flight. Otherwise this kind of thing could go down a 4-ft diameter pipe, and boy will it be a difference in cost because it may have to go down almost like a 40-ft diameter pipe if it is going to be free flight.

Cable:

Once again it depends on how much aerodynamic data do they want; how much free flight do they want.

For the length, I can't imagine building under a kilometer.

QUESTION 22

Cable:

Question number 22, is it desirable or feasible to utilize a 1 or 2 stage light gas gun to accelerate models prior to entering the EML launch tube in order to decrease/minimize rail wear. Will the g-loads associated with the light gas gun destroy the model? I think it's a good idea.

Swift:

I think we can say, in general, the g-loads from a 2 stage light gas gun are somewhat larger than the g-loads from EML but they are comparable.

Cable:

Probably 1 1/2 times the g-loads of EML. Now, I don't think rail wear is a problem. My experience in track work is the rails don't wear. The model wears some. In EML, rails erode from arcs.

Swift:

It (EML rail erosion) is not a wear process; it is an erosion process. But it is very serious.

Cable:

Will the g-loads associated with light gas guns destroy the model? No, not if you pick your condition right. If we try for 6 km/s with the light gas gun and add 2 km/s for the EML, they are probably comparable.

Swift:

I think that is a good point. In fact that may be a compromise. I talked about this to Witcofski, that is to build the thing with a light gas gun and build space into it for an EML velocity booster. If the EML technology comes along, is demonstratable, and really works, you then can go to super light gas gun velocities. If it doesn't, you have still got a facility. The only other conservative approach is to put this whole thing in abeyance and wait very patiently for the ultimate shakeout from the weapons EML program, and you may have a design which you can copy and scale or you may come to conclusion that it can't be done. But if you depend upon the EML and go ahead and commit to this thing and get well down the path, you are risking coming up with a terrible embarrassment.

Cable:

That is the Los Alamos approach, to use the light gas gun to go as fast as they can go, then add an EML on to the front and get a kilometer or two per second more.

They will add another stage on and keep on building it up. Then you keep the advantage of the light gas gun and try to utilize the EML. EML started from zero velocity, and I think that everyone knows that you have to hit the rails at some velocity to avoid arcing and rail damage. So why not start them at a pretty high velocity?

Swift:

I think you now have a proposal to start at 60 m/s.

QUESTION 23

Cable:

Question 23, what is the largest bore feasibility for the launcher and why?

Swift:

To cover that I would say 9 in., energy constraint with realistic models.

Cable:

It is obviously cost and manufacturing capability, and you know that there are 16-in. naval guns.

Swift:

We're just now getting ready to build a 22-in. gun. As a matter of fact, it is a free piston gas compressor for NASA-Langley.

Cable:

That is not a very high pressure gun?

Swift:

Thirty-five thousand psi. That is getting up there.

Mouring:

Of what material would this be constructed?

Swift:

Probably the only thing that is feasible with those sizes is chrome moly steel. There are some fancy classy steels around which have some advantages over chrome moly steel, but when it comes to huge sections of that sort, I think chrome moly is the only act in town. There haven't been any naval guns built since the forties.

Cable:

No, but Watervliet Arsenal, I think, still has the capability to build a 16-in. gun.

Swift:

But they're not really big enough. No, because we are talking about a 9-in. launch tube, we're talking about like a 30-in. bore pump tube, and it is not clear that can be done. I'm pretty sure that it can be done by hook or by crook, but it is not abundantly obvious.

But its going to have to be not as high as an artillery piece, but in the order of an artillery piece. We have to get a piston going at least 1300 to 1400-ft/s. By the way, those pistons are rather non-trival devices, too.

Cable:

And if you're going to lift the rest of the thing around, you've got past the stage of 2 guys lifting the piston, anyway. You might as well build the equipment to do it.

Swift:

I really want to, for the first time, consider a reusable piston.

Cable:

People have used the reusable pistons or reusable parts. NOL (Naval Ordinance Lab) has.

Piekotowski:

Do we want to expand any more on question 23? What is the largest bore feasible for the launcher and why?

Cable:

I would say cost and manufacturing capability.

Swift:

Yes, but I think we should emphasize that this isn't just a lightly given answer because the costs rise at least with the cube of the dimensions. Once costs start to become prohibitive, it becomes impossibly prohibitive very quickly.

Cable:

But I've noticed in their (U. Texas) cost estimate, Langley was going to provide the site, they were going to provide the range, and all those sort of things. That is why they could get theirs down to a mere 50 million dollars or so.

Yes, I think there are innovative ways you might be able to do this. You get the biggest forging you've got, and then you wire wind it or cast it in concrete or something to it to keep it together. Again, you can't really give a very good answer until you've got a pretty good idea of the concept.

The other thing I was going to look at is this page (see Appendix E) of Aeroballistic Range Technology where they sort of describe the facility. They talked about the g's and the megajoules and the 18 in. (46 cm) bore and being able to pump down to 2 x 10 to the minus 4 millimeters for rarified flow studies. I assume that would be a fairly small section of this range.

Swift:

We might want to comment by the way and give them some warnings about the valves. By the time we get valves scaled up to the size required by this facility, how fast can they open?

Cable:

At the best I think the time will go up with size. Fig. R-QA; Other Issues.

Swift:

You said 20 milliseconds for 5 inches?

Cable:

Seven inch. Like 3 milliseconds per inch. So maybe 50 milliseconds for a 15 inch valve.

Swift:

The other thing is the gun. Both electromagnetic and light gas guns belch out materials that will produce virtual leaks. Those materials could be a real mess for getting to these very high vacuums. One caveat, I think, is the chamber where you do your evacuation will never be used to capture the sabot because at these kinds of velocities even at ordinary light gas gun velocities you vaporize a lot of your plastic sabot components when you catch them. When you vaporize that material, it plates out as soot on the inside of the range, and once the range is well sooted it has got to be steam cleaned and then probably baked before you can ever hope to get to those kind of vacuum levels. So 2 x 10 to the minus 4 torr levels are very doable levels to get to, but you need a very clean facility to get them. You can't get them in a sloppy dirty facility with the best of pumping capability.

