TRAINING CENTER FOR EXPERIMENTAL AERODYNAMICS

LOW PRESSURE AERODYNAMIC FACILITIES

Proceedings of the Round Table Conference
held in London (25-27 October 1960)

Edited by

J.J. SMOLDEREN

Rhode-Saint-Genèse, Belgium.
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Research Programs in Low Density Aerodynamics

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Program at A.R.D.E.
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The development of a new technical field begins usually in a single laboratory, and while a few others may gradually develop an interest, a number of years will elapse before a scientific break-through or important practical applications suddenly bring this field to the attention of a wider segment of the scientific community. Low-pressure aerodynamics provides a good illustration of this phenomenon. Starting about 15 years ago with the pioneering work at the University of California and the Ames Laboratory, experimental work in low-pressure aerodynamics remained limited to a small number of laboratories, and only recently did its connection with upper atmosphere physics and space exploration create a widespread interest, leading to the establishment of serious plans for new facilities.

At this stage, when a considerable amount of experience had been accumulated by some groups and when other groups were in the process of designing or constructing new equipment, it appeared profitable to arrange for an informal meeting of active researchers so that the advantages and limitations of tried approaches could be discussed within the framework of future plans. Not only is there a large amount of experience buried in not easily accessible reports, but a great deal of it, in particular the unsuccessful attempts to solve various problems, has never been brought down to paper. A round table conference without firm agenda, where questions could be asked and answered freely, seemed to be the most suitable tool for the spread of this important information. The Advisory Group for Aeronautical Research and Development, AGARD (NATO), in cooperation with the Office of Scientific Research of the U.S. Air Force, and the U.S. Office of Naval Research, and with the British government installations interested in this field of research, made the necessary arrangements for this conference, and the results are incorporated in the following pages. As a by-product, plans for future research, both with the existing and the new facilities, were discussed around the table and in private meetings, and it is expected that these discussions will result in a better utilization of equipment and faster scientific progress.
I. DIFFUSION PUMP SYSTEMS

Mr. Clayden
A.R.D.E., Fort Halstead, U.K.

Introduction

It seems useful to quote the different ranges of vacuum distinguished in practice and the corresponding available pumping systems.

a. Coarse vacuum, from 760 mmHg down to 1 mmHg: Piston pumps, vane pumps, and steam ejectors.

b. Medium vacuum, from 1 mmHg to .001 mmHg = 1 μHg: Mercury and oil ejectors, booster diffusion pumps, steam ejectors, ROOTS blowers and the more recent cryogenic pump ("Cryopump").

c. High vacuum, below 1 μHg: Oil and mercury diffusion pumps and cryopumps.

Low density wind tunnels are usually operated in the medium vacuum range and booster pumps, steam ejectors and cryopumps have been used.

For high vacuum research facilities, such as molecular beams and whirling arms, diffusion pumps have to be used and these require medium vacuum pumps as backing pumps.

At A.R.D.E., our experience has been mainly with diffusion booster pumps, which operate our low density wind tunnel, but the diffusion pump will briefly be described first.

Diffusion Pumps

The design of these pumps has been based largely on empirical data. Fig. I, 1 schematically indicates the operating principle: Gas molecules diffusing into the pump chamber because of their random motion are caught by the vapor jets produced by the electrically heated boiler. The jets condense on the cooled walls and the gas molecules are removed from the diffusion pump by a backing pump. The molecular mean free path in the vacuum system is usually larger than the pump dimensions.

The efficiency of a good diffusion pump is usually not more than about half that of a perfect vacuum (i.e., half of the incoming molecules are reflected into the vacuum vessel).

The main trouble encountered in operation is backstreaming of vapor into the vacuum system. This is normally cured by fitting a baffle system preventing any "optical" path between the vapor jets and the vacuum system. The molecular conductance from vacuum system to pump remains comparatively high, but is decreased by these baffles and efficiency is accordingly cut down by 20 to 30%. In some diffusion pumps, the baffles are
incorporated in the valve system. The backing pump has to provide a vacuum of about .5 mmHg. Warming up period for a large diffusion pump is of the order of one hour. Initial evacuation of the system is obtained through the backing pumps (usually rotary type) and the diffusion pump will normally take over when the pressure has dropped below .001 or .0001 mmHg. (This requires a valve system shown on Fig. I, 2.)

Fig. I, 3 shows a few manufacturer's curves for big, commercially available diffusion pumps. These go up to $10^4$ l/sec. Bigger pumps are available only on special order.

Typical of diffusion pumps is the nearly constant pumping rate below about $10^{-3}$ mmHg; this is independent of the fluid used down to $10^{-4}$ mmHg, when the operation then depends on the nature of the fluid.

Typically, a pump with a speed of $10^4$ l/sec has to be backed up by a rotary pump of 100 cu.ft/min.

**Booster Pumps**

The operation of booster pumps is similar to that of the diffusion pumps. The essential differences are:

1. The booster pumps operate at much higher pressures, up to .1 mmHg.
2. They use a much larger boiler and much higher heat input.
3. The pressure difference maintained across the jets is much higher.

The problem of backstreaming becomes very severe in the case of booster pumps and has to be solved by the use of special devices, such as a cooled copper ring to trap and condense the escaping vapor (see Fig. I, 4), which seems to work successfully. It cuts backstreaming down to about 6% of its original value.

Booster pumps will work, typically, against back pressures of 2 to 3 mmHg. Fairly large boiler pressures (15 to 40 mmHg) are required to produce the high density vapor jets. Fig. 5 shows the performance of a typical booster pump as a function of heat input. The fore pressure tolerance goes up nearly linearly with the heat input and this explains why such large heat inputs are required at the higher pressures. The pumping speed exhibits a rather surprising behaviour in dropping off after an initial expected increase. The reason for this is not clearly understood, but has possibly something to do with the "cracking" of the fluid.

Typical characteristics for commercial booster pumps are shown on Fig. I, 6 (Manufacturer's data).

The A.R.D.E. low density tunnel is driven by six 18.B.3 booster
pumps\(^{(1)}\) giving a total pumping speed of 7,000 l/sec. The same pumps are used in the U.T.I.A. low density facility in Toronto. With an extra stage added to these pumps a higher pumping speed can be obtained at low pressures\(^{(2)}\).

The N.P.L. low density facility will use five bigger booster pumps, the 30.B.4\(^{(3)}\), giving a total pumping speed of about 20,000 l/sec. A still larger pump\(^{(4)}\) in the same range gives a pumping speed of 10,000 l/sec and is believed to be the largest standard commercial booster pump available at the moment.

The pumping speed of the pumps used to operate low density wind tunnels is again nearly constant from 1 to 70 \(\mu\)Hg. At A.R.D.E., the booster pumps are backed by two 200 cu.ft/min pumps. The N.P.L. uses a system of 5 ROOTS blowers and two rotary pumps.

**Types of Fluids used in Diffusion Pumps**

Mercury and oil are used in diffusion pumps. Mercury has been used in nearly all earlier diffusion pumps, but oil is preferred at present for most applications (exceptions being mercury arc rectifiers, or when a very clean atmosphere is required, such as in chemical work or in molecular beam apparatus).

The following oil types are widely used:

**APIEZON oils:** The vapor pressure of these oils is lower than \(10^{-7}\) mmHg and very low pressures can therefore be reached. They cost from £10 to £40 a gallon, depending on the type. Their main drawback is the heavy decomposition they exhibit when exposed to air at higher pressure and high temperature.

**SILICONE oils:** These oils do not decompose even when exposed to air at high temperatures and pressure. Unfortunately they are very expensive (about £80 a gallon). (The cost of silicone oil in the N.P.L. low density wind tunnel would be between £4,000 and £5,000 which would be a fair percentage of the cost of the complete pumping system.)

**BOOSTER PUMP fluid:** This fluid is very cheap (£3 a gallon) but subject to heavy decomposition.

It is important to mention that decomposition is accelerated by electrical discharges so that there might be a case for using silicone oils

---

\(^{(1)}\) Pump n° 4 in Fig. I, 6.
Manufactured by EDWARDS HIGH VACUUM LTD., Manor Royal, Crawley, Sussex, Gt. Britain.
18.B.3 means 18" diameter, Booster, 3 stages.

\(^{(2)}\) Pump n° 3 in Fig. I, 6.

\(^{(3)}\) Pump n° 2 in Fig. I, 6.

\(^{(4)}\) Pump n° 1 in Fig. I, 6.
in facilities working with ionized gases, such as plasma jet wind tunnels, etc.

As mentioned before, the pumping speed of diffusion pumps is nearly independent of the type of oil used except at the very low pressures.

Operating Experiences with A.R.D.E. Booster Pumps

These pumps were found to be pretty reliable in use. The one-hour warming up period is not a serious drawback since they can be started before working hours.

We operate with the cheap booster fluid, which, as mentioned, may not be exposed to air at atmospheric pressure (decomposition). A fully valved system is available, so that the test section can be shut off from the pumping system. A model can then be changed at atmospheric pressure while the booster pumps are still operating. Sufficient vacuum can be reached in the test section very quickly, after which the booster pumps are again connected. The whole operation takes about ten to fifteen minutes.

When running the tunnel with air, we check the pumps weekly and find that about 1 pint of oil is lost every six months. No change in performance is observed during such long periods. However, when operating the plasma jet, a marked decrease in performance is observed in the course of time and the pumps have to be decoked every few hundred hours. There might be a case for the use of silicone oils here but they have not been employed up till now. Stripping down and cleaning one booster pump occupies one man for one day.

As can be seen from the diagrams, pumping speed is constant up to about 70 μHg, and beyond that, the mass flow is constant. Sometimes a nozzle is started at a higher pressure (several hundred μHg) and this causes stalling of the pump and severe backstreaming of oil vapor into the system. The oil being a low vapor pressure fluid, no great inconvenience results. If the plasma jet is used, however, backstreaming results in coking of components and should therefore be avoided as much as possible.

Cost of Diffusion Pump Systems

Fig. I, 7 shows the capital cost of various systems, including the cost of backing pumps, per 1/sec of pumping speed, as well as the power requirement per 1/sec of pumping speed as a function of the pressure level in the vacuum system.

It is seen that the economic advantage of diffusion pumps disappears at pressures higher than 1 μHg, when booster pumps become much cheaper. (Minimal values being 5 shillings/1/sec for diffusion pumps at $10^{-4}$ mmHg and 13 shillings/1/sec for booster pumps around $10^{-2}$ mmHg.)
DISCUSSION ON MR. CLAYDEN'S PAPER

Dr. Maslach wishes to have some information about the typical Mach numbers and sizes of isentropic core of the wind tunnels referred to in the paper using diffusion booster pumps systems.

Mr. Clayden: The order of magnitudes are as follows:
   A.R.D.E. facility: \( M = 4 \), nozzle diameter: 5" (six 18.B.3 booster pumps)
   N.P.L. planned facility: \( M = 2 \), nozzle diameter 7" (five 30.B.4 booster pumps) (isentropic cores are slightly less than half the nozzle diameter at a pressure of about 20\( \mu \)Hg).

Dr. Devienne: (asked to give some comments on the diffusion pumps he used in his facility): We have been using both diffusion and booster pumps. No trouble was experienced when working with neutral gases, but serious difficulties arose in tests with ionized gases. Liquid air and freon traps are used but it is impossible to prevent minute quantities of oil to reach the system. The strong electrical fields used to produce ionization will cause severe destruction (cracking) of the oil and modifications in the behaviour of test surfaces and probes are then observed. To have a good pumping speed and a clean system, our experience is that cleaning is required every two days.

   In our molecular gun, we must clean our probes regularly by heating them up to 1000°C in order to get reliable measurement of ionization and molecular velocity.

   Many difficulties are caused by oil escaping in the system but we have already solved some of these.

Dr. Talbot mentions that no difficulties of this order were encountered in the BERKELEY facility using steam ejectors to drive a plasma jet. This might be an important advantage of steam ejectors over oil pumps when tests with ionized gases are considered.

Dr. Stalder made some cost comparison, about five or six years ago, between multistage steam ejector pumps and oil diffusion or booster pumps, and the steam ejector system was then considerably cheaper. Things may, however, have changed since, or the situation might be different in Europe and in the U.S.A.

Dr. Holder says that when evaluating the cost for his facility, the locally available steam ejectors were not cheaper but the Ingersoll-Rand ejectors were about half the price.

Dr. Devienne thinks that steam ejector pumps are cheaper than oil diffusion booster pumps but cannot be used for extremely low pressures.

Dr. Wegener mentions a U.S. made commercial vacuum pump, the KS2000 (made by the Consolidated Vacuum Co., Rochester, N.Y.). It is a combination, in
a single unit, of an oil ejector and a diffusion pump. The shut-off pressures is \(1\mu\text{Hg}\). The pumping speeds are: 2500 l/s at \(1\mu\text{Hg}\), 3000 l/s at \(5\mu\text{Hg}\), 1000 l/s at 100 \(\mu\text{Hg}\) and still 100 to 200 l/s at 1 mm\(\text{Hg}\). It is quite cheap at $3000 complete with oil.

Dr. Chuan observes that it falls on Mr. Clayden's capital cost curve.

Dr. Estermann asks whether anybody has experience with the use of silicon oil, or whether the price of these oils was considered prohibitive.

Dr. Holder: Silicon oils have been used successfully at the N.P.L. for very clean work in a small shock tube.

Dr. Estermann: We had a disagreeable experience with silicon oil. A leak developed in the vacuum system and severe backstreaming and operating at near atmospheric pressure resulted. Some silicon oil was cracked and as a consequence a nearly unremovable deposit appeared on the equipment and it was almost necessary to replace it completely.

Dr. Cox asks whether anybody had obtained spectroscopic evidence of the contamination by oil, in a plasma stream. In the A.R.D.E. argon plasma jet facility, NH and OH bands were observed on spectrograms but it is not clear whether they are caused by decomposed oil or by impurities of the commercial argon used in the facility.

Mr. Clayden thinks it came from the oil. Oil vapor could be surrounding the jet.

Dr. Talbot mentions that hydrogen and nitrogen lines were observed in an argon plasma jet driven by steam ejectors. It is possible that the presence of hydrogen was due to contamination from atmospheric air leaks or to impurities of the commercial argon utilized. The hydrogen lines might have been caused by water vapor from the steam ejectors, but it seems unlikely.

Dr. Cox: It would be useful if standard evidence could be obtained about oil contamination.

Dr. De Leeuw: In a plasma jet using a mechanical pump, we found the same thing: NH, OH, Balmer series, etc. Everybody gets this, no matter what type of pump is used.
II. EJECTOR PUMPS

Dr. Maslach
University of California
Berkeley

There are two separate categories of ejector pumps: steam ejectors, and for lower pressures, oil ejectors. The latter somewhat overlap the systems described by Mr. Clayden.