Cable:

We have a little range where we do that down to a micron or so.

Swift:

This is way below a micron, this 10 to the minus 4 mm.

Piekotowski:

It is 10 to the minus 4 mm, and this chamber would be a secondary chamber.

Swift:

So that is only a tenth of a micron. That is reasonably crude as vacuums go.

Cable:

There were certain issues we were to address. Review the following issues and identify and review others that are appropriate.

a. Test chamber design - length, diameter, compartmentation, pressure range, track configuration, measurement stations.

I think we have sort of covered that.

Swift:

I would make one comment, the smaller diameter we can make the vacuum tankage the easier it is going to be to do really classy external observations of the model because we can get the equipment in a shirt sleeve environment up closer to the trajectory. If we do decide to go for a free flight range of some 40 ft in diameter, this means that you either have to move the instrumentation inside and run the instrumentation within the range, which is very painful, or you're going to have to be looking from 20 ft away. That is also very painful.

Cable:

We think the movable track concept with the movable range attachment is probably something that ought to be explored.

Swift:

I think the real thing here is a decision has to be made early on, do we want to build a facility capable of free flight or don't we, and it changes by an order of magnitude of what happens to the range. I think we can take as a given that a track is a requirement. Now do we only build a track, or is free flight also required?

Cable:

Something we haven't addressed is test techniques, and I think you ask the question is free flight really necessary. I think you need all the standard measurements to get velocity, pressure, and temperature; and I would like to see as many x-ray stations and laser stations as we can fit in there to get information out.

Mouring:

What about scattered x-rays so far as being a potential environmental problem?

Swift:

No problem. Here is the situation. If you put a piece of regular film up and fire one of those x-rays at it, you wouldn't expose it. You have got to use intensifier screens even to detect the pulse. The pulse dose rate is enormous. If you got it for even a second you would be fired to a cinder, but you get it only for a few nanoseconds. As a result, you have to use fancy techniques even to record it on film, and one dental x-ray is probably 25,000 flashes of this equipment. Relative to the x-ray you have taken, one dental x-ray is a lifetime of standing around these things close by, and these things are operated typically when you are away from them. The only time you get close to one of these things is when you are checking them out. You are in the control room and you're behind concrete and many feet away and things like that when these things fire off.

Cable:

You just need to close off the area when you're checking them.

Piekotowski:

Typically, most of these have a fairly small cone in which they produce radiation too, and if it is not directed at you, you're okay.

Cable:

If you have pulsed lasers, you have more problems if you get in line with them, but if you have some cardboard or something in the way, you are safe.

Swift:

One thing, you will have to wear film badges, but that is just life.

Cable:

Maybe, it depends on how much exposure you are going to get. The other thing that is not mentioned here is the triggering of these instrumentation devices is always the fundamental problem.

Swift:

It sure is. I thought that was a neat idea that Jerry Parker came up with. I was hoping he was going to come up with something cute when I asked that question on how he triggers to get his pictures of the Taylor instablity.

Cable:

What we use are piston probes or things like that to set things off. Once you've got the light gas gun in motion it is usually pretty repeatable. It is getting it started that's not repeatable.

Piekotowski:

In a free flight or a track range, once they get away from the launcher environment, there are all kinds of things you can use.

Swift:

Yes, a laser or a pin diode are fine.

Cable:

O.K., model-sabot separation techniques we've talked some about that. Deceleration techniques we talked about. Launch techniques.

Swift:

Do we want to summarize all that we had to say here?

Cable:

What I think we said here is if you stick to 6 to 8 km/s, why bother with an EML when you can do it with a light gas gun.

Swift:

And we can say another thing. If you are going to build an EML, build the EML as a velocity amplifier on the end of a light gas gun, and that way you still have a useful facility if the EML technology doesn't come on line in time to cover you.

Cable:

That EML is to enhance velocity. Identify R&D studies, we have done that and documented for final report.

MODEL SIZE LIMITATIONS - 1

- 18 IN. BORE DIA. TOO LARGE FOR 22 LB. MODEL
- 8 - 9 IN. BORE DIA. IS MORE REASONABLE
- 220 LB. MODELS MORE SUITABLE FOR 18 IN. BORE

4/10/89 WKSHP43

MODEL SIZE LIMITATIONS - 2

FACTORS

- MATERIALS
- LAUNCH LOADS
- DISPERSION - Decreases with Model Size
- RECOVERY/IMPACT
- SABOT DESIGN - Force Application to Model

6/15/88 WKPSHP16

MODEL DECELERATION - 3

- GAS DYNAMIC DECELERATION RECOMMENDED WHERE TRACK CAN BE USED

- FOAM/FLUID RECOVERY IS A REMOTE POSSIBILITY FOR FREE-FLIGHT MODEL

6/15/88 WKSHP17

COAXIAL LAUNCHER - EFFECTS ON MODEL/SABOT - 4

- SIMILAR TO RAIL GUN

- CONCERN ABOUT CRYO-COOLING OF SABOT - MODEL - GUN BORE

6/15/88 WKSHP18

CURRENT TESTING OF INSTRUMENTED MODELS 5

- TESTS OF SENSORS AND TELEMETRY CONDUCTED AT AEDC

  Max Acceleration = 10^5 G'S

- EMP TESTING COULD BE ADDED -OR CONDUCTED SEPARATELY
- HARRY DIAMOND LAB HAS FUSE ACCELERATION TEST FACILITY IN OPERATION -

  TAILORED ACCELERATION PROFILES AVAILABLE

6/15/88 WKSHP19

OPERATIONAL SAFETY/COST 6

- HORIZONTAL OPERATION VIRTUALLY MANDATORY

  RANGE LENGTH :

GUN	200m
FLIGHT	1000m
RECOVERY	2000m
TOTAL	3200m

- BURY DANGEROUS COMPONENTS

6/15/88 WKSHP20

PROTOTYPE SUBSCALE TEST 7

- SUBSCALE TESTING OF LAUNCHER -
  - MANDATORY FOR EML
  - ADVISABLE FOR L.G.G.
- MODEL/SABOT TESTING AT AEDC
- DECELERATION/RECOVERY
- TEST REQUIRED FOR CURVED TRACK SCHEME FOR PROMOTING ASYMMETRICAL MODEL TESTING

6/15/88 WKSHP21

TRACK AND RECOVERY OF NON-SYMMETRICAL MODELS 8

- FEASIBLE IF MODELS ARE SUPPORTED AHEAD OF BORE-FITTING SLUG
  - WAKE STUDIES PRECLUDED
- CURVED TRACK MAY ACCOMMODATE LIFT LOADS

6/16/88 WKSHP22

BOUNDARY LAYER TRANSITION -10

- FEASIBLE IN TRACK MODE

6/16/88 WKSHP23

EXPERIMENTAL CONSTRAINTS -11

- LIMITATIONS ON HIGH LIFT/
  HIGH ANGLE OF ATTACK/
  HIGH ATMOSPHERIC PRESSURE/
  HIGH VELOCITY

6/16/88 WKSHP24

MAJOR SAFETY CONCERNS -16

- RELEASE OF FRAGMENTS FROM FACILITY
  - LAUNCHER/POWER SUPPLY FAILURE
  - MODEL IMPACT
- ELECTRICAL - MAGNETIC EFFECTS ON SURROUNDINGS
- BLAST

6/16/88 WKSHP25

SITING CONCERNS -17

- REMOTE PREFERABLE
- ACCESS TO:
  - RAIL OR BARGE
  - HIGHWAYS
  - ELECTRICITY
- GEOLOGIC/FOUNDATION STABILITY
- EXPERIENCED MANPOWER

6/16/88 WKSHP26

MODEL DESIGN PITFALLS -18

- C.G. / INERTIA CONSTRAINTS
- ANGLE OF ATTACK LIMITATIONS
- PACKAGE ACCELERATION STRENGTH

6/16/88 WKSHP27

LIGHT-GAS-GUN PRE-ACCELERATOR -22

- L.G.G. ACCELERATION LEVELS ~ 1.5 TIMES HIGHER THAN E.M.L. OPERATING AT THEORETICAL LEVELS
- RECOMMEND L.G.G. PRE-ACCELERATOR TO VEL. = 6-7 KM/S
- E.M.L. VELOCITY MAGNIFIER USED IF TECHNOLOGY DEVELOPS

6/16/88 WKSHP28

LARGEST FEASIBLE BORE -23

- 9 TO 10 INCHES SET BY:
  - KE CONSTRAINTS
  - MANUFACTURING CAPABILITIES

6/16/88 WKSHP29

OTHER ISSUES

- FAST-OPENING VALVE LIMIT
  - 3msec/inch of Aperture
- HIGH VACUUM REQUIRES SPECIAL CLEAN RANGE TANK
- DON'T SKIMP ON CONVENTIONAL RANGE INSTRUMENTATION
  - Triggering always creates special problems

6/16/88 WKSHP30

Fig. RQ-A

APPENDIX E

PORTIONS OF THE INFORMATION PACKAGE SENT TO THE WORKSHOP PARTICIPANTS

* Goals of the workshop
* Instructions to the individual working groups
* Background information on the proposed facility
* A list of questions posed to the participants

Goals of the Advanced Hypervelocity Aerophysics Facility Workshop

The purpose of this workshop is to bring together experts in the fields of aerodynamics/aerothermodynamics, electromagnetic launcher (EML) technology, ballistic range technology, and instrumentation technology to critically assess the potential for the development of an advanced hypervelocity aerophysics research facility capable of launching large, complex, instrumented models into a preselected environment at velocities and densities representative of Earth and planetary entry flight conditions. If the endeavor appears to be feasible, an outline of the R&D efforts necessary to attain technical readiness to proceed is desired.

Experts in EML technology will be requested to review the state of the art of EML and to critique potential concepts for an advanced range facility. It is desired that the R&D requirements associated with the facility be defined and prioritized.

Experts in aerodynamics/aerothermodynamics will be requested to define current deficiencies in hypersonic knowledge and suggest experiments which might be conducted in such a facility to resolve those deficiencies. Definition of those experiments and the measurements to be made will be done in concert with experts in instrumentation to assure that instrumentation and data acquisition requirements (both onboard the model and external) are defined.

Experts in instrumentation will be requested to define the R&D requirements necessary to develop the onboard and remote measurement systems for the range and the models.

Experts in ballistic range technology will be requested to review the current technology with respect to test chamber design and test techniques and to recommend and define the studies needed to design an advanced range with appropriate test capabilities.

The workshop will be conducted with the four groups of experts studying concurrently the previously mentioned areas of technology. Each group will have a chairman who will be responsible for the conduct of the session, the preliminary session reports, and the documentation of the session findings and recommendations. There is obviously a need for certain groups to confer with one another because of the interdependency between them. Efforts will be made to schedule this cross communication during the workshop session. It is tentatively planned to have the aerothermodynamics and instrumen-tation groups to meet jointly for the major portion of the first work session. In addition, each group will be made up of a mix of experts in the various technology disciplines which are to be considered.

The findings of the individual groups will be prepared in writing prior to the end of the workshop. The deliberations and plenary session reports of the individual groups will also be recorded electronically unless otherwise requested.

INSTRUCTIONS TO INDIVIDUAL WORKING GROUPS

Experiment Identification and Design

Many areas in the science of hypervelocity aerodynamics-aerothermodynamics have been identified as areas that cannot be properly addressed with current ground facilities. No one facility or flight test technique can address all of them. We would like to identify those areas that can be properly addressed in an aeroballistic facility where models on the order of 2-feet long containing onboard measurement systems, can be tested. Several areas were identified by the CFD workshop at Ames in July 1987 as being critical issues above Mach 6. They are shown in figure 1 in the background material. In addition to those issues, are those associated with hypervelocity entry into planetary atmospheres and Earth entry from planetary return. Velocities in this area range from 30,000 to 44,000 ft/s. At these velocities radiation heating becomes a major concern. The types of experiments required to help resolve these issues need to be identified, defined, and quantified. The types of measurements to be made must also be identified.