The first low density wind tunnels built and operated, the Ames laboratory, NASA and the BERKELEY wind tunnels, used oil ejector pumps, of the small KB 300 variety (1), used in parallel.

The second series of wind tunnels built and operated there used steam jet ejectors.

The range of operation of steam ejectors reached from 30 μ Hg up to several hundred μ Hg (static pressure in test section). At the Ames Laboratory, for instance, several nozzles were operated at 400 μ Hg.

The following are typical characteristics of steam ejector driven wind tunnels:

M = 2, nozzle diameter 9", static pressure from 50 to 80 μ Hg.
M = 6, nozzle diameter 5", same operating static pressure.

At Berkeley, we operate below 100 μ Hg and therefore need a multistage steam ejector system. Five stages are used, the first three of which operate from the low vacuum end into the condenser (which removes the steam) and the last two stages remove air and the rest of the steam collected along the way.

These steam ejector systems are characterised by an enormous first stage booster (Fig. II, 1). The largest ejectors built have inlet diameters of about 36" and an overall height of approximately 24 ft. The steam pressure used ranges from 100 to 150 psi at the ejector nozzle inlet.

The steam jet traps and compresses the low pressure air and drives it towards the next stage. The compression ratio per stage is approximately 10 to 1.

The second stage is tacked on to this and so on (Fig. II, 1).

(1) Made by Consolidated Vacuum Co. Inlet diameter 6", maximum pumping speed 350 l/s. Operating range between 2 and 400 μ Hg.
The following figures, representative of the BERKELEY facility, give an idea about the steam requirement compared to the air flow produced: 7000 lbs steam per hour, at 150 psi, must be generated to remove about 70 lbs of air per hour, so that the steam to air ratio is of the order of 100, which is enormous. A large and efficient steam plant is therefore required, as well as all the auxiliaries, such as feed water pumps, hot wells, cooling towers or surface condensers, etc.

The steam ejector is a very reliable device where little can go wrong. The only possible failure is the loss of steam pressure, usually caused by a failure in auxiliaries.

Fig. II, 2 indicates the pumping speed characteristics of our steam jet ejector plant. The blank off point is about 10 μ Hg but it is possible to lower this by a slight modification in the design of the ejectors which would result in a slightly higher pressure ratio in the first two stages.

The graph shows that at 100 μ Hg, the pumping rate has reached the enormous value of 80 lbs of air per hour, or about 70,000 l/sec. The considerable slope of the curve giving the pumping speed versus pressure is a unique feature of steam ejectors systems. At 400 μ Hg, we have an air mass flow of 240 lbs/hr.

Similar performances were calculated in a project study by Mr. Menard at the INSTITUT AEROTECHNIQUE DE ST. CYR.

A few additional remarks should be made about the steam ejector system: The ejectors used are commercial units, originally developed for general pumping purposes. These steam ejectors will pump any type of gas and even solid particles in suspension will not damage the device.

No contamination of the vacuum system is to be feared, as is the case with oil ejectors.

An additional advantageous feature of the system became apparent recently, at BERKELEY, when the hot tunnel was operated using the same steam ejectors. The stagnation temperature had been raised to 2000° R by means of electrical resistance heaters. At M = 5, we have used the same nozzle as in the cold tunnel and obtained the same core diameter at a static pressure of 100 μ Hg (the mass flow being, of course, reduced to about half its value for cold operation). Core uniformity was quite good.

Oil Ejectors

A number of oil ejector pumps are now commercially available as complete packages, off the shelf. In the U.S.A., the most commonly used oil ejectors made by the Consolidated Vacuum Co. (Rochester, N.Y.) and are quite similar to the British EDWARDS SPEEDIVAC pumps.
Dr. Wegener already mentioned the KS 2000 model of the Consolidated range, which is a comparatively small pump. Several larger models exist, the largest of which is the KS 16000. This pump has an enormous flow capacity (19,000 l/s at 4 μ Hg) (Fig. II,3). Steam jet ejector characteristics are shown on the same picture for comparison.

Because of the recent emphasis on fluid dynamics at still lower densities, the trend is for the steam ejector to leave the picture somewhat and be replaced by oil ejectors.

Cost

Oil ejector costs fit quite accurately on Mr. Clayden's graph (see Fig. I,7).

Approximate breakdown of the capital cost of the BERKELEY facility is as follows:

<table>
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<th>Description</th>
<th>Cost</th>
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<tr>
<td>Two sets of 5-Stage steam ejectors systems</td>
<td>$35,000</td>
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<tr>
<td>Steam boiler</td>
<td>$20,000</td>
</tr>
<tr>
<td>Additional equipment (cooling towers, pumps, etc.)</td>
<td>$25,000</td>
</tr>
<tr>
<td><strong>TOTAL (approximate)</strong></td>
<td><strong>$80,000</strong></td>
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This system provides a pumping speed of about 70,000 l/sec at 100 μ Hg. The corresponding point is indicated on the cost diagram of Fig. I,7.

Criterion for Design of pumping Systems

A design criterion for low density wind tunnel pumping systems must be based on the consideration of two types of data:

1. Performance of pumps
2. Demand of nozzles

The first point has just been discussed.

Concerning the second data, demand of nozzle, let us mention a very interesting report by K.R. ENKENHUS describing the history of the development of the UTIA low density wind tunnel (1). This report contains in an appendix very useful equations for the scaling of nozzles leading to complete prediction of nozzle requirements at various pressure levels, and for various dimensions. The results from these equations agree very well with experimental checks carried out in Toronto, Berkeley and other institutes.

Conclusion

We feel that low density facilities development is now a mature field and does not present any great design challenge any more. If no major pumping system is considered, almost everything can be purchased commercially. It is even simpler, now, to design a low density wind tunnel than a normal or high density tunnel.

DISCUSSION ON DR. MASLACH'S PAPER

Dr. Estermann asks more details about the low pressure limit of the system, which seems to be in the range of 50 to 100 μ Hg at present.

Dr. Maslach: Blank off pressure is 10 μ Hg in our facility. We feel that this could be improved by minor modifications to steam ejector shapes without altering the whole structure. As an example, the INGERSOLL-RAND Co. has built a four stage steam ejector system with blank off at 20 μ Hg, so that a five stage ejector system of similar design could reach a blank off point of 2 μ Hg, assuming a compressing ratio of 10.

Dr. Estermann: What would be the performance of such a 5-stage system at 20 μ Hg?

Dr. Maslach: At 20 μ Hg, this would already be a very high flow device. The curve of Fig. II, 2 would be shifted slightly to the left, which would make a huge difference on pumping speed because of the considerable steepness of the curve.

Dr. Estermann: Is it not preferable to use oil ejectors below 20 μ Hg?

Dr. Maslach: Yes, commercially available steam ejectors nowadays do not go below 30 μ Hg and commercial oil ejectors or cryopumping should therefore be used below this pressure.

I think the most useful part of this session would be the comparison between the different pumping systems, but this should perhaps better be postponed until after Dr. Chuan's presentation.

Mr. Clayden: Have you ever experienced backstreaming of water into the system?

Dr. Maslach: Yes. We actually experienced flooding of our system at the beginning of operation (during an official visit!). We cured these difficulties after realizing that the steam plant is critical in this respect, and can actually be designed to prevent such occurrences. We ourselves rely on quick acting valves.
The only signs of backstreaming experienced since then appeared on one occasion while measuring local temperature on a glass model by means of vacuum plated (thin film) thermocouples, a very sensitive device. Some discrepancies were observed and attributed to backstreaming, mainly because traces of corrosion were discovered on the iron film of the thermocouple. There was definitely no corrosion before the test.

However, we feel that the effect of backstreaming must be small because of the large dimensions of our facility and the long connecting pipes used.

Dr. Lobb: In some laboratories, compressed air is available and steam is not. Have you any data about air ejectors performance for large facilities?

Dr. Maslach: I cannot give any comparative figures. All the information I have concerns small air ejectors and is contained in a report by Mr. SIESTRUNK (1).

Dr. Stalder: I think air ejectors are much more expensive unless compressed air is available free.

There is a question of ratio of molecular weights involved here.

Dr. Maslach: The NASA Ames Laboratory is now building a giant steam ejector plant to drive a low density tunnel.

Dr. Stalder: A large steam plant, covering one or two acres, is being built. A coal boiler from a cruiser is used which can produce about 200,000 lbs. steam per hour. The uniform core in the test section will have a diameter of 2 ft. No information seems to be available about the upper Mach number of this facility (Mr. Goodwin, from NASA, was unable to attend the conference).

Dr. Stalder mentions that a 30 MW arc heater is going to be used in this new Ames facility. High Mach numbers will be obtained with a Reynolds number of the order of 100.

Dr. Maslach remarks that one must make up one's mind about the type of work contemplated, very early in planning a new facility. If a research tool is considered, all sorts of low cost oil ejectors are available for small flow systems with, say, a few inches diameter. If a big facility is planned, for development work and prototype testing, higher Reynolds numbers and pressures will be required and the steam ejector system seems to be the most favourable for such purposes.

(1) The report alluded here seems to be
Dr. Hall: The intermittent shock wind tunnel is one alternative to the continuous flow low density tunnel for low pressure hypersonic work. The shock tunnel is much cheaper for it enables one to study rarefied gas dynamics without extensive vacuum pumping devices.

Dr. Maslach: The problem there is pressure measurement at low densities in a short time of the order of 1 ms.

Dr. Hall: This is of course the real problem but we now have satisfactory instrumentation for the pressures down to $10^{-4}$ and even $10^{-5}$ psi ($5 \mu$ Hg, $0.5 \mu$ Hg) with adequate response. Piezo-electric transducers are used.
The U.S.C. Engineering Center started only recently in the field of low density, but was the first to use a cryogenic plant for wind tunnel operation. Some of the problems encountered in the development of the system, its merits and limitations can already be discussed.

The U.S.C. wind tunnel may be considered as a two phase wind tunnel where the air flows in as a gas and out as a solid, but the back part of the system is actually a pump which we call a cryopump. The same principle is of course widely used in the high vacuum technique where cold traps are used with temperatures above 100°K but our pump works at 20°K.

Reasons for selecting the Cryopump System

We planned to study fundamental problems in the field of really rarefied flows (not cases with hypersonic interaction parameter in the range of say 1 to 10, but cases where the KNUDSEN number becomes significant). Such problems were, for instance, strong shock wave structure and flows over flat plates with thin leading edges.

The question of the choice of a characteristic dimension then arises. We took 1 cm in order to obtain adequate probe response and model dimensions. The flow field diameter should then be larger by one or two orders of magnitude, i.e. of the order of 10 to 100 cm.

As we planned a free jet, the vessel had to be comparatively large compared to the jet, its diameter consequently had to be of the order of 1 m.

The flow rates for such jets are large, of the order of $10^5$ to $10^5$ l/sec at, say, 1 μ Hg static pressure in the test section.

The basic characteristics of the system contemplated were then:

- Typical model dimension: $L = 1$ cm
- Mach number: $M = 10$
- Molecular mean free path: $= 1$ cm
- Interaction parameter: $= 100$
- Knudsen number: $K \gg 1$

We realized that the required flow rate would necessitate the use of a good number of pumps and, without knowing anything about vacuum technology, decided to look for something new. The two phase system decided upon led to a lot of trouble initially but is working reasonably
well at present. Enough experience is available now to point out the way towards improvements to the system and to establish its limitations. The latter is especially important in view of the blind enthusiasm so often encountered for a new development.

Operating Principle

In principle, the cryopump consists in a flat cooled surface. The gas condenses on the surface as a solid layer (operation below the triple point is usual). The amount of gas to be condensed is immediately obtained from the flow requirement, but the real problem is to compute the effect on heat transfer of the growth of the layer.

In fact, the cryopump is not a strictly continuous operating device because condensation will stop when the heat transfer becomes too low to maintain the required temperature at the interface (there is some similarity here with a vacuum vessel considered as a pumping device, the inlet pressure rising in time because of the inflow).

Running time depends, of course, on the flow rate and the area of the condensing surfaces.

There are therefore two things to consider in the design of a cryopump.

1°. Growth of the condensate layer and condensation rate that can be sustained in presence of a fairly high rate of gas flow. The study of this growth has to be made at the continuum limit of operation of the facility (higher pressure ranges).

2°. Effectiveness of the cooler surfaces to trap the incoming gas molecules. This may be treated as a free molecule problem because the effectiveness in trapping becomes critical only in the lowest density range. The mean free path of molecules is then larger than the surface dimensions. It is a surface interaction problem.

In our own facility, we were working close to the continuum end (high density range) and did not consider going very far into the free molecule regime. Furthermore, we wanted to run for long periods in order to make true steady state measurements. We were therefore mostly concerned with the first problem.

This is a non-stationary heat conduction problem. We made calculations to solve it and realized afterwards it was a classical problem (freezing of the ocean, and also inverse of sublimation problem encountered in ablation cooling techniques).

The solution enables one to calculate the total cooling surface required for given flow rates and running time, knowing the density and thermal conductivity of the solid layer.
Our own cryopump was designed, on this basis, for a running time of 10 hours at a condensation rate of 1 g/s. This corresponds to a flow rate of the order of $10^6$ l/s at 1 $\mu$Hg. Normally, we operate with condensation rates between 0.05 and 0.3 g/s.

The nozzles used have diameters ranging between 0.5 and 1 m. At $M = 8$, the expected core is about 2" but we have had no opportunity yet to survey the second (we hope to increase the core diameters by cooling the nozzles).

After the question of required surface and layer growth has been solved, two further problems remain, the design of refrigeration system and the thermal insulation of refrigerator and the ducting problem. The latter is common to all vacuum systems and will not be discussed here.

The choice of refrigeration system was settled by the availability of a Helium refrigerator with 350 W power at 20°K.

The thermal insulation and radiation shielding of the cooler surfaces turn out to be the most critical parts of the design because of the difficulty of shielding the surfaces from radiation without impeding the flow. But it turns out that it is not the radiation shielding that one is worried about, for the cooling surface not only has to remove the latent heat of sublimation but also the sensible heat of the flowing gas, which is usually at a temperature close to or even higher than room temperature. A precooler is therefore indicated to raise the overall efficiency of the system and it seems useful to combine both precooling and radiation shielding functions in a single device.

No definite design rules are available here because of the lack of data about heat exchange at the very low Reynolds numbers involved. A sporadic, empirical search for efficiency results and we are accordingly modifying our precooler geometry every two months or so.

According to our present experience, about 70 % of the refrigerator power is dissipated in radiation losses and only 30 % are used for gas condensation when the radiation shields are uncooled. Cooling of these shields with liquid nitrogen may reduce the radiation losses by a factor five, or if one is careful, even a factor ten.