In addition to experiment definition, another factor that needs to be examined is model scale. Although the major advantage of the proposed facility is performance (increased velocity and true enthalpy and the use of models large enough for onboard instrumentation), are there additional advantages in having larger models? One obvious advantage is that free-stream Reynolds numbers based on model length can be increased by five to eight times.

Outlined below are several tasks for this workshop session:

1. Review the issues listed in figure 1 of the background information and identify other (planetary entry etc.,) that are appropriate, and determine if a relevant experiment can be designed for the hypervelocity range.

2. Define each experiment identified as to the appropriate techniques, models, and specific measurements to be made, both onboard and from stationary sites.

3. Identify design studies that are necessary to more clearly define the experiments, the techniques, and measurements.

4. Document the results of the above tasks along with any pertinent recommendations that resulted, for integration into a final workshop report.

In preparation for this workshop session it is desirable that you identify and define experiments in the areas of aerodynamics and aerothermodynamics prior to attending. As an aid in defining an experiment, some examples of model sizes (compatible with the net kinetic launch energy) that have been worked out to date are listed below:

(a) A 36-inch long, 6.25 degree aluminum cone with a launch velocity of 16,135 ft/s.

(b) A 27-inch long, 6.25 degree aluminum cone with a launch velocity of 18,233 ft/s.

(c) A 10-inch diameter, blunt body with a launch velocity of 31,000 ft/s.

Measurement-Data Systems

The onboard model measurement system must be miniaturized to fit within the model volume and must have small mass. It must also have extremely fast response (because of the short test times) and in some cases, high sensitivity. It must be able to perform the signal processing and data collection, storage, and transmission functions in extremely short times. The system must be able to withstand the high launch loads and electromagnetic interference of the launcher. The stationary measurements system must incorporate advanced measurement technology and elements of it should work in concert with the onboard system to provide comprehensive data.

The tasks that would be accomplished during this workshop session are outlined below:

1. Review the measurements (onboard and stationary) identified by the experiment design group.

2. Identify areas where advanced technology will be required to develop the necessary instrumentation.

3. Define the R&D effort to develop specific instrumentation as identified in (2) above.

4. Define the R&D effort required to develop integrated data systems, power, signal processing, multiplexing, storage-retrieval and transmission.

5. Document the results of the above tasks for integration into a final workshop report

EML Technology

The emerging EML technology sponsored by DARPA and the army over the past several years, and, more recently, by the SDIO offers the promise of capability to develop a hypervelocity aerophysics range with greatly increased performance over that of existing ranges. The current R&D effort, however, has focused on weaponry which requires dense payloads to be launched in short distances with corresponding high launch acceleration loads. The requirements of the proposed NASA hypervelocity facility, on the other hand, tend to dictate a very long, large bore launcher with relatively low launch accelerations.

The conceptual study by CEM/UT has produced the only information relating to the applicability of EML technology to a hypervelocity range. With this information as a beginning, several tasks are outlined below:

1. In addition to the concepts discussed in the CEM/UT report, define additional applicable approaches that should be studied.

2. Define the R&D that is needed to determine the most applicable EML concept.

3. Define the R&D that is required to develop the most applicable EML concept to a long, large-bore launcher.

4. Document the responses to the above tasks for inclusion in a final workshop report.

In preparation for this workshop session it is desirable that your critically review the CEM/UT report to gain an insight in to the concepts introduced therein. You may have comments regarding these concepts and you are encouraged to air them, but the main purpose of this session is to arrive by consensus to the most applicable EML concepts.

Aeroballistic Range Technology

The facility as envisioned in the background material would be capable of testing models at velocities ranging from 4,000 ft/s to 45,000 ft/s, depending upon the mass of the model/sabot combination. The launch accelerations would range from 400 to 50,500 g. This represents a design net kinetic energy level of 186 megaJoules. The launch-tube bore is tentatively set at 18 inches, but this is subject to final model size and test requirements. With a bore of this size, models large enough to contain onboard measurement systems could be launched. The facility will have several test compartments separated by fast-acting doors, with the capability to reduce the pressure in at least one of them to 2 x 10^{-4}mm for rarefied flow studies. It is also desired to provide a model deceleration capability. Outlined below are several items to be addressed in this workshop session. With the acknowledgement that current aeroballistic range technology is fairly well advanced, it is desired that this newly proposed facility be addressed with more advanced techniques.

1. Review the following issues and identify and review others that are appropriate.

a. Test chamber design - length, diameter, compartmentation, pressure range, track configuration, measurement stations.

b. Test techniques.

c. Measurement techniques.

d. Model-sabot integration/separation techniques.

e. Deceleration techniques.

f. Launch techniques.

2. Identify the R&D studies required to bring the above design and technology issues to a stage sufficiently mature to initiate design activities.

3. Document the results of the above tasks for inclusion in a final workshop report.

BACKGROUND INFORMATION ON A PROPOSED HYPERVELOCITY AEROPHYSICS RESEARCH FACILITY

OBJECTIVE - The objective of this effort is to establish the feasibility of developing a large hypervelocity aerophysics range facility. The purpose of the facility is to provide the capability to conduct fundamental and applied research on the aerodynamic/aerothermodynamic research on complex models and full-scale vehicle components at velocities and densities representative of hypervelocity flight in Earth or planetary atmospheres.

Justification - There is interest within NASA to increase the scope of hypersonic research in the near future to support sustained hypersonic flight and hypersonic entry technology. Several areas were identified by the NASA Computer Fluid Dynamics (CFD) Workshop at Ames Research Center (ARC) in July 1987 as critical to the advancement of the aerophysics sciences associated with hypervelocity flight, and in need of better definition and understanding. They are listed in figure 1. The Office of Aeronautics and Space Technology (OAST) Hypersonic Research Program envisions that much aerothermodynamic information could be learned from entry research vehicles released from the Space Shuttle, and from new hypersonic propulsion facilities. New ground-based hypersonic aerothermodynamic research facilities will also be needed. Many different kinds of hypersonic facilities have been built to simulate portions of the hypersonic flight regime; however; the ability to produce test flows containing sufficient energy for chemical reactions to occur in the gas medium exists only in part. Shock tunnels and ballistic ranges can simulate portions of the aerothermochemical environment of entry flight, but these facilities are limited to extremely short test times or to small model sizes and limited measurement capability. The emerging electromagnetic launcher (EML) technology offers the promise of developing a hypervelocity test facility capable of conducting research on large (sufficiently large to contain onboard instrumentation), complex models in a real-gas environment here-to-fore not possible. With an EML system, the potential exists to build an aeroballistic facility that can achieve high velocity with large mass over a time period that allows meaningful measurements to be made. Such a facility would permit the study of the aerothermodynamic characteristics of models of advanced Shuttle vehicles, Trans-atmospheric vehicles and Aeromaneuvering Orbital Transfer Vehicles (AOTV) in a real-gas environment, i.e., exact simulation of altitude and velocity. Such a facility would also aid in the verification of advanced computational fluid dynamics codes.

This effort is considered to be a high risk endeavor in every aspect. First, an electromagnetic launcher of the size and capability envisioned has never been built and the feasibility of designing and building one needs to be established. The very high model acceleration environment requires innovative approaches to model and sabot design and onboard instrumentation. The fact that the model will probably not be recovered presents problems in data recovery and model expense that must be solved in unique ways. The feasibility of adequately separating the model and sabot with minimum disturbances must also be studied. Because the model/sabot carrier may be an electrical conductor, and may be heavy, the separation problem may be difficult to solve. Although the above problems make this effort vulnerable to failure, the potential future payoff is high, in that much needed aerothermodynamic test data may be obtained repeatedly in a controlled environment.

Description - The desired envelope of altitude and velocity to be provided by the facility is shown in figure 2 along with the trajectories of several spacecraft, both past and planned. As can be seen on the figure, the envisioned envelope of the facility would include the greater portion of the spacecraft flight environments. The maximum altitude shown appears to be attainable for at least one part of the test section. This would enable some rarefied flow studies, since the mean free path is 10 to 15 cm at this altitude. The maximum velocity would enable studies in planetary entry and return aerophysics. Existing ballistic ranges provide a large portion of this envelope, however, their maximum velocities are lower, and their models are very small.

A sketch of the proposed facility is shown in figure 3. The dimensions shown are somewhat arbitrary since the factors affecting them have yet to be studied in depth. The launch tube bore of 18 inches (46 cm) is the result of a preliminary study of existing model test requirements. More detailed analyses of model test parameters are required to establish the maximum diameter, the final value may be smaller. Additionally, it may not be possible to build an EML with a diameter this large. The test chamber length is a function of model dynamic test requirements and data transmission time. The EML length was chosen as a function of the maximum allowable acceleration for the onboard model instrumentation. Longitudinal accelerations can vary from 400 to 50,500 g, depending on the desired test velocity. The desired performance envelope of the facility is shown in figure 4 and table 1. The output performance of the EML is based on a total 10 kg mass of the model and sabot being accelerated to a test velocity of 6.096 km/sec. This mass excludes the parasite mass of the armature/carrier vehicle for which additional energy must be supplied. The resulting kinetic energy of the model/sabot combination is 186 megaJoules. The curve of figure 4 illustrates the distribution of mass and velocity at the given constant kinetic energy level (186 mJ). If we trade mass for velocity, a smaller model can be tested at very high velocity (up to 13 km/sec for a 2 kg model/sabot combination). Moving to the right of the design point on the curve permits the testing of much larger models at lower velocities. It is envisioned that any other combination of model/sabot mass and velocity could be utilized in the area under the 186 mJ maximum performance curve.

The test flight sequence is shown in figures 5(a) to 5(c). The model-sabot are accelerated in the carrier to the desired velocity in the EML evacuated launch tube. The carrier is electromagnetically decelerated in the last section of the launch tube and the model and sabot pass through a quick-opening valve into a gas-filled separation chamber where the model and sabot are aerodynamically separated and the sabot is stopped at the exit. The model then flies through a quick-opening valve into the main test chamber. During the transit through the main test chamber, both onboard and remote measurements are made. The onboard measurements are either recorded onboard or transmitted via telemetry. At the end of the test chamber the model passes through a quick-opening valve into the deceleration section, where it is decelerated sufficiently to enable recovery of recorded data.

The facility is considered to be a long term research facility designed to provide hypervelocity test capability well into the next century. It is desired that the components be as maintenance-free as possible, and at the same time adaptable to updating and modernization where necessary.

NASA CFD WORKSHOP - ARC, JULY 1987

CRITICAL ISSUES ABOVE M-6

1. BOUNDARY LAYER/SHOCK LAYER CHARACTERISTICS
   - LAMINAR/TRANSITION/TURBULENT
   - GRADIENT EFFECTS (ENTROPY, ETC.)
   - SEPARATION/REATTACHMENT
2. REAL GAS EFFECTS
   - EQUILIBRIUM
   - NONEQUILIBRIUM (CHEMICAL KINETICS, SPECIES, REACTION RATES)
   - FROZEN
   - RADIATION
   - GAS PROPERTIES (VISCOSITY, THERMAL CONDUCTIVITY, ETC.)
3. LOW DENSITY EFFECTS
   - CONTINUUM BOUNDARY (MACH, ALTITUDE)
   - NOSE/LEADING EDGE EFFECTS
   - TRANSITIONAL FLOW MODEL
4. MACH NUMBER EFFECTS
   - COMPRESSIBLE TRANSFORMATION
   - TURBULENCE MODEL/PHYSICS
   - SHEAR LAYER STABILITY AND MIXING
5. WALL EFFECTS (REQ'D IN 1., 2., 3.)
   - COOLING
   - ROUGHNESS
   - CATALYSIS
   - MASS ADDITION (TRANSPIRATION/ABLATION)
6. OTHER
   - COMPLEX GEOMETRIES
   - THERMAL RESPONSE OF VEHICLE STRUCTURE EFFECTS ON FLOW FIELD

Figure 1.- Areas identified as critical to the advancement of the aerophysical sciences.