Removal of Noncondensables

Another important problem arising in the operation of cryopumps is the removal of noncondensable components. Normally, there is about 0.016 % (by volume) of such components, namely H$_2$, Ne and He, in atmospheric air. It is not practical to try to condense these components for the temperatures required would be so low as to make the refrigeration plant prohibitive, so that other techniques have to be found.
In static systems, it would seem possible to reduce the amount of uncondensables by successive filling with pure purging gas and evacuating (2 or 3 such operations would be required). In our experience, such a pure gas is not available (1), and the only solution would be to produce one's own pure gas by distillation (as the cryogenic physicists do).

We were planning to condense nitrogen on a cooled plate and re-evaporate it after evacuation of the vessel, but accidentally found another interesting method for dealing with noncondensables. During trial runs, a nitrogen burst was sent in the cryopump at a rate of 100 g/s (100 times the design rate), and a steady rise in pressure was expected in the cryopump as a result of the interface temperature rise. However, after a sharp rise from $10^{-5}$ mm Hg to over $10^{-3}$ mm Hg, a rapid decrease of pressure down to $3 \times 10^{-8}$ mm Hg was observed and the pressure remained at this level for half a minute, after which it started rising again as expected. The minimum pressure reached was close to the saturation pressure at the pump temperature ($20^\circ$ K). Dr. T. KOGA, of U.S.C.E.C., suggested that the large flow of condensables could have entrained and trapped the noncondensables in the crystal lattice of the condensate. This method of removal of noncondensables was termed "trapping".

The same effect was found nearly simultaneously by two other groups working on different problems (A.D. Little, Inc., and Balwanz at the Naval Research Laboratory). This confirmed Dr. Koga's suggestion. The A.D. Little group showed that it was dynamical phenomenon in that the pressure rose immediately if the external flow was stopped.

Though we were not directly interested in the phenomenon itself, systematic tests were carried out by MOORE at U.S.C.E.C. in 1959, on CO2 condensation on a W shaped condenser. Trapping was not directly observed but there was good evidence of entrainment of noncondensables by the CO2 flow with the noncondensables removed by a mechanical pump.

We are now working on a second generation cryopump for a U.S. Navy altitude chamber, which will involve a simple trapping device involving a gutter shaped cooling surface with noncondensable collected at the center by an auxiliary pump. It appears that the partial pressure of noncondensables can be reduced by one order of magnitude by means of such a simple trapping device at pumping rates between $10^4$ and $10^6$ l/s.

Three other groups are now working on cryopump development per se and not necessarily for aerodynamic use: a helium cooled cryopump is under development at the A.D. Little Co., another one at the G.E. Laboratory in Philadelphia, and several large scale cryopumps (several orders of magnitude above ours) at A.E.D.C., Tullahoma.

(1) If one plans to work at $10^{-9}$ atm vacuum, a purity of 1 part in $10^{11}$ in volume would be required even with multiple purging while commercially available "pure" gases have purities of 1 part in $10^7$. 
Cost of a Cryopump System

In our case, the overall cost is difficult to assess, because we did not develop the pump itself but rather the wind tunnel.

If one considers the cost of the refrigeration plant to be dominant, a pumping speed of $5 \times 10^5$ l/s at pressures between $10^{-3}$ to $10^{-5}$ mm Hg could be obtained for £50,000. This involves a 200 to 300 W refrigerator and the cryopump itself. The cryopump unitary cost is therefore approximately $0.1/1/s.$

This is indicated on Fig. 1,7 (£0.03/1/s).

This type of cryopump is not exactly an off the shelf item but may be purchased custom made at present.

DISCUSSION ON DR. CHUAN'S PRESENTATION

Dr. De Leeuw: At UTIA, a preliminary design study has been made about a cryopump using liquefied neon rather than helium to drive a low density plasma tunnel. The results have been published in an UTIA report (1). The temperature of liquefaction for neon is 27.6°C, which is sufficiently low for the pressure ranges contemplated (around 1 μHg).

Reason of the choice of the system is that two compressors are available which can liquefy neon or hydrogen when combined with a simple Joule Thomson expansion process, but not helium.

Theoretical studies and pilot tests on a model simulating the pumping system were carried out. In the tests, the condensing surface was a copper rod, cooled by liquid helium. Temperatures corresponding to liquid neon were obtained by an electric heater. Temperature of the incoming air was brought to the expected full scale values of 80 to 100°C by cooling the vessel walls to these temperatures and fitting baffles to ensure at least one wall collision for each incoming molecule. The ratio of mass flow to condensing surface area had the full scale value.

Pressure history was recorded in the chamber with auxiliary pumps off, so that the cryopump speed could be derived (see reference (1)).

We do not believe that the analogy with the problem of the freezing of the ocean is a very close one because of the different boundary conditions.

(1) J.B. FRENCH and E.P. MUNTZ : Design Study of the UTIA low density plasma tunnel. UTIA Technical Note n° 34 (March 1960).
conditions. In the case of the wind tunnel the mass flow is constant, while in the ocean case, the temperature at the interface is constant.

The most striking of our experimental results seems to be that the heat conductivity of the solid layer depends on the rate at which it is deposited. This dependence is in the unfavorable direction, in that the conductivity decreases with the rate of condensation.

The results of this is that the increase of condensing surface will not lead to the expected increase in pumping time. This expected increase would be proportional to the square of the surface (1) and the measured increase is only roughly proportional to the surface.

A cost estimate was finally made, based on quotations from manufacturers. The pump itself, with small intercoolers and radiation shield, would cost about $22,000 for a flow of 7 lbs/hr. (This corresponds to a power of 300 W at liquid helium temperature). We could use our existing three stage compressor plant if we were willing to fit intercoolers. About 4,500 l of neon will be required, which would cost about $4,500 ($1 a liter). If one has to buy the compressors, which are not very expensive, the total cost would reach about $40,000.

When working with neon, the temperature is 7° C higher than with helium so that the temperature drop across the layer that can be tolerated will be small if one works at very low pressures and this reduces the running time. We have calculated that we could obtain a running time of the order of 1 hour at a few μHg by using 200 to 250 sq.ft of cooling surface.

Dr. Chuan: Three cases may be considered in the treatment of layer growth: constant mass flow, constant pressure and constant interface temperature. We analyzed theoretically the third case only, because it is the simplest but our tests were made in the constant mass flow case (it is very difficult to work at constant pressure).

The interest of the analysis with constant interface temperature is that it provides an upper boundary for the time after which the pressures in the vessel come up to a certain point. Analysis and experiments agree quite well in that respect (cf. U.S.C.E.C. Rept. 42-201, Dec. 1955).

(1) For a given temperature drop across the layer and given heat conduction coefficient, the layer thickness must be inversely proportional to the flow of incoming gas per unit surface. This being inversely proportional, for given mass flow, to the condenser surface, the total amount of condensate for a given temperature drop in the layer is proportional to the square of the surface.
Thermal Conductivity of the Layer

It is true that the thermal conductivity depends on the rate of deposit because the nature of the deposit depends on pressure and rate. This is due to the fact that the condensation of the gas can occur either before the interface or on the interface itself, depending on the distribution of temperature near the layer, which depends on the heat transfer rate. In the first case one gets a snowy deposit with poor conductivity, in the second case an icy deposit with good conductivity, but at very low pressures, or at the beginning of the experiments, snowy deposits appeared: for 1,500 l/sec at 1 μHg (fairly low rate), a frosty or snowy deposit was observed with CO₂.

In some other experiments, when using alcohol as a gas and at a much higher flow rate (corresponding to M = 3), the deposit was hard, clear "ice" (heat transfer rate much higher).
Dr. Estermann: A comparison should now be made between the three major systems mentioned for evacuation of large scale facilities, taking into account merits, limitations and cost. The systems are:

- Oil ejectors and boosters
- Steam ejectors
- Cryopump

Diffusion pumps have not been mentioned in connection with large scale facilities.

To the subject of cryopump, I may mention that the Philips Co. (Eindhoven, Holland) manufacturers of a very compact and efficient air liquifier, have recently built a two stage machine of the same type using helium and a regenerative cooling system, and they were able to reach about 20° K, which is quite sufficient for all aerodynamic requirements. The possibilities of cryopumping may advance substantially if this device becomes commercially available. It might be of interest to groups planning new facilities to inquire about this apparatus before making a final choice of pumping system.

Dr. Devienne is asked to comment on the diffusion pumps used in his facility.

Dr. Devienne: The choice of pumping systems depends on the regime one is interested in. In intermediate regime or slip flow regime, I suppose that boosters and ejector pumps are the best or, at least, the cheapest. The only advantage of diffusion pumps is the possibility of reaching very low pressures. The problem of wind tunnels with molecular flow regime is very difficult because the flow is not in equilibrium in the nozzle if the molecular mean free path is larger than the nozzle diameters, and one tends to use nozzle diameters in excess of 20 cm. Diffusion pumps are not interesting then because the largest pumps (from the U.S. or Germany) are very expensive and insufficient if high Mach numbers and therefore large pumping speeds are required.

Dr. Maslach: The equation for nozzle scaling indicates that at $M = 4$ and 1 μHg static pressure, which is in the diffusion pump range, a pumping speed of about 370,000 l/s would be required. This requires a battery of eight of the largest available diffusion pumps (48" inlet diameter). The diffusion pumps seem therefore to be unsuitable.

Dr. Talbot: The ion pumps should be mentioned. They still are relatively expensive and their pumping speed is rather limited, but their great advantage is that they will pump everything, including noncondensables, and
chemically inactive gases (ions trap molecules and bury them on the surface).

**Dr. Chuan** considers that the ion pump is in the same stage of infancy as the cryopump because they both are trapping devices and present a difficult basic problem of geometry design, for the mechanism of surface interactions is not yet understood in details.

**Dr. Talbot** observes that great progress has been done in the field of ion pumping since a few years.

**Dr. Chuan** mentions that his laboratory had such an ion pump on loan for a limited period, but it could not be given a fair trial because of an electrical failure. It would be interesting to use an ion pump in series with a cryopump to remove noncondensables.

**Dr. Estermann**: It appears that cryopumps and ion pumps are the only tools available for research in the very low pressure range (1 μHg or less). The cost of ion pump is at present enormous because no large scale production exists but it is to be hoped that they may become cheaper and more efficient if production engineers develop them, as was the case with diffusion pumps, etc.

**Dr. Chuan**: Present limitation of ion pump seems to be its peculiar geometry with narrow passage to the "egg crate", resulting in very low pumping rate. He does not know whether this limitation is a basic one. The ion pump used at U.S.C.E.C. had a pumping rate of 270 l/s and cost about $5,000.

**Mr. Clayden**: Summary of presentation on oil diffusion and booster pumps

Booster pumps are cheapest in the range between a few μHg to 20 or 30 μHg. (Above this range, steam ejectors and below this range, cryopumping appear to be more economical.) (See Fig. I, 7).

The boosters are commercially available, very efficient and free of trouble. Main drawback is the cracking of the oil under the influence of air at higher pressures (leaks) or possibly of electric discharges. This reduces the pumping speed.

**Dr. Maslach**: Summary of presentation on ejector pumps.

See pumping curves on Fig. II, 2.

Commercially available steam ejectors are satisfactory down to approximately 50 μHg. To discuss the merits of the different systems, type of work and dimensions of the wind tunnel should be taken into account. Steam jet ejectors clearly seem to be the better ones for the BERKELEY wind tunnel size and pressure range.

A small amount of development on the steam ejectors might lower the range but not more than one order of magnitude.
Dr. Estermann: If an order of magnitude could be gained, the steam ejector would reach pressure ranges where even the oil ejectors are not very satisfactory.

Dr. Maslach: The main advantage of oil ejectors is their flexibility. Altering the power input provides a wide range of operating conditions, corresponding each to a fairly constant volumetric pumping speed.

Dr. Estermann: Major disadvantages of the steam ejectors seem to be

a. blank off point is a little high
b. very steep dependence of volumetric pumping speed on pressure level (oil ejector pump has nearly constant pumping speed over one or two decades in pressure range).

The second point may be an important consideration in the choice of pumping system: constant pumping speed can be obtained by means of oil ejectors, very steep dependence of pumping speed on pressure level, by means of steam ejectors.

Dr. Talbot: mentions that mass flow is more nearly constant in the case of steam ejectors and the ensuing discussion seems to indicate that in some applications it is the mass flow and in others the volume flow which are the relevant quantities.

Dr. Estermann reformulates his statement:

The choice of a pumping system depends very much on the requirement of the facility. One should therefore not only consider the blank off point and probable cost but also the shape of the pumping speed versus pressure curve, and select according to whether constant volume flow or constant mass flow as function of pressure are required.

Dr. Chuan: Summary of Presentation on Cryopumps systems.

The useful range of the cryopump seems to be from $5 \times 10^{-4}$ to $10^{-6}$ mm Hg.

Lower pressure limitation is due to difficulties in reaching temperatures much below $20^\circ$K.

Higher pressure limitation of $10^{-4}$ Hg is a power limitation. Also, there is a heavy heat loading of the pump because of considerable free convection between shields and structure. Operation around $10^{-4}$ Hg requires minimizing the free convection (baffling).

Dr. Estermann: Conclusion

It is to be expected that the two most recent pumping devices the cryopump and the ion pump, will find increased use as interests develop towards the lower pressure ranges.
It is important to note that there appears to be little hope that diffusion pumps will also play a significant role at these low pressures.
It is well known that the three classical visualization techniques, Schlieren, shadowgraph and interferometer, are not sufficiently sensitive at low pressures.

Their ranges of applicability may be roughly delimited as follows, according to a study made in 1954 by Dr. R.A. EVANS of our laboratory (1). The comparison is based on the observation of a cylindrical shock having a 10 cm radius of curvature, and an assumed lower limit of sensitivity which is rather arbitrarily taken as corresponding to a 10% change in illumination.

The minimum detectable differences in density across the shock are then:

- **Schlieren system** \( \rho_2 - \rho_1 \gtrsim 4.8 \times 10^{-3} \text{ mm Hg/°K} \) (2)
- **Shadowgraph** \( \rho_2 - \rho_1 \gtrsim 5.7 \times 10^{-2} \text{ mm Hg/°K} \)
- **Interferometer** \( \rho_2 - \rho_1 \gtrsim 0.19 \text{ mm Hg/°K} \)

The Schlieren system is the most sensitive and the interferometer, the least. **Example**: Normal shock in a flow at a static pressure of 100 \( \mu \) Hg (such as in the BERKELEY facility):

- for \( M = 4 \), \( \rho_2 - \rho_1 = 5 \times 10^{-3} \text{ mm Hg/°K} \): shock barely detectable with well designed Schlieren system.
- for \( M = 6 \), \( \rho_2 - \rho_1 = 7 \times 10^{-3} \text{ mm Hg/°K} \): shock clearly visible but nothing else.