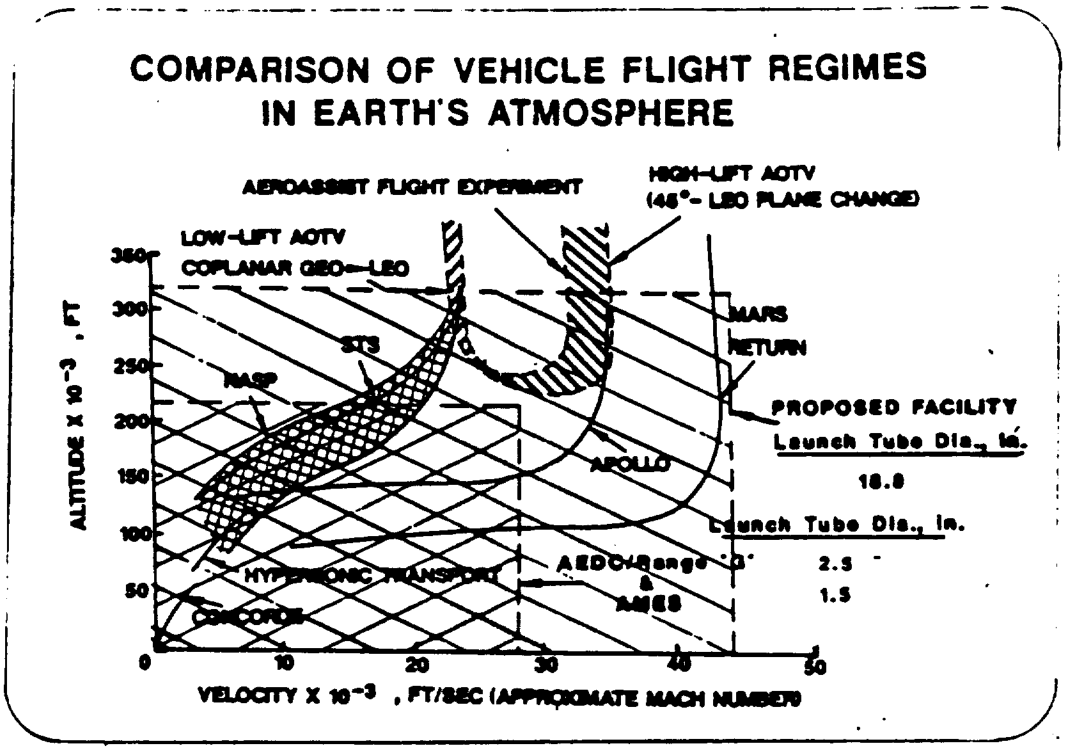


Figure 2.- Desired test capability of the proposed facility.

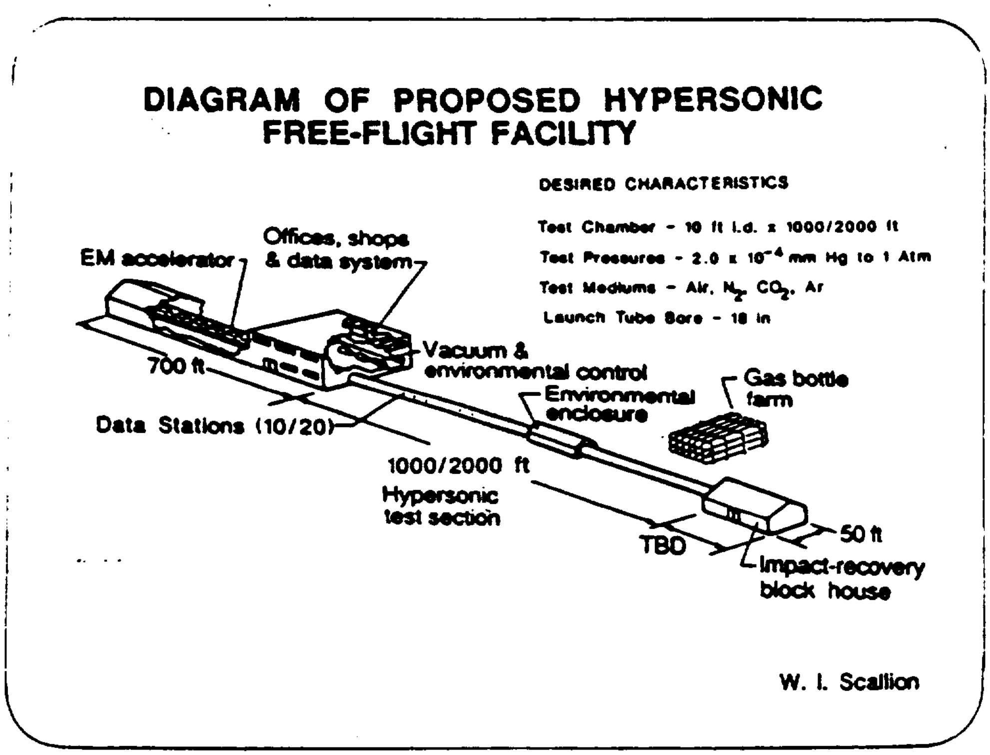


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Figure 3.- Preliminary sketch of the proposed facility.

Table I.- Desired operating envelope of mass and velocity.

HF3 OPERATING ENVELOPE

MASS* KG	MASS* LB	ACCELERATION 'G'	TACC SEC.	VF/S	$V_{KM,S}$	TEST • TIME,S
62.2	137	1601	0.155	8000	2438	0.125
49.1	108	2027	0.138	9000	2743	0.111
39.9	88.0	2500	0.124	10000	3.048	0.100
30.0	66.1	3357	0.107	11587	3.531	0.086
28.0	61.7	3596	0.104	11994	3.655	0.083
26.0	57.3	3873	0.100	12447	3.793	0.080
24.0	52.9	4196	0.096	12955	3.948	0.077
22.0	48.5	4586	0.092	13545	4.128	0.073
20.0	44.1	5045	0.087	14206	4.330	0.070
18.0	39.6	5606	0.083	14974	4.564	0.066
16.0	35.2	6307	0.078	15883	4.841	0.062
14.0	30.8	7207	0.073	16979	5.175	0.058
12.0	26.4	8409	0.067	18340	5.590	0.054
10.0	22.0	10000	0.062	20000	6.096	0.050
8.0	17.6	12613	0.055	22462	6.846	0.044
6.0	13.2	16818	0.0479	25937	7.905	0.038
5.0	11.0	20140	0.044	28383	8.651	0.035
4.0	8.8	25227	0.039	31766	9.682	0.031
3.0	6.6	33566	0.034	36642	11.168	0.027
2.0	4.4	50454	0.028	44924	13.693	0.022

* Mass includes sabot and model
• Based on a 1000 ft test chamber length.

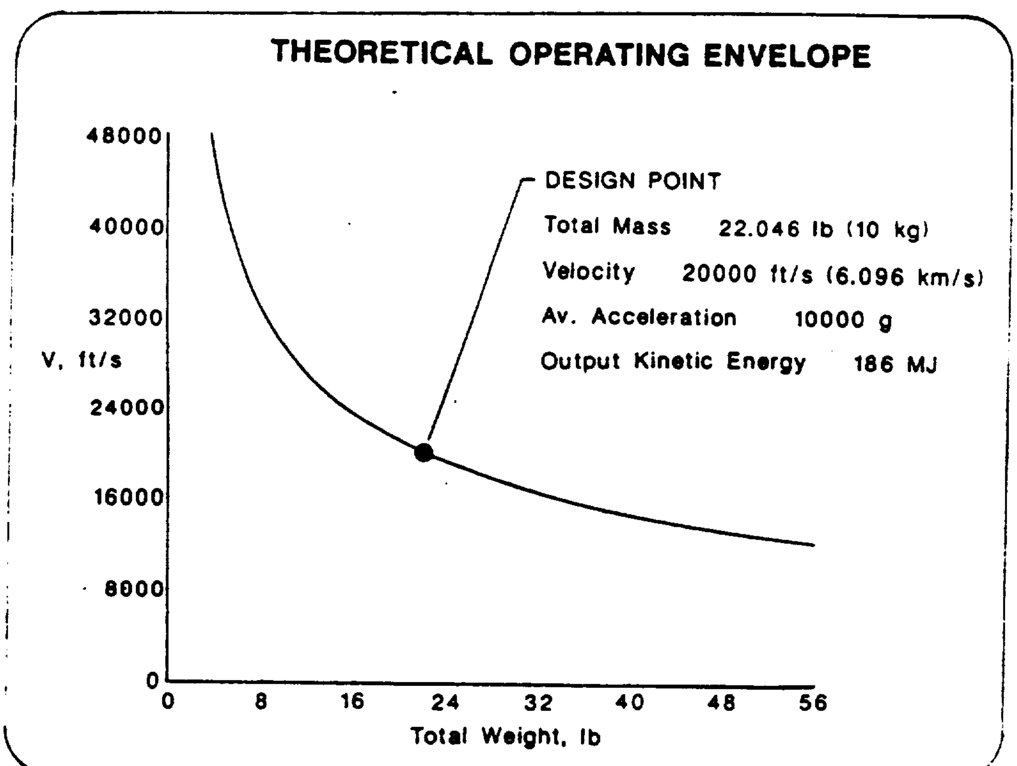
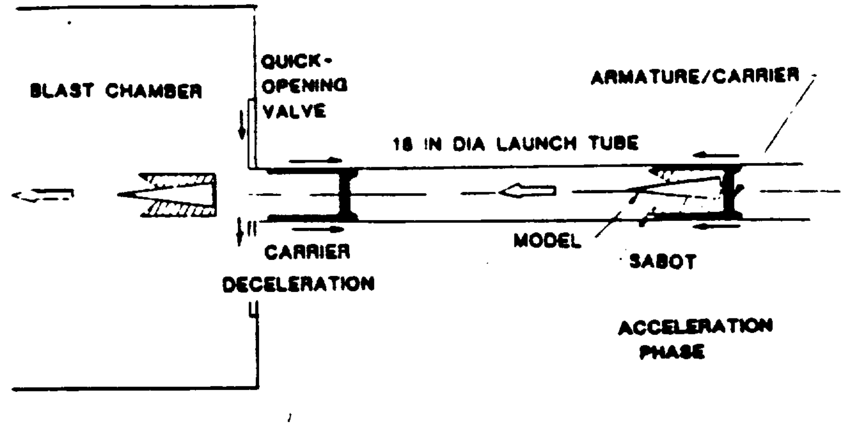
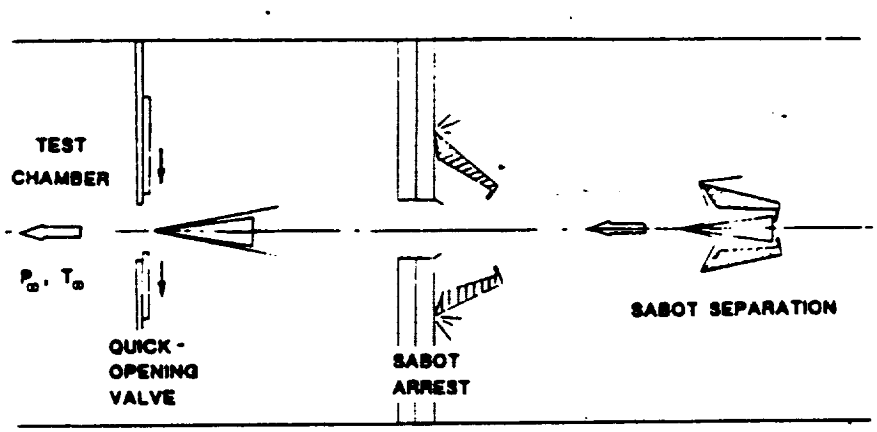