Other methods clearly must be devised for density measurements in the low pressure range. We will discuss two types of methods: the attenuation measurements and the measurement of a luminosity produced in the flow.

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(2) This unit is not really a density but the numbers are proportional to the densities.
a) **Attenuation measurements**

One can measure the attenuation either in beams of photons (visible light, X-rays) or of particles (electrons, atoms).

The mass absorption of such beams is described by the formula

\[
\frac{I}{I_0} = e^{-\int_0^l \mu \rho \, dx}
\]

where \( I_0, I \) are the beam intensities respectively before and after passage through the medium, \( \mu \) the mass absorption coefficient of the beam in the medium, \( \rho \) the density and \( x \) the distance along the beam in the medium.

Table I shows a comparison between the different attenuation techniques, based on the indication of the gas density \( \rho \) corresponding to \( I/I_0 = 1/e \) along a path \( l = 5 \, \text{cm} \) (\( \rho = 1/(\mu l) \)).

The static pressure indicated corresponds to the \( \rho \) value just quoted and \( T = 273^\circ\text{K} \) (in air, \( O_2 \) or \( O_3 \)).

Because of the high collision cross-section for atom beams, the corresponding mass absorption coefficient is the highest. Potassium atoms are used because they are easily detected by ionization techniques (sodium and cesium would do, also).

Any one of the attenuation techniques, except X-rays (1), could be used at much lower pressures than conventional visualization techniques.

The oxygen line absorption technique looks very promising and we have tried to use it to obtain an overall flow picture. This turns out to be difficult, for optical elements of lithium or calcium fluoride are required but not readily available. (The radiation is in the vacuum ultraviolet range). However, if this technique is used for local measurements only, as in the case of electron beams, then photocells can be used and some of the optical difficulties avoided, and the method becomes very practical.

b) **Luminosity (or glow) techniques**

The principle of these techniques is to use some physical process to make the gas glow and then observe the glow intensity. Table II indicates the characteristics of various glow techniques used in the BERKELEY wind tunnel. It is important to note that glow techniques are only qualitative, because the exact dependences of the luminosities on the density, temperature, etc are not known.

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(1) X-ray results are early NACA results. Dr. Stalder describes new development in this field in his contribution.
TABLE I. COMPARISON OF ATTENUATION FLOW VISUALIZATION TECHNIQUE

(Table Courtesy Dr. F.C. Hurlbut)

<table>
<thead>
<tr>
<th>Technique</th>
<th>Oxygen Absorption</th>
<th>Ozone Absorption</th>
<th>X-Ray Absorption</th>
<th>Electron Beam</th>
<th>Atomic Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Gas Beam, Particle or Radiation</td>
<td>$\text{O}_2 \text{ only}$</td>
<td>$\text{O}_3 \text{ only}$</td>
<td>any</td>
<td>any</td>
<td>any</td>
</tr>
<tr>
<td>$\mu$ (mass absorption coefficient) $\text{cm}^2/\text{gm}$</td>
<td>$2.5 \times 10^5$</td>
<td>$1.7 \times 10^5$</td>
<td>$790$</td>
<td>$10^5 \text{ to } 10^6$</td>
<td>$8 \times 10^7$</td>
</tr>
<tr>
<td>Minimum gas density $\text{gm/cm}^3$</td>
<td>$7.7 \times 10^{-7}$</td>
<td>$1.2 \times 10^{-6}$</td>
<td>$2.5 \times 10^{-4}$</td>
<td>$2 \times 10^{-6}$ to $2 \times 10^{-7}$</td>
<td>$2.5 \times 10^{-9}$</td>
</tr>
<tr>
<td>Minimum test section static pressure in mm Hg for $\ell = 5 \text{ cm}$ and $T_{\text{static}} = 0^\circ \text{C}$ (corresponding to above minimum gas density)</td>
<td>0.46</td>
<td>0.7</td>
<td>150 (b)</td>
<td>1.2 to 0.12</td>
<td>1.5 $\times 10^{-3}$</td>
</tr>
</tbody>
</table>

(a) This minimum gas density is based on an e-fold attenuation of the beam in 5 cm. Naturally, smaller fractional attenuations can be detected, so the corresponding minimum densities and pressures can be made smaller.

(b) A minimum value of test section pressure based on the work of Dimeff, NASA Ames Laboratory, for a 10 cm optical path would be 5.3 mm Hg.
TABLE II. COMPARISON OF LUMINESCENT GAS FLOW VISUALIZATION TECHNIQUES

(Table Courtesy Dr. F.C. Hurlbut)

<table>
<thead>
<tr>
<th>Techniques</th>
<th>Lewis - (a) Raleigh</th>
<th>Short (b) N₂</th>
<th>Air (c) Glow</th>
<th>Noble Gas (c) Gows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Gas</td>
<td>N₂</td>
<td>N₂</td>
<td>Air</td>
<td>A, He</td>
</tr>
<tr>
<td>Useful range of</td>
<td>60 mm Hg or higher</td>
<td>2-3 mm Hg</td>
<td>0.5 to 13.0 mm Hg</td>
<td>0.2 to 0.5 mm Hg</td>
</tr>
<tr>
<td>Stagnation pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mach number</td>
<td>M = 2.6 or larger</td>
<td>M = 3</td>
<td>M = 2 to M = 4</td>
<td>M = 1.3 to M = 2.0</td>
</tr>
</tbody>
</table>

(a) In Langley NASA Laboratory 1.5" x 3.75" supersonic wind tunnel as reported by BENSON, J.A.P. 23, 757, 1952.

(b) In early "close coupled" configuration of University of California Wind Tunnel.

(c) As available in the present U.C. Berkeley Wind Tunnel configuration.
It is important to notice that the lifetime of excited molecules should be long enough so that they can reach the test section in an excited state after having been created upstream, but not so long that they have time to diffuse all over the test section and prevent observation of the jet.

The first type of afterglow, the LEWIS-RAYLEIGH nitrogen afterglow, is produced by recombination of dissociated nitrogen with emission of a photon. This recombination requires a three-body interaction so that the rate is very slow at low pressures. Therefore, this type of glow is useless for low density wind tunnel applications. (The whole test chamber becomes suffused with the glow).

The short nitrogen glow, not clearly understood up till now, seems to involve a two-body interaction and has a fairly high rate of decay.

Air afterglow is a more flexible method. It is, in fact, a chemical phenomenon and not an afterglow in the accepted sense. The air is excited in such a way that free oxygen and NO are formed and they combine together to give NO₂ (two body interaction) \(^1\). The NO₂ is in an excited state and emits the observed radiation when reverting to the ground state.

The air glow is the most useful process we have investigated so far, because the glow intensity may be controlled by adding NO to the flow. It is useful up to \(M = 4\).

We have discovered other glow processes in noble gases (argon and helium). The mechanism of these is not clearly understood, but the lifetime involved again point to two body collision processes. These glows are brighter than the others discussed previously. It seems that a diatomic ion of the rare gas is formed and later dissociates and neutralizes, causing the glow.

The usefulness of glow techniques is limited in the Mach number range for the following reason: the glow must still be visible in the test section. Typical time for the glow decay is the mean free time (collision time) when binary collisions are involved. The mean free time is proportional to \(p_o^{-2}T^3\) \(p_o = \) stagnation pressure, \(T = \) absolute temperature). For given test section static pressure, \(p_o\) is proportional to \(M^\gamma\) \((\gamma = 1.4)\) and the glow decay time is therefore proportional to \(M^{-1.4}\). This calculation leads to an upper Mach number limitation of about 4 for a test section static pressure of 100 \(\mu\)Hg \((p_o\) being of the order of 13 to 18 mm Hg). At higher Mach numbers, the glow will be quenched before reaching the test section.

\(^1\) See KAUKEI and HURLBUT, J.A.P., 28, 827, 1957.
List of Figures

Fig. IV, 1: Optical bench and spectrograph separating 1470 Å line from neon light source (the whole has to be operated in high vacuum because of the high absorption of this radiation by air).

Fig. IV, 2: Spectrograph system in wind tunnel (the system is evacuated separately).

Fig. IV, 3: Results obtained by the use of 1470 Å radiation. They are rather limited and only the shock is visible (results could be improved by making local measurements by photocells).

Fig. IV, 4: Electron beam apparatus (used for scattering measurement). Electron current: 1 μA (1). Traverse of an axisymmetric flow yields local density after simple calculation.

Fig. IV, 5: Electron beam apparatus in wind tunnel (each part has to be evacuated separately). The whole apparatus can be moved around to obtain overall picture of the flow through many local measurements (2). Detector is an electrometer.

Fig. IV, 6: Electron beam results for a sphere, M = 2, p = 100 μHg (apparatus was moved along the axis).

Fig. IV, 7: Additional measurement of flow field by means of electron beam measurement (good agreement was obtained with inviscid calculations).

Fig. IV, 8: Glow installation, using RF exciter in bypass (3KVA at 60 MC).

Fig. IV, 9: Air glow over a sphere at M = 3,8.

Fig. IV, 10: Argon glow over a sphere at M = 1,7.

Fig. IV, 11: Short nitrogen afterglow.

(1) UTIA uses higher intensity beam, so that radiation due to ionization can be measured (see contribution by Dr. DE LEEUW).

(2) A T.V. type scanner could be used to obtain the whole picture automatically.
DISCUSSION ON DR. TALBOT'S PAPER

Dr. Chuan: The problem of quenching of the glow may partially be solved by exciting the glow in the nozzle itself, using for instance a RF exciter around the nozzle. This allows operation over a wide range of pressures. Dr. Wegener, I think, used the same principle.

Dr. Wegener: No, ours was a very simple layout using a spark coil to produce the glow, no RF.

Dr. Talbot: One difficulty is that the discharge in the nozzle could ruin the flow uniformity.

Dr. Chuan: Unlikely, for the power input necessary for sufficient seeding is very low (less than 100 W in our tests).

Dr. Devienne: What is the reason of the choice of a high frequency excitation in visualization?

Dr. Talbot: It is desirable to use as high a frequency as possible, for better coupling of the power through the glass pipe into the stream, and for more uniform excitation of the flow. The upper limit on the frequency is in practice dictated by the size of the pipe and the availability of high frequency power supplies.

Dr. Devienne: We have used 15 MC in argon at low pressures (between 1 and 10 μ Hg) and a lower frequency for nitrogen.

Mr. Cox: Where would the Schlieren Interferometer fit in the sensitivity scale?

Dr. Talbot: The sensitivity is better but a double path Schlieren system should be more sensitive. I think that Schlieren sensitivity can be improved somewhat but not several orders of magnitude.

Dr. Maslach: The analysis of visualization techniques by R.A. EVANS dates back to 1954. Since then good Schlieren photographs of weak shocks at 100 μ Hg have been obtained at the SANDIA corporation.

Two remarks may be made about this. One should try to improve the optics of the system and, furthermore, it appears that the 10 % detection assumption is too rough (entire system is in vacuum, so that the noise level is very low).

Dr. De Leeuw: The electron gun may be considered as a means of qualitative analysis of the flow, for the many electrons wandering around in the test section because of the electrical bias of the structure produce a visible glow showing the flow.

This is merely a by-product of the use of the electron gun as a local temperature measuring device (1).

(1) See contribution by Dr. De Leeuw.
DENSITY MEASUREMENTS

A NEW LOCAL DENSITY MEASURING DEVICE BASED ON X-RAY SCATTERING

Dr. Stalder

The real difficulty in all methods described so far is that they do not measure local density but integrals such as \( \int \mu \rho \, dV \) etc. \( \rho \) can be computed only if the flow pattern is 2-dimensional or axisymmetric, and not in many situations where no symmetry exists, such as glider vehicle configurations or axisymmetric bodies at angle of attack, etc..

The method I am going to describe for local density measurement has not been tested in a wind tunnel yet, but the hardware is ready.

A collimated X-ray beam is sent into the test section and the scattered photons are collected by a special collimator. This is a circular cross plate through which hundreds of cylindrical holes are drilled, the axis of which converges into a point \( P \) of the flow field, where we intend to measure the local density (fig. V,1). Counters, located behind the plate, will monitor the scattered radiation from \( P \).

The highest powered, commercially available X-ray tube is going to be used (130 KV, 200 mA electron current).

A traverse mechanism will be used to enable local measurement to be taken in the whole flow field. The wind tunnel in which the apparatus is going to be used has a 6" diameter.

To be accurate, the total volume of interest for the scattered radiation is about 1 cm\(^3\) around \( P \) but most of the scattered power recorded comes from a much smaller volume, so that this is a good approximation to a point measurement.

Limitation of the present arrangement is that the counting time is one second and we can record 200 counts, which corresponds to a density level of 10\(^{-5}\) of the atmospheric density.

It is envisaged to use a similar device in a shock tunnel of 1 ms flow duration. In this case, a pulsed, 30 KV X-ray tube will be employed. The pulsed current is 2000 A during less than 1 \( \mu \)s.

Modification of collimator geometry could be carried out in order to measure average density over a larger volume.

The first apparatus is built and will be tested within a month in the NASA Ames Laboratory plasma tunnel.
DISCUSSION

**Dr. Estermann**: What kind of anticathode is used in the X-ray tube?

**Dr. Stalder**: A rotating, water cooled tungsten anticathode.

**Dr. Estermann**: The spectrum of the X-rays emitted is then essentially continuous. It seems that a monochromatic beam would be better.

**Dr. Schaaf**: Is the phenomenon accurately defined so that no calibration of the apparatus would be required?

**Dr. Stalder**: The device will be calibrated in a still air vacuum tank. Counts will be recorded at different pressure levels.
The UTIA uses an electron beam apparatus for local density measurements at low pressures.

The electron gun is very similar to the one described by Dr. Talbot for absorption measurements (back end of a TV tube mounted in a copper tube which must be evacuated separately to high vacuum). The 15 KV electron accelerator is placed in a long tube and a 100 μA beam, with 0.8 mm diameter, is produced and sent into the test section through an orifice. The path of the beam in the gas becomes luminous and a small part about 1 mm in height of this luminous trace is focused on a photomultiplier tube (fig. V,2).

At pressures below a few hundred μHg, the luminosity is strictly proportional to the number of particles in the beam, so that a local density measurement is possible in a volume of the order of 1 mm³ by measuring the photomultiplier current.

Calibration of the device is easy (electron beam of known strength is sent into still gas at known pressure and the photomultiplier current is measured).

The method has now been extended by analyzing the spectrum of the light emitted. In air or nitrogen, it was found that practically all the emission is produced by the molecular nitrogen ion transition from the first excited state to the ground state. This is a well known process and the transition probabilities involved (excitation of ion by electrons from the beam, emission of photon by excited ions) can be computed. Rotational temperature of the ions may be deduced from an analysis of the distribution of the intensities in the spectrum of the rotational levels.

We were initially worried about the possibility of the electron beam upsetting the population of the rotational energy levels in the gas. The question was settled favorably by experiments in which electrons were sent through a static gas at known temperature and the rotational temperature deduced from the method was found to be within 2 % of the correct value.

The spectrogram of the light emitted thus yields the rotational temperature of the molecular nitrogen, which was shown to be close to the actual gas kinetic temperature, and also the density of the molecular nitrogen in the flow, with comparable accuracy (a few %). The partial pressure of the molecular nitrogen can be deduced from these data.

Tests were carried out in an arc jet and we convinced ourselves that we could distinguish the partial pressure of the molecular nitrogen from the total pressure of the nitrogen. This, then, represents a possible method for measuring the degree of dissociation in the flow.
DISCUSSION

Dr. Estermann: Do you take into account the attenuation of the beam along the path due to absorption?

Dr. De Leeuw: A correction should be made at high densities, but in our case the total absorption of the beam was less than 3%. There might also be a partial compensation because some scattered electrons from the primary beam contribute to the luminosity further on.

Dr. Estermann: I am quite convinced that the electrons will not upset the rotational distribution of states because their mass is so small that thousands of collisions would be required to produce a measurable change in the rotational energy distribution. It is therefore obviously safe to assume that the method yields the true rotational temperature.

Dr. De Leeuw: The reason why we worried is that the electrons have such a high energy compared with the gas molecules.

Dr. Estermann: I think this can be solved by a simple calculation of momentum exchange.

Mr. Cox asks how a flow picture could be obtained.

Dr. De Leeuw: The optical system is designed in such a way that a particular position on the spectroscope slit corresponds to a particular position in the flow along the beam. The exposure time is about 4 minutes.

Dr. Maslach: As mentioned by Dr. Talbot, the electron beam absorption technique has been used at BERKELEY for local measurements of density in axisymmetric flow. The sensitivity of the method when used for local density measurement is about 1% at 100 μ Hg pressure level. The calculations involved are quite laborious. They could be programmed for computers.
The field of pressure measurements has been more thoroughly explored than any other in the low density range by many groups.

The main facts will now be summarized. More details and an extensive bibliography on the subject can be found in a paper presented to the AGARD meeting on pressure measurements (London, March 1958) (1).

First, the typical pressure levels encountered in wind tunnel work will be quoted.

The static pressure will be in the low micron range, the impact pressure in the small mm region and the stagnation pressure will be in the large mm region.

Ordinary manometers can thus be used for stagnation pressure measurements. Impact pressure measurement require oil column manometers or thermistor Pirani Gauges.

For the static pressure, or for pressures in wakes behind blunt bodies, etc., the choice of instrument is very limited. Thermistor PIRANI gauges may be used but must be kept scrupulously clean and frequently recalibrated.

Basic instrumentation will include McLeod gauge, as a standard for calibration, manometers covering various ranges, and finally, the thermistor PIRANI gauges.

Building these things in tunnels, miniaturizing the probes and manometers and remote reading require all sort of ingenuity.

**Probe Response Time**

This important subject was treated, for free molecule flow regime, by SCHAAF and CYR in 1949 (Journ. Appl. Physics, Vol. 20, n° 9, p. 80). We use their results for optimizing the geometry of orifices, tubes, volumes, etc. These results are more conservative than those based on Poiseuille flow and were confirmed by years of measurements.

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(1) G.J. MASLACH: Some problems associated with the measurement of very low pressures. AGARD Report 175 (March 1958)
Temperature Creep and Thermal Transpiration

These effects should be taken into account in the lower pressure ranges, and were already considered by KNUDSEN and others. KNUDSEN's results are semi-empirical but were recently extended and checked by an extensive test program by HOWARD at the California Institute of Technology (1).

A plot of dp/p per unit of dT/T versus Knudsen number based on tube radius for circular, long tubes, is shown on fig. VI,1. No theory is available for the range of Knudsen number between 0.1 and 10 where the Knudsen semi-empirical curve applies. This was checked very thoroughly by HOWARD, and surprisingly good agreement was obtained with the earlier results.

The slip flow theory is valid below K = 0.01 and the free molecule limit of 0.5 for the ratio is closely approximated above K = 10.

DISCUSSION

Dr. Estermann: The results contained in fig. VI,1 are valid only for long tubes, for which the Knudsen number is clearly defined, but would not apply to more complicated geometries and irregular shapes defined by more than one geometrical parameter, where no single Knudsen number can be defined.

Dr. Maslach: Tests referred to, used long tubes with length to diameter ratio between 20 and 100.

Dr. Estermann: No theory being available for the central part of the curve, extrapolation of quoted results to geometries other than long tubes requires careful analysis.

Unfortunately, the data is not applicable for short tubes which are required in experimental devices with sufficiently fast response.

Dr. Chuan: contributes to the problem of pressure measurements in the range below the lowest range considered by Dr. Maslach (i.e. below \(1\mu\text{Hg}\)). Dr. Maslach mentioned that thermistor, Pirani and ionization gauges are available for this but they require frequent recalibration and a high degree of care if accurate results are to be obtained.

At U.S.C.E.C., the need was felt for a reliable secondary gauge which would involve a single calibration parameter, preferably geometrical, and a simple device based on the PASCHEN breakdown voltage curve was finally developed. The breakdown voltage is a function of density only, for a given gas. Calibration is very accurate and easy to carry out. Calibration in the range from \(5 \times 10^{-5}\) mm Hg has been obtained and is completely repeatable.

Concentric cylindrical electrodes are used, which has the advantage that the breakdown voltage can also be theoretically calculated.

High frequency breakdown is used rather than DC breakdown to prevent arcs and the resulting electron erosion changing geometry and calibration. (The HF breakdown also requires less voltage.) From time to time, reverse biasing is applied to eliminate ions (this is done automatically and regularly 10 to 100 times per second). Steady readings can then be obtained.

Primary calibration is made by standard type McLEOD gauges placed inside the wind tunnel and remote controlled, so that only very short pressure leads are used.

Dr. Hall: Pressure measurements in Low density shock tunnel

Testing times range from 1 to 10 ms and fast response transducers are thus required.

Small piezoelectric pressure transducers have been used at CORNELL AERONAUTICAL LABORATORY for several years. Barium titanate crystals were initially used, but more recently lead zirconium titanate has been
preferred because of its higher sensitivity and stability (based on Bureau of Standards work in the field).

Currently, the most advanced transducers for installation in models are capsules with 3/8" diameter and 1/8" thickness (lead zirconium titanate). The sensitivity can be made in the range 1 to 10 volts/psi. Temperature compensation is obtained through special mechanical construction and mounting and sensitivity to acceleration is eliminated by using a second, dummy crystal to back out the acceleration signal of the pressure sensing crystal.

Initially, the transducers were mounted in a flat plate and recently yielded the first reliable pressure distribution data from the shock tunnel in the range M = 9 to M = 16 at free stream static pressures ranging from $10^{-3}$ psi (50 $\mu$Hg) upwards.

The measurement of static pressure levels down to about $10^{-4}$ psi (5 $\mu$Hg) was carried out successfully using a commercial ALTEC LANSING condenser microphone, carefully shock mounted on the wall.

It is planned to replace the present 11" x 15" nozzle on the shock tunnel by a 6 ft diameter conical nozzle, which will permit the use of substantially larger models and requirements for miniaturization of transducers will become less severe (1). It is expected that the shock wind tunnel can be developed to the Mach number range between 15 to 25, with free stream static pressure levels down to about 1 $\mu$Hg.

Dr. Maslach: What is the sensitivity and noise level of your voltage measuring system? Is it in the V range? It seems that the sensitivity is about 2 $\mu$V/ $\mu$Hg.

Dr. Hall: The sensitivity, which depends on the dimensions of the crystals, is reasonable now and will be improved in the larger scale nozzle. The prototype of the model had a pressure orifice of 1/6" diameter with internal transducer placed at 1/4" from the leading edge. The response time was then of the order of 10 to 100 ms, so that the connecting channel dimensions had to be increased, a difficult problem in a flat plate, close the leading edge but not with a blunt body.

Dr. Stalder: Are these gauges individually calibrated?

Dr. Hall: Yes they are, and different techniques are used: mounting the transducers in shock tubes or employing several other dynamic or semi-dynamic techniques. The stability of calibration is generally very good. (In the shock tube method, shock strength is deduced from a shock speed measurement.)

Dr. Talbot: Is signal leakage important?

(1) These developments have been reported at the 1960 summer IAS meeting (West Coast), and at the 1960 IAS National Symposium on Hypervelocity Techniques in Denver.
Dr. Hall: The time constant of the measuring circuit is very long compared with the duration of the test (with good electrometers it can be of the order of hours). For millisecond tests it is sufficient to use a good cathode follower circuit.
MEASUREMENT TECHNIQUES IN IONIZED GASES AT LOW DENSITIES

Dr. Talbot

At BERKELEY, we limit ourselves to ion concentration measurements at present. Two techniques are used and good agreement is obtained between the results:

a. Probe Techniques
b. Microwave Absorption.

a. Probe Techniques

The probes used are classic LANGMUIR probes, where the ion current drawn by the probe is measured. The following difficulty is encountered when the probe is used in a flowing gas: the ion current collected is proportional to the number density of the ions and also proportional to the sheath area $S$. $S$ is well known for simple probe geometries (sphere, cylinder) in an ionized gas at rest, for the sheath has also a simple geometry (sphere, cylinder concentric with the probe), so that the number density can be derived from the measurement of the current. In the presence of a flow, however, the sheath is distorted in a complicated fashion and $S$ is no longer known, so that no simple way exists to relate the number density of ions to the collected current.

At BERKELEY, this difficulty was solved, in a moderate density flow, by putting the collector at the stagnation point of a flat nosed body. A plane sheath then results, which is actually imbedded in the boundary layer and the sheath area is, for practical purposes, well defined.

To relate the collected current to the number density in the flow, one must then calculate the ion diffusion through the boundary layer. This can be done assuming ambipolar diffusion of the ions and electrons up to the sheath (calculations are analogous to those concerning diffusion of dissociated atoms in a dissociating boundary layer). One can then relate the current to the free stream ion density by using the boundary layer equations and the shock equations.

The measurements have shown current versus voltage curves as indicated on fig. VII, 1. The full curve shows the classical LANGMUIR probe effect (saturation current for large negative voltages, etc.)

The sheath effect is characterized by the change of ion saturation current as a function of voltage (change of sheath area with voltage). In our case, the slope of this curve is very small, indicating that the sheath...

area is practically constant, as expected from a plane geometry. The desirable result of a well defined relationship connecting current to ion number density (as shown by theory) is therefore obtained.

At much lower density, with probe Knudsen numbers of, say, ten, the problem becomes very difficult and no theory seems to be available. Small spherical probes have been studied for satellite work at similar Knudsen numbers. Ion trajectories have to be computed taking into account the potential distribution due to the ion density itself so that a complicated non linear problem results. This problem has been solved numerically only in the simplest cases (sphere, cylinder) and no solution seems to be available for plane geometry.

It would be worthwhile to try and solve this case for the plane probe which could then be used in free molecule flow as well.

b. Microwave Measurements

This type of measurement has been used by several groups.

It is well known that microwaves are not transmitted through a plasma if their frequency is less than the plasma frequency, which is proportional to the square root of the electron number density in the plasma. Measuring the cut off frequency for transmission therefore yields the plasma electron number density (technique used by DR. CHUAN and others). The only difficulty here is that this frequency is very high in highly ionized gases (40 KMc or even higher frequencies).

Another technique is to use a LANGMUIR probe and excite it with RF and measure the DC current. A resonance type curve is obtained if the probe current is plotted versus the frequency, the resonance peak occurring at the plasma frequency. In this case, the probe can be used without solving the difficult sheath problem, because the resonance frequency does not depend on the sheath or the flow. The method is practicable only if the plasma frequency is in the RF range or lower. In the case of a plasma jet with, say, $10^{12}$ to $10^{13}$ ionized particles per cc, the method becomes impracticable because of the difficulty of getting the high frequency signal to the probe. However, in the range of $10^9$ to $10^{10}$ ions per cc, the frequency is lower than 100 MC and the excitation can reach the probe and a local measurement of ion number density is possible by the resonance method.
DISCUSSION

Dr. Chuan: In the theory of the plane stagnation point LANGMUIR probe, you have to assume that the gas is frozen in ionization as it comes through the boundary layer.

Dr. Talbot: Either that, or one must work back and compute the error resulting from the assumption, which is very hard to do. If the density is low enough, you can assume that it is frozen. One can compute transit times and deduce how much unfrozenness can be tolerated, etc.

Dr. Chuan: What accuracy do you obtain from the cut-off type of measurement as compared to the phase shift and attenuation measurement?

Dr. Talbot: The cut-off measurement is much more accurate. We do it by a difference method. There are two paths available for the waves: one through the jet and the other through vacuum. The difference of the two emerging signals is measured by a detector. By an ingenious electronic arrangement, the difference signal can be displayed on an oscillograph and one can obtain fringes similar to that of an optical interferometer. The fringes disappear at cut-off, which gives an accurate determination of the plasma density. If the test is carried out by turning off the jet at the start of the oscilloscope sweep, one obtains a display of fringes which shift downward on the screen. The total shift gives additional information on the dimensions of the plasma, but these phase shift measurements are subject to much more uncertainty than the cut-off measurement.

The sensitivity of the measurement depends on the smallest frequency adjustment that can be made, which is about .5 KMC or 2%.

Dr. Devienne: Measurement of Velocity in a High Speed Molecular Beam

A technique for the measurement of velocity used in a high speed molecular beam will be described, which could perhaps be useful also at higher density levels.

In the case of an ion beam, a signal is applied to the ions by means of a special square wave generator (pulse durations between one and a few μs), and the response is observed on a tungsten strip heated at 1400°K.

The signal and response traces are recorded on a C.R.O. and the velocity is obtained by comparing them.

In the case of a neutral molecule beam we use two strips at two locations in the stream, about 65 cm apart. The velocity being 25 km/s, the flight time over this distance is quite small.

The same technique could be used in a nozzle and the distance between signal source and plate where the ion impact is recorded could be made much smaller because the velocity is much lower (2 to 3 km/s).
We have also calibrated static pressure probes by measuring directly the total flow rate in the stream and comparing the actual reading to the correct value for different flow velocities.