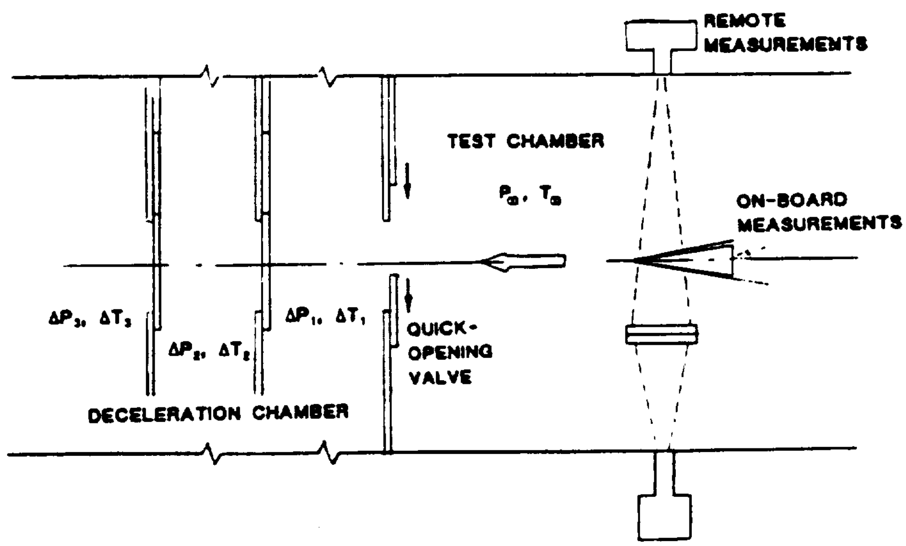
Figure 4.- Curve showing the upper boundary of the desired operating envelope.



(a) Launch phase



(b) Sabot separation phase



(c) Test and deceleration phase.

Figure 5.- Model test flight sequence.

QUESTIONS FOR WORKSHOP

1. What factors can be expected to limit model size, velocity, or design?

2. Should the armature for a railgun facility be an integral part of the model/sabot configuration or must it be independent from and perhaps separated from the model/sabot? Will current destroy or make inoperable the instrumentation onboard the model? What are the advantages or disadvantages associated with designing the model/sabot such as to keep the model well ahead of the armature?

3. What are feasible methods for decelerating models?

4. What are the magnitudes and implications of the pressure loads acting on the model/sabot for the coaxial concept?

5. Is it possible to conduct meaningful instrumented model tests with current/existing facilities, the purpose being to determine whether the instrumentation can withstand the gee forces and electromagnetic environment? What applicable investigations have already been done?

6. What are the operational, safety, and cost implications of constructing such a facility below ground level, in the ground vertically, or above ground horizontally?

7. What prototype or subscale tests/R&D should be done prior to any commitment to design and construct such a facility?

8. Is it possible/practicable to have a tracked and possibly compression tube model deceleration and/or recovery system with nonsymmetrical models such as winged bodies?

9. Provided both the railgun and coaxial concepts are judged feasible, which concept should be pursued and to what extent? Are there "show-stoppers" or pivotal issues regarding any "go" or "no go" decision to proceed with such a facility?

10. Can a model/sabot combination for perhaps a boundary layer/ transition experiment be released in a manner such that the model (optically smooth for experimental purposes) will not be damaged such as to preclude valid data acquisition?

11. Are there experiments which place constraints or demands upon such a facility which could or would make it impractical from the standpoints of physical size or operation aspects?

12. Would the total destruction of the model and onboard instrumentation at impact/flight termination make testing in such facilities so costly as to make the facility impractical from the standpoint of cost?

13. Are there limitations to the accuracy with which data (velocity, etc.) could be obtained in such a facility which would compromise its value as a research tool? If so, what are they and what, if anything, can be done to improve the situation?

14. What R&D needs to be done in the area of instrumentation, both onboard and off-board the model, and with respect to the facility itself?

15. What, if any, are the major electrical equipment R&D areas which need work if such a facility is to become a reality? Are there areas of overlap with DARPA and/or SDIO R&D?

16. What are the major safety concerns of such a facility and how can they best be addressed? To what degree will safety concerns adversely affect the cost of such a facility?

17. What are the major concerns regarding siting such a facility?

18. What, if any, are the pitfalls associated with model launch, model release methodology, and model oscillation and divergence from the flight corridor?

19. Will the type of experiments which might be conducted in such a facility require a section of range with a high density gas such as nitrogen to heat up the model prior to entering the desired test atmosphere?

20. Regarding the coaxial launcher, will cooling of the armature to close to -320_{o} F be harmful to instrumentation within the model?

21. To what extent will eddy currents and electric and magnetic fields destroy or make inoperative the instrumentation in the models in the coaxial and railgun concepts?

22. Is it desirable/feasible to utilize a one or two stage light gas gun to accelerate models prior to entering the EML launch tube in order to decrease/minimize rail wear? Will the gee loads associated with light gas guns destroy the model?

23. What is the largest possible bore feasible for the launcher, and why?

24. What is the smallest model that can attain the experimenta[redacted] appropriate onboard measurement s[redacted]e required envelope?

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16. Abstract

The NASA Langley Workshop on an Advanced Hypervelocity Aerophysics Research Facility was conducted on May 10-11, 1988, at the Langley Research Center. The primary objective of the workshop was to obtain a critical assessment of a concept for a large, advanced hypervelocity ballistic range test facility powered by an electromagnetic launcher, which has been proposed by the Langley Research Center. It was concluded that the subject large-scale facility was feasible and would provide the required ground-based capability for performing tests at entry flight conditions (velocity and density) on large, complex, instrumented models. It was also concluded that advances in remote measurement techniques and particularly onboard model instrumentation, light-weight model construction techniques, and model electromagnetic launcher (EML) systems must be made before any commitment for the construction of such a facility can be made.

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