**Dr. Talbot:** Is the gauge used a heat transfer probe?

**Dr. Devienne:** No. The electron emissivity of tungsten is recorded by means of an oscillograph and the velocity can be measured because the response time of the device is very short (2 to 3 $10^{-2}$ s according to our measurements). This is much shorter than the response time of heat transfer gauges. The problem of response time is a very important one for high speed molecular beams. We have spent a whole year to study the various phenomena which could provide very short response time instruments. For instance, we tried to use the ROSTANI effect (emission of electrons by a copper surface due to impact of molecules) but did not obtain definite evidence of the effect. Finally, we developed a special device to record the impact of molecules. The molecule or ions impinging on a heated tungsten strip modify the thermo-ionic emission collected by a special external electrode, which is measured.

**Dr. Peters:** We have applied the DOPPLER effect to measure random motions in iron arcs of 6000°K. On account of the very small broadening of spectral lines by collision damping, iron, chromium and the rare earths should be qualified for these measurements.

The DOPPLER measurements of the molecular velocities in the iron arc (about 2000 m/sec), carried out at the Siemens laboratories, were in proper agreement with other spectroscopic measurements of the temperature. (BURHORN, F. : Z. Physik 140, 440 (1955)).

We hope now to apply the method to measurements of plasma jet velocities in the range of 3000 m/sec with an accuracy of about 150 m/sec by injecting small amounts of iron or rare earths in other gases (nitrogen, air, etc.).

At MACH numbers of 10 or higher, the gas starts radiating itself and the radiation emitted depends upon pressure and temperature so that a spectroscopic study of the gas radiation can provide information on pressure and temperature without the use of any probe. The structure of the jet flow, moreover, will be directly visible by this radiation, as it may be illustrated by the picture of the MACH disc configuration (fig. VII, 2) in a water plasma jet of about 6000 m/sec and 8000°K. (See also PETERS, Th. : Naturwiss. 24, 571 (1954) and FINKELNBURG, W. and MAECKER, H. in Encyclop. of Physics, Vol. XXII, p. 301, 403, Springer-Verlag).

We also hope to be able to apply the DOPPLER technique in this case.
In view of the great number of new low density wind tunnels, it is important to analyze the methods available for the calibration of the test section.

In the low density wind tunnels at BERKELEY, UTIA, Ames (designed by DR. STALDER), one was fortunate in just barely having an isentropic core and could therefore rely essentially on the measurement of stagnation conditions and some corrected impact pressure data.

In most of the new facilities, designed for still lower pressures, great difficulties will be encountered because of the lack of isentropic core, so that one does not know any of the three variables (M, p, T for instance) required to define an equilibrium uniform flow.

There are, as we have seen, several good and promising methods for measuring density.

a. Impact Pressure Probes

Reynolds number effect on impact tube calibration at a given Mach number has been tested extensively and the results are classical (Fig. VIII, 1). At high Reynolds numbers the measured pressure tends to the ideal value, but below a Reynolds number of about 100 increasing departures from unity are observed, an effect well known since many years. Since then, more knowledge has been gathered about this effect.

b. Effect of Temperature on Pressure Measurement on Models

(Ref. Flow Regime)

This is a new effect that has been recently realized. If one plots, for instance, the static pressure on a cone compared to the ideal cone pressure versus the interaction parameter $M^3 Re^{-1/2}$ (1), one obtains a curve which is strongly dependent on the temperature conditions of the boundary layer (expressed, for instance, by the ratio of stagnation temperature $T_o$ to wall temperature $T_w$) (Fig. VIII, 2). This effect can produce changes by factors up to 5 and has been experienced in the calibration of high altitude sounding probes. All results published earlier on the subject of impact pressures or static pressures on models are therefore valid only for one particular model temperature.

(1) There is an additional practical difficulty here in that one has to measure another data in order to be able to calculate the Reynolds number itself.
c. **Free molecule probes**

The behaviour of these probes is easy to calculate, because they operate with free molecule flow regime. The work of SHERMAN on molecular hot wires shows a very marked dependance of equilibrium temperature on Mach number \( \left( T_{equ}/T_{static}, \text{flow} = f(M) \right) \). This is a good Mach meter up to \( M = 3 \). At higher Mach numbers, the heat transfer also has to be measured. There are of course practical difficulties, due to radiation and support heat losses but also due to the fact that surface emissivity and energy accommodation coefficients play a role.

UTLA has developed a free molecule pressure probe based on theoretical calculations (2). This is a cylindrical probe with axis normal to the flow direction with an orifice in the side. The dimensions are such that the mean free path inside the tube is much larger than its dimension. Good data about the flow may be obtained when pressure is recorded for different angular positions of the orifice with respect to the flow, for the ratio \( (P_{probe})/(P_{free stream}) \) is a function of \( M \) alone so that no calibration is required in practice. (It does not depend on surface accommodation coefficients).

These probes appear to be much more promising than impact tubes for tests in slip flow regime (slipping boundary layer measurements, etc.). Impact tube require Reynolds number in excess of 100 to give easily interpretation of readings, so that they tend to become too big to probe a boundary layer, for instance. They can perhaps be used to calibrate the flow in favorable cases. However, all these probes require further information to interpret the results in non insentropic flow and this causes great difficulties. It is not sufficient, strictly speaking, to measure locally three quantities, for everything becomes extremely dependent on gradients.

The main difficulty with free molecule probes is that the interpretation of readings depends on free molecule calculations assuming equilibrium, so that they are not applicable in a boundary layer for instance.

In general, these probes give only one numerical data about the molecular distribution function \( f \) and this is not much information unless one has an equilibrium distribution or something similar. They are, of course, quite satisfactory for qualitative work even in the non equilibrium cases. Examples of this are the tests by Laurmann on the flow field in the vicinity of the leading edge of a flat plate at \( M = 2 \) (3) and the shock wave structure measurements by Sherman and Talbot (Ref. cit.). In both cases free molecule hot wires were used.

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In the flat plate tests by LAURMANN, lines of constant wire temperature in the flow field were obtained but no data about the flow parameters M, p, are obtained. It is a purely qualitative test which shows the shock wave location and no more (fig. VIII, 3). (At M = 6, even the shock cannot be detected unless the isotherms are plotted for fractions of 1° C. The shock could be detected if heat transfer measurements were made as well.)

As the probe response depends on the full molecular distribution function, quantitative results can be obtained, in non-equilibrium cases, only when detailed theoretical data is available about the particular form of distribution function in the application considered.

For instance, in the case of a flat plate in free molecule flow one can construct a simple model whereby the distribution function has values corresponding to upstream equilibrium conditions of flow for velocities associated to trajectories not originating on the plate, and the value corresponding to equilibrium with the wall for velocities associated to trajectories originating on the plate (assuming complete accommodation).

Then one can compare results of measurement of the pressure density product by means of a probe with the values predicted theoretically. Reasonable agreement has been obtained (1).

Infinitesimal departures from equilibrium also could be treated but the problem is still very complicated. Available theories point to the necessity of measuring 13 independent parameters at a given point (2). In addition to $v_i$, p, and T, one should measure, for instance the stress components $p_{ij}$ and the heat flow $q_i$ and equilibrium temperature probes, heat transfer probes, local stress probes, etc. should be designed. This is possible in principle, but not practically.

In conclusion, it can be said that free molecule probes are very promising for qualitative probing of non-equilibrium flows (boundary layers, shock waves, etc.) and very well suited for the calibration of a wind tunnel without isentropic core, but with uniform test section flow. However, they are completely unusable at the present stage for local measurements in non-uniform flows.

This lack of measuring methods is going to be the main problem in the many research programmes involving boundary layer traverses and study of velocity distributions in slipping boundary layers, etc.

(1) E.L. HARRIS: Investigation of Free Molecule and Transition Flows Near the Leading Edge of A Flat Plate, UTIA Report n° 53.

d. Dynamic pressure probe (q-probe)

A recently developed probe for isentropic flow measures the force $F$ on a sphere (1), which is given by $c_DqA$ ($A = \text{area}$). $q$ is proportional to $M^2$ in isentropic flow so that a Mach meter is available after one has calibrated to get $c_D$.

This type of probe was using with surprising success in the isentropic flow in a "hot shot".

e. Effect of thermal transpiration on pressure measurements

One of the most appealing aspects of piezoelectric gauges is that they can be put flush in a surface and require no orifice like all other gauges.

An orifice layout is not hopeless if the effect of the orifice on the flow can be calculated or if calibration is possible, but if the static pressure is of the order of one micron, the thermal transpiration effect leads to considerable difficulties. If one uses an orifice such that the Knudsen number based on its dimensions is of the order or greater than one, a pressure difference due to thermal transpiration will appear, because the gas in the boundary layer close to the orifice is usually hotter than the model. Dr. Talbot tried to compensate for the effect in systematic tests in the course of his experiments on surface pressures on cones, but no reliable result could be obtained.

The error in static pressure measurement resulting from the effect depends on thermal conditions and can be of the order of 0.1 or even 1 micron. The thermal transpiration effect depends on the full molecular distribution function outside the hole and we have again a complicated problem typical for flows at slightly lower densities than those studied so far at Berkeley and UTIA.

This is a good reason for developing the flush gauges where no flow to the gauge is involved and pure momentum transfer is measured, which does not require detailed knowledge of the flow or the distribution function for interpretation.

(1) Described during the low density meeting at Berkeley in June 1960.
DISCUSSION

Dr. Chuan: Surface interaction phenomenon (as characterized by accommodation coefficients, for instance) should be considered when dealing with flush gauges in the lower pressure ranges mentioned.

Dr. Schaaf: Yes. The theory is clear: the reading of a flush gauge depends only on the normal accommodation coefficient. However, according to recent tests we carried out at BERKELEY, the normal stress seems to depend surprisingly little upon the normal accommodation coefficient.

Dr. Estermann: To put people's minds at rest, I want to remind that diffuse reflection may be assumed for any engineering surface except in extremely peculiar conditions.

Dr. Schaaf: The tangential momentum accommodation coefficient $\sigma$ is always close to unity, corresponding to diffuse reflection (cosine law of emission). However, the energy accommodation coefficient $\alpha$ and the normal momentum accommodation coefficient $\sigma'$, which have the same order of magnitude, may be quite different from unity (fast incoming molecules can come off much faster than if they were in thermal equilibrium with the wall). $\alpha$ and $\sigma'$ are thus much more variable than $\sigma$. However, the dependence of the actual pressure measured on $\sigma'$ is a very weak one (say 10% raise in pressure reading for 100% raise in $\sigma'$). This pressure is a simple moment of the distribution function.

Dr. Estermann: These remarks apply to any type of sensing instrument, if it is essentially flush. There is little choice then: if a transducer needing an orifice is used, trouble will be encountered with thermal transpiration, and if a flush gauge is used, one has difficulties with $\sigma'$.

Dr. Schaaf: The latter seems much easier to deal with than the first.

Dr. Cox: Is there any good method available for direct measurement of velocity?

Dr. Stalder: We tried very hard to develop such a method during the last six months but were not successful. Ion tracking was tried but trouble was encountered because of ion diffusion. The "blobs" therefore change shape between successive tracking stations, and show little correlation.

Dr. Chuan: The fact that correlation techniques are now in a much more advanced state than 5 years ago could improve the situation.

Dr. Stalder: Yes. But right now, people are working very hard on the problem but encounter considerable difficulties.

Dr. Talbot: We have experimented with the tracking of ion clouds and have obtained a $\pm 5\%$ accuracy in measuring velocities.
Dr. Stalder: It works well, but it is different when you have to track a cloud at 20,000 ft/sec as in the more recent tests.

Dr. Talbot: Our tests were carried out at 3,000 ft/sec.

Dr. Estermann: Would it be possible to use the DOPPLER effect in this application?

Dr. Talbot: The shift is so small that an enormous spectrograph would be needed to obtain sufficient resolution (40 ft long grating). One can measure a fraction of Angstrom with a Fabry spectrograph, but there is always an ambiguity as to whether the shift is due to DOPPLER effect.
Dr. Lobb

Nozzles for low density are of course not commercial items like the pumping systems described earlier. They are usually designed by the investigator who plans to use them, and each research worker has his own ideas about the design. The following contribution contains the author's own views and interpretations which may be incorrect in some cases. Unfortunately, no data about nozzles developed in Europe could be included because of lack of information.

At the Naval Ordnance Laboratory, the nozzles operate at low densities only because of high Mach number operation, so that the situation is somewhat different from the case of the low density flow in the accepted sense, because the Reynolds numbers are much higher.

The initial development of nozzles for low density flows was carried out in the early 1950's at the University of California, BERKELEY (SCHAAF, OWEN, SHERMAN) and at the AMES Laboratory of NASA (STALDER, GOODWIN, and CREAGER). This was followed by the construction of a low density wind tunnel at TORONTO (UTIA) and more recently at the University of Southern California and in France and Great Britain.

**Basic Considerations**

Continuum flow theory is still applicable in the design of low density wind tunnel nozzles since the molecular mean free path is generally quite small compared with the nozzle dimensions. Indeed, for the acceleration of a flow to sonic velocity at the throat with a subsequent expansion to supersonic speeds, it is necessary for many intermolecular collisions to take place in a small volume of the gas.

As the density is lowered in a conventional supersonic nozzle, the boundary layer thickness increases considerably. As a rough value of the laminar boundary layer thickness at the nozzle exit, the value for an insulated (adiabatic) plate given by COHEN and RESHTOKO may be used for order of magnitude evaluation.

\[
\delta = \frac{5.248}{\sqrt{Re_L}} \left( 1 + 0.0914 M_e^2 \right) L \tag{a}
\]

where \(L\) is the nozzle length (from throat to exit), \(M_e\) is the exit Mach number and \(Re_L\) is the Reynolds number based on exit free stream conditions. The KNUDSEN number based on nozzle exit diameter \(d\) is

\[
K_d = \frac{\lambda}{d} = \sqrt{\frac{8 \pi}{2}} \frac{M_e}{Re_d} = \sqrt{\frac{8 \pi}{2}} \frac{M_e}{Re_L} \frac{L}{d} \tag{b}
\]
The boundary layer will fill the jet when $\delta = d/2$ or, according to (a) and (b), when

$$
K_d = \frac{0.0134 M_e}{(1 + 0.0914 M_e^2)^2} \frac{d}{L}
$$

For $d/L = 0.2$ (a typical value) and $M = 5$, we obtain $(K_d)_{max} = 0.004$ so that the mean free path will be less than $0.4\%$ of the exit diameter at the time the boundary layer fills the jet.

Slip flow may be expected to occur at the wall when $K_d = \lambda/\delta = 0(0.01)$ (Tsien's criterion) or, in the present case when $K_d > 0.005$. Hence, little, if any, slip flow may be anticipated on the walls of a low density supersonic tunnel nozzle (slip flow has, however, been observed on the walls of a short subsonic nozzle at UTI A, but this was largely due to the fact that the gas temperature was still high so that the mean free path was rather large.

The preliminary considerations indicate that supersonic low density nozzles will have thick laminar boundary layers with little or no slip at the wall. The maximum size of molecular mean free path in the test section will be only a few thousands of the nozzle exit diameter. Consequently, to test model under free molecule flow conditions it is necessary to use either a very small model or an extremely large nozzle. The latter approach has been attempted at the University of Southern California.

Methods for Reducing Nozzle Boundary Layer Thickness

At Ames, Stalder, Goodwin and Creager introduced a rather novel remedy to the thick boundary layers by applying suction to the boundary layer on a porous nozzle, constructed from a stack of thin metal sheets, held together by four bolts running parallel to the nozzle axis (fig. IX, 1). Washers were slipped on the bolts between adjacent metal sections, thereby providing suction slots. The width of the slots was increased towards the nozzle exit so as to provide uniform suction along all the length of the nozzle.

Altogether, three porous nozzles were constructed which produced Mach numbers of 2, 2.5 and 3.15 with only a $2\%$ variation in Mach number over a range of test section static pressure between 80 and 200 microns. Fig. IX, 2 shows a typical plot of Mach number profile and the improvement due to suction can be clearly seen.

The pumps used for boundary layer suction could, of course, be used to pump downstream of the nozzle, which should permit the use of a bigger nozzle and lead to a larger uniform core as well but the only advantage of boundary layer suction is that good Mach number distribution can be achieved for a wider pressure range.

Dr. Chuan, at the University of Southern California, plans to control the boundary layer thickness for a $M = 8$ conical nozzle operating at $3 \mu$ Hg by
using controlled cooling (fig. IX, 3).

Fig. IX, 4 shows the effect of cooling on the boundary layer thickness at two typical high Mach numbers. It can be seen that in these cases, the boundary layer displacement thickness can be thinned by only a factor two for a wall temperature equal to $0^\circ$ R. This could, of course, be used to produce a substantial increase in the test section Mach number and also to maintain the Mach number constant for various pressure levels.

At lower Mach numbers, substantially larger decreases in $\delta^*$ can be achieved. For example, for some of the highly cooled nozzles designed at the Naval Ordnance Laboratory, we find that the displacement thickness can be negative at the nozzle throat; however, the total thickness is never equal to zero under these conditions.

The cooling is, of course, quite favorable from the point of view of mass flow requirement, but not necessarily from the point of view of flow uniformity. However, at very high Mach numbers, the displacement thickness tends to the total thickness and both results are achieved, one of the rare instances of a favorable effect at high Mach numbers.

**Design of Supersonic Low Density Nozzles**

Experience has shown that supersonic low density nozzles can be successfully designed by adding a boundary layer correction to an inviscid core designed to achieve the uniform parallel jet at the desired exit Mach number. In constructing the nozzle, the wall is displaced outward from the isentropic core boundary by a distance $\delta^*$, the displacement thickness, so that the mass flow of the real flow will be the same as that carried by the core of the potential flow in the absence of a boundary layer. The radius of the uniform flow at the exit of the nozzle is $r_u = r_i - \delta (1 - \frac{\delta^*}{\delta})$.

For high Mach numbers, with an insulated wall, $\delta^*$ tends to $\delta$ so that the radius of the uniform flow approaches the isentropic core radius even though the boundary layer may be quite thick.

While two dimensional nozzles have been successfully used for low density work, generally speaking, axisymmetric nozzles are preferred for low density work because the boundary layer correction may be uniformly applied. A method widely used was developed by OWEN and SHERMAN (1) in which the isentropic core is calculated by the method of characteristics for a specified axial Mach number distribution. The flow in the immediate vicinity of the nozzle throat is obtained from a solution of a potential equation perturbed about $M = 1$. If the specified axial distribution has a continuous first derivative, then the second derivative of the wall profile will be continuous, etc.

A digital computer program was developed at the Naval Ordnance Laboratory, which is similar to the scheme used at the University of California several years ago and is now being used to design axisymmetric nozzles for air and other gases with a constant $\gamma$.

The $M = 4$ nozzle at Berkeley was found to be within 0.4% of the predicted Mach number distribution and the boundary layer thicknesses were within 1 or 3% from the calculated values.

The early low density wind tunnel tests were made at Mach numbers up to about 5, or so, with cold air. In these cases it was found that a suitable laminar boundary layer correction resulted from a momentum integral calculation for an adiabatic wall assuming either a straight line or a sine arch velocity profile.

I might add here that a brief discussion of the effect of the varying radius of curvature on the boundary layer characteristics has been given by Lynes at the University of California\(^\text{(1)}\). He has concluded that the radial term has an effect similar to an adverse pressure gradient. The second major assumption that has been used in many of these nozzle designs is to assume that $d\delta/ds = 0$ at the nozzle throat and thus to begin the calculation at this point. This procedure was found to give fairly good results although it is not necessary because the boundary layer can be calculated all the way from the subsonic section up through the supersonic portion. This, I might add, is the method in use at the Naval Ordnance Laboratory.

Design of Nozzles for High Temperature Low Density Flow

This final part will discuss some work carried out at N.O.L. on the design of nozzles for hypervelocity ($M = 10$ to 20) or high temperature low density flow (design study for 2 sq.ft nozzle). Several new problems arise, in this case, which tend to make the simulation of free flight rather difficult. The three main problem are:

a. At high Mach numbers the supply pressure required to simulate free flight conditions becomes enormous. For example, for a test section pressure of $10^{-4}$ Hg and a static temperature of $400^\circ\text{R}$ a supply pressure of 1000 atm. is needed to achieve a Mach number of 19.

The supply temperature required is in excess of 8000 $^\circ\text{K}$.

b. With such elevated supply pressures and temperatures the heat transfer rates in the vicinity of the nozzle throat become very large and create a need for special cooling methods or else very restricted running times.

c. At high temperatures and low pressures, frozen flow is encountered due to finite oxygen recombination rate, and produces a basic limitation on low density simulation.

Real Gas Axisymmetrical Nozzles with Equilibrium Flow

A number of nozzles for air in dissociation equilibrium have been designed at the Naval Ordnance Laboratory by the method of characteristics. The thermodynamic properties used in these calculations were determined from National Bureau of Standards data.

After the isentropic core coordinates and the flow quantities along the contour were determined, a laminar or turbulent boundary layer correction was added to the boundary layer contour. An example of a nozzle designed by this means is shown in fig. IX, 5.

The chief difference from a perfect gas nozzle, as far as the isentropic core is concerned, is the much smaller throat size at the elevated stagnation conditions.

Boundary Layer Growth and Heat Transfer

When hypersonic nozzles are considered, the supply pressures are often high enough, so that the boundary layer may be expected to be turbulent, at least under the most severe operating conditions. Calculations for a family of real gas nozzles for \(11 < M < 19\) with supply temperatures up to 7500°K gave throat Reynolds numbers ranging from 450 to 16000 for stagnation pressures ranging from 50 to 500 atm. In general, the favorable pressure gradient and high wall cooling tend to favor laminar flow. Laminar boundary layer calculations have also been made by the Cohen and Reshotko technique for a family of perfect gas nozzles over a wide range of temperatures for a stagnation pressure of 10 atm.

The values of Reynolds number varied from 290 to 760 at this pressure level, and at other pressure levels would be proportional to the square root of the stagnation pressures. For a hypersonic nozzle, the values of Re peaks sharply at short distance downstream of the throat so that, as the operating pressure is raised, transition may be expected to occur near the nozzle throat rather than at some other point in the nozzle. This is shown in fig. IX, 6.

The turbulent boundary-layer calculations were made using the momentum integral equation, with the more or less standard procedures employed for a perfect gas. The chief difference being that the enthalpy in the boundary layer was evaluated from the velocity by assuming that the Crocco integral relation holds.

The heat transfer which was determined from Reynolds's analogy always peaks sharply in the vicinity of the nozzle throat as can be seen on fig. IX, 7.

From a total of 27 runs for nozzles designed for Mach 11 to 19, supply pressures from 50 to 500 atm, and supply real gas temperatures from 4,500 to 13,500°R, it was found that the heat transfer could be correlated by the equation shown on fig. IX, 8. It has to be kept in mind that this applies only to turbulent boundary layers. But even so, the test section
static pressures are very low in all these cases, say from 50 to 100 \( \text{Hg} \).

The results are only slightly influenced by changes in nozzle inlet contour. It can be seen that the values of peak heat transfer range from 1600 to 60,000 BTU/ft\(^2\)/s. Heat transfer rates up to 10,000 BTU/ft\(^2\)/s can be handled by conventional water cooling using a copper nozzle. In addition, higher heat transfer rates can probably be overcome by water film cooling.

The heat transfer rate in a laminar flow nozzle -say at 10 atm supply pressure, is only about 65 BTU/ft\(^2\)/s for a supply temperature of 5,000\(^o\)R.

Non-Equilibrium Flow in Hypervelocity Nozzles

When air is expanded in a nozzle from a high supply temperature, the finite vibrational relaxation rate and recombination rate of dissociated atoms may produce departures from thermodynamic equilibrium. Departure from vibrational equilibrium do not alter the flow very much because only a small part of the energy is in this form. Following the work of Heims at NASA\(^1\), calculations of non equilibrium flows have been made by GLOWACKI at the Naval Ordnance Laboratory for a wide range of conditions in hypersonic nozzles. The gas was assumed to consist of oxygen and nitrogen molecules and atomic oxygen only.

First, an isentropic expansion of such a gas, assuming thermodynamic equilibrium was computed by integrating the equations of mass, momentum and energy in finite difference form. In this case the fraction by weight \( X_e \) of oxygen in atomic form depends on \( K_e(T) \), the equilibrium rate constant, where \( T \) is the local static temperature in the flow. Given the supply conditions, the IBM 704 equilibrium program computes the temperature, pressure, density, compressibility, velocity and sound speed as a function of area ratio assuming one dimensional flow. The results obtained agree well with real air up to a temperature approaching 5000\(^o\)K, i.e., when only oxygen dissociation is present.

Secondly, the effect of a finite oxygen-recombination rate on this flow was determined by another computation. An additional equation is required for this, which states that the rate of change of oxygen atom concentration with distance is directly proportional to the amount by which the concentration departs from equilibrium, and inversely proportional to the relaxation length. This equation, together with those used for the equilibrium calculations, and a specification of the nozzle geometry (area \( A(y) \) in function of axial coordinate) are sufficient to determine a solution. Conical nozzles with a circular arc throat, of the same length and area ratio as real gas nozzles designed by the method of characteristics were the basis of the calculations. These nozzles ranged in length from 13 to 20 ft, and has an isentropic core area of 2 ft\(^2\) at this exit. A typical plot of \( X \) and \( X_e \) versus area ratio for \( T = 5000^oK \) and various supply pressures is shown in fig. IX, 9.

\(^{(1)}\) S.P. Heims, Effect of Oxygen Recombination on One-Dimensional Flow at High Mach Numbers. NACA, T.N. 4144 (Jan, 1958).
In all cases, the flow "freezes" and remains frozen for $M$ higher than about 4. Fig. IX, 9 shows the values of $X$ as a function of supply conditions. In these calculations the oxygen recombination rate constant was computed by the formula of Wigner\(^{(1)}\).

Now, recombination occurs when two oxygen atoms simultaneously collide with a third body which carries away the excess energy and momentum. Recently, an experimental study of oxygen mixed with argon has been made by CAMAC and VAUGHAN at AVCO. The results seem to indicate that recombination takes place more slowly than predicted by WIGNER's theory which was the basis of the Naval Ordnance Laboratory calculations. In other words, freezing of the flow will be more severe than our initial calculations indicate. It seems safe to conclude that any wind tunnels achieving slip flow with dissociated air will be operating with completely frozen flow. An indication of the effect of frozen flow on the flow parameters in hypersonic nozzles is shown in fig. IX, 10.

Generally speaking, the departures may not be very serious even though the flow is frozen, provided that the fraction frozen out is not too large.

**Diffusers for Low Density, Hypervelocity Wind Tunnels**

A long, straight tubular diffuser is planned for the N.O.L. hypersonic facility. The idea is to use the considerable momentum available in the core at the nozzle exit, which should not be wasted. At the outlet the flow will be subsonic, as a result of shock waves and boundary layer interaction.

The only force acting on the system is friction, and the duct should therefore not be too long (tests have shown that for $L/D = 18$ and for $M = 12$, the friction losses are only 2 to 3%). It is then expected that most of the momentum will be recovered. The equations of continuity and conservation of momentum and energy may be applied and it is seen that this leads to much less than normal shock recovery because of the change in area from $A_1$ (equivalent momentum area of incoming flow) to $A_2$ (area of the duct, $A_2 > A_1$). Pressure ratios of 10 to 20 have been obtained in long ducts, and 20% to 30% of Pitot pressure is recovered. This might make all the difference for we will be able to use simple mechanical pumps and no expensive steam ejectors will be required.

For instance, if the test section pressure is about 200 \(\mu\)Hg, the diffuser outlet pressure would be about 4 mmHg.

\(^{(1)}\) See, for instance, S.P. HEIMS, Loc. cit. (NACA T.N. 4144, 1958)
DISCUSSION

Dr. Schaaf: Don't you expect backflow on the sides in a diffuser with such thick boundary layer?

Dr. Lobb: We don't think so. Anyway, one could put vortex generators to provide mixing. The main problem would be the adherence of the jet to one side of the wall, which would completely destroy the efficiency of the diffuser. We think we can avoid this as has been the case with most of our supersonic and hypersonic tunnels so far.

In our case, Al (equivalent momentum area) was 3.7 ft$^2$. This straight through, tubular diffuser seems to be the cheapest and most efficient device, even for supersonic flow (L/D would be 9 to 10 in the supersonic case). We have been using this for several years. If such a tubular diffuser gives us the expected efficiency, it will be very important for it means that steam ejectors will not be needed, and simple mechanical pumps will be sufficient.

Dr. Maslach: In view of our own experience, I doubt whether such a diffuser will work satisfactorily in presence of models or cross stream supports for probes, etc.

Dr. Lobb: The boundary layers are probably much thicker in your range of operations and furthermore, we will have much more momentum available because of the high Mach numbers.

Dr. Talbot: We have tested this type of diffuser, based on LUKASIEWICZ's analysis, in supersonic flow but could never obtain the predicted performance in practice. It is true that in hypersonic flows, a huge amount of momentum is available to be recovered, but in supersonic flow a moderate amount could, at least, be recovered. This does not seem to be possible in our experience.

Dr. Schaaf: The main problem is mixing and it is difficult to force the flow to mix. Our experience is that if you try to recover any part of the available momentum, separation occurs which may choke the flow in the test section and in the nozzle.

Dr. Chuan: One should keep in mind that Dr. Lobb is dealing with Reynolds numbers much larger than for most low density facilities and with turbulent boundary layers. This is always advantageous from the point of view of recovery.

Dr. Lobb: Yes. I insisted on this.

We realize that an important decision has to be made here whether steam ejectors will be needed or not. (The cost of the ejector plant would be about $1,000,000). However, free steam is available and could be used to drive ejectors if the diffuser is not efficient enough.

Dr. Chuan raises a question about equilibrium in the flow. Does it seem
advantageous to allow the flow to dwell a while in the medium low Mach number range to allow sufficient time for equilibrium condition to be reached?

Dr. Lobb: No, this does not help much. We use small cone angles for the nozzle in order to obtain larger transit times.

Dr. Wegener: Very little, if any choice of geometry is available if one wants to prevent freezing out. Enormous changes will be required (scaling up by two orders of magnitude) if freezing is to be eliminated.

Dr. Hall: Calculations about non equilibrium air flows were carried out at CORNELL AERONAUTICAL LABORATORIES, using a simple kinetic model: the calculations were made by considering only the oxygen dissociation and recombination as finite rate processes. The limiting cases of zero and infinite rates were considered. Temperatures of 4,000, 5,000 and 6,000°K and stagnation pressures of 100 and 1000 atm were considered. The results for the frozen case are indicated on fig. IX, 11. Comparison of these results with experimental data seems to indicate that it is reasonable to neglect the NO₂ reaction up to 6,000°K.

Typical rates of $10^{15}$ particles per cc and per s were encountered for the oxygen reaction. The dependance of the effect of freezing on nozzle flow in function of both pressure and temperature is enormous as shown on fig. IX, 12. For instance at 6,000°K and 100 atm stagnation pressure, differences of 20% to 50% appear between finite rate and equilibrium Mach number, and 200% between the corresponding Reynolds numbers. At 5,000°K, or at a stagnation pressure of 1000 atm, these differences drop to about 10%.

The lowest test section static pressures were of the order of 10 to 100 µ Hg. In conclusion, it appears to be preferable to operate shock tunnels at the highest possible stagnation pressures to minimize non-equilibrium effects.

Some calculations were carried out on the freezing of electron mass concentration in order to investigate the possibility of sending microwaves through large scale shock tunnel nozzles (6 ft diameter) (1).

The electron concentration profiles were computed in the first stage nozzle (two dimensional) of a shock tunnel, which is upstream of the large second stage nozzle. The basic assumption in the calculation is that the important ionization kinetics are the classical three body recombination (the rates of which can be calculated) and the dissociative recombination (data based on AVCO low density shock tube experiments by LIN). The results are shown on fig. IX, 13.

The freezing turns out to be analogous to the case of atomic dissociation and recombination. The classical equilibrium for the NO reaction

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(1) These calculations will be reported in the I.A.S. meeting in December 1960.
was assumed, which seems to be a good approximation, and a perturbation method may be used in the calculations. The dissociative recombination, which is a two body collision process, becomes quite important at low pressures. The pressure level again has a significant effect on the departure from equilibrium.

Dr. Talbot asks Dr. Lobb what sound speed is chosen in the reacting gas nozzle calculations: the frozen sound speed or the equilibrium sound speed.

Dr. Lobb: We have used the frozen sound speed, which can be calculated knowing the composition of the gas (molecular and atomic oxygen, etc.)

Dr. Chuan: There has been a controversy on this subject.

Dr. Wegener: The controversy has been resolved to some extent. Most of the available calculations (BRAY, HALL et al.) refer to one-dimensional, variable area case where the question does not arise. However, if a nozzle for reacting gas is to be designed by the method of characteristics, one has to consider the two speeds of sound. The frozen and the equilibrium speed of sound ( \( \sqrt{dp/d\rho} \) calculated for isentropic process assuming either constant, frozen concentrations of the components of the reacting gas or variable concentrations obeying the law of mass action). The difference between these speeds can be quite significant for largely dissociated medium. A priori, therefore, the Mach number and the direction of the characteristics are not well defined. The characteristics are, in fact, governed by the frozen speed of sound because it appears in the highest order terms of the partial differential equations governing the flow of a reacting gas in equilibrium. On the other hand, one has to evaluate how fast the small disturbances propagating with the frozen speed of sound decay in the flow. The characteristics starting from a point with a slope governed by the frozen speed will therefore gradually go over into those defined by the equilibrium speed of sound and there is no clear cut way of applying the methods of characteristics to the design of reacting gas nozzles.

There are some calculations by Dr. COLE and myself, which we checked experimentally, showing that the frozen speed of sound governs the characteristics(1).

Dr. Schaaf: The design of a nozzle then requires the solution of a third order hyperbolic partial differential equation.

Prof. Brun: Where do the boundary layer thickness versus wall temperature curves come from?

Dr. Lobb: They result from a theoretical calculation by COHEN and RESHOTKO\(^{(2)}\).

Prof. Brun: What pressure level do they refer to, for the pressure has an influence?

Dr. Wegener: They are valid for one particular nozzle pressure, for the thickness ratio depends on the pressure.

To heat air and then expand it to obtain a stream of air in equilibrium at room temperature going at, say, 25,000 ft/s seems to be a wrong approach to hypervelocity simulation, but no other method (turbine, etc.) was found to be practically feasible up till now.

There are two main groups of heating techniques used in this respect, the transient and the essentially steady state techniques.

1. Transient Techniques

The first of these methods was the shock tube, later developed into the shock tunnel by the CORNELL AERONAUTICAL Laboratory group. Recently, a free flight firing range was used at NASA Ames Laboratory to fire models into a shock tunnel, which seems to be the limit of what can be reached by such techniques.

A "brute force" method has also been used at NASA, utilizing a piston compression heater and a breakable diaphragm. The piston is driven by an explosion (fig. X, 1).

The "hot shot" has also found wide use in the U.S.A. This device is based on the release of a large amount of electrical energy in a high pressure chamber fitted with a breakable diaphragm bursting during the discharge (fig. X, 2).

The running times for all these facilities are of the order of one millisecond.

2. Steady State Heaters

The first heaters of this type used refractory metals and oxides and were therefore limited to temperatures certainly below 3000° K.

The largest tunnel using such a heater employed Al₂O₃ pebbles (NASA, Langley Laboratory), and a zirconium oxide heater was fitted to a NASA Ames Laboratory tunnel, which permitted operation up to 4000°F.

The main weakness of these systems is that they do not allow simulation of real gas effects but are valuable only for materials testing and for high temperature boundary layer studies.

At present, the trend seems to be to use electric arc heating. This was initiated by a paper by FINKELNBURG (1) on water stabilized arcs.

producing superheated steam, which was ejected through a Laval nozzle. Aerodynamicists then started testing with vortex stabilized liquid nitrogen arcs and a great amount of work on arc heaters for wind tunnels is going on, at present, in the U.S.A.

Before planning a heated tunnel, the question of the purpose of the tests should be decided first.

The major problems requiring hot tunnels are, at present:

a. Study of real gas flows around glider type vehicles, re-entry capsules, etc.

b. Communications studies, i.e., study of propagation of radio waves through boundary layers around such bodies.

c. Development of heat resistant materials for various types of trajectories (this, of course, requires running times much larger than milliseconds).

Recently, there has also been a surge of interest for the high temperature wind tunnel as an inexpensive way to simulate rocket exhausts (some people recently suggested to blow hydrogen and hydrochloric acid through an electric arc, which we do not contemplate with great enthusiasm).

**Electric Arc Tunnel (fig. X, 3)**

Fig. X, 3 shows the simplest form of such a tunnel. A sustained arc is produced in a high pressure chamber. The power supply is usually, but not necessarily, D.C. Superficially, this appears to be an attractive device but many drawbacks appear when going into details: the flow is contaminated by NO, NO₂ and products of combustion of electrodes materials with air and considerable departures from equilibrium are observed.

The first arcs used carbon electrodes and measurements have shown that all the oxygen was spent in electrode combustion, so that no free oxygen was left in the flow, which contained only CO, CO₂, N₂, CN, NO₂, etc. Considerable study was devoted to electrode configurations minimizing contamination and combustion.

One of the first successful configurations was developed at the NASA Ames Laboratory and used strongly cooled concentric copper rings for cathode and anode (high velocity water cooling). These electrodes were placed in the axial field of an electromagnet to spin the arc in the annular gap so as to prevent local electrode overheating (fig. X, 4). The resulting air stream was uncontaminated.

The major problems arising with any of these configurations are:

1. Radiation heat transfer losses,
2. Electrode heating,
3. Lack of equilibrium in the flow.
1. Radiation Losses

These losses are enormous and calculations based on available data (1) on air emissivities result in very discouraging figures.

For example, if a stagnation enthalpy $H_0 = 10,000$ BTU/lb is considered (this corresponds to getting room temperature in the gas after it has been expanded to reach 22,000 ft/s) and a stagnation pressure of 100 atm, the radiation loss from a 3" diameter sphere of gas would be about 2000 KW.

One also has to consider the radiation losses from the arc column itself, which will usually be even greater because of the higher temperatures in the arc. It seems therefore unlikely that wind tunnels using stagnation pressures higher than 100 atm and enthalpies higher than 100,000 BTU/lb are possible because of the radiation losses alone and no future can be seen for hypersonic wind tunnels with full temperature simulation, because it will prove impossible to put enough energy in the flow.

2. Electrode Heating

This is another difficult problem. A cathode, for instance, would be subjected to heavy ion bombardment and heating by arc radiation. There will be some amount of cooling due to electron emission, radiation from the electrode, convection to the gas and internal cooling.

It turns out that local heat transfer rates for typical electrodes are about ten times higher than the maximum rates encountered in a very steep re-entry case.

The power requirement for a large hypersonic wind tunnel with true enthalpy simulation is about 10 to 30 MW in the air alone. Taking into account a typical arc efficiency between 20 to 60 % (depending on configuration), it is seen that the total arc power should be of the order of 50 to 150 MW, so that a multitude of arc discharging into a common chamber will be needed. The surface area will therefore increase and also the radiative and convection losses and a vicious circle is created. True enthalpy simulation therefore appears to be impossible by the use of arc heaters at high pressure levels.

For low density wind tunnels with stagnation pressures equal or lower than 1 atm., however, true enthalpy simulation may well be obtained (stagnation enthalpies of 20,000 BTU/lb were obtained in argon).

A real breakthrough is needed in the field of accelerating air and means other than the chemical engineering method of expansion have to be found.

DISCUSSION

**Dr. Peters:** The first water vortex stabilized arcs had no connection with aerodynamics and were used to simulate temperature conditions in O- and B-stars for spectroscopic measurements in cooperation with astrophysicists. (MAECKER, H.: Z. Physik 129, 108 (1951).

The water vapour arcs were developed in order to obtain high velocity plasmas. (WEISS, R.: Z. Physik 138, 170 (1954) PETERS, TH., see above).

Last years we have gone over to nitrogen arcs for tunnel use and hydrogen arcs for propulsion devices.

Our arrangement is somewhat different from the GIANNINI plasma jet configuration (fig. X, 5). In this configuration, a whirling gas is used to cool electrodes and walls so that hot gas passes only in the center line. The disadvantage is that the temperature distribution in the jet is far from uniform (see fig. X, 5).

We tried to avoid this in our arrangements (fig. X, 6). No rotation is set up in the gas and a tungsten cathode is used. The gas inlet is a very small ring slit nozzle and the inlet flow is axial with a speed of about 50 m/sec. A water cooled copper anode in the form of a nozzle is used (about 15 m/sec. water flow speed).

All the gas has to blow through the arc column and the resulting temperature distribution in the jet is uniform to some extent.

Such an arc is operating now in our laboratory with 30 KW at pressures up to 10 atm. (fig. X, 7).

**Dr. Stalder:** It is true that swirling improves the situation for convection losses but it does not solve the problem of radiation losses.

**Dr. Peters:** In our arc 25 % of the power goes in the cooling water.

**Dr. Stalder:** Several methods are available for the measurement of arc losses. If these losses are calculated by measuring the temperature increase of the cooling water, efficiencies of about 50 % are obtained. Another method is to compute the efficiency by measuring the mass flow of gas. The stagnation pressure and throat area being known, the gas temperature may be computed. The efficiency calculated in this way always turns out to be much lower than that obtained by the first method, in the case of strongly cooled copper walls.
Dr. Estermann: Is the chemical energy in the frozen gas included in the second method of calculation, for the effect of this would be comparable to the sensible heat?

Dr. Stalder: Yes, the energy of formation of NO and NO₂ is included.

Dr. Chuan: The calculations used in the second method give the kinetic temperature but not the temperature of the internal degrees of freedom.

Dr. Talbot: No discrepancy should occur in argon because the amount of energy in ionization in argon is very small.

Dr. Cox: Some fine work on arcs has been carried out by KING at the Electrical Research Association (results presented, two years ago, at the Amsterdam Meeting on Spectrography). These researches show an oscillatory behaviour of an arc with axially blown air. If such a situation arose in an arc heated tunnel, the flow measurement could be ruined.

Dr. Stalder: The same trouble has been experienced at the PLASMODYNE Co. where BULER was able to show similar type of oscillation in velocity. Instantaneous velocities of 14,000 to 18,000 ft/s were observed in a flow of average velocity of 12,000 ft/s. This was ascribed to the AC ripple of the rectified DC supply used, which resonated with some arc chamber.
XI. REVOLVING ARM TECHNIQUES

Dr. Devienne

1. Principle of the Method, Description of Various Facilities

The revolving arm techniques use an arm, with or without streamlined shape, rotating in a vacuum tank or evacuated cylinder. The driving motor can be external or internal. The measuring devices (pressure probes, ionization micro-gauges, measuring plates with thermocouples) are placed either at the extremity of the arm or along the arm.

It is possible, as described later, to place sensing devices close to the trajectory of the arm in order to observe the interactions between a moving body and the rarefied gas.

To our knowledge, two revolving arms have been built for rarefied gas dynamics investigations. The facilities built in our laboratory will be described first because they are the earliest devices in the field, chronologically. Our first revolving arm was built in 1953 (fig. XI, 1).

This arm, of 1.25 m length, which was extensively modified since, is revolving in a vacuum tank of 1.50 m (5 ft) internal diameter (fig. XI, 2). It is driven by an external motor through a rotating seal which will easily maintain perfect air tightness up to 9000 r.p.m. We have, in fact, been able to maintain a pressure of about 0.001 Hg in the tank with the seal rotating at 12,000 r.p.m. (no arm was mounted for this test). The pressure rise with pumps off, was less than 1 μ Hg/hour.

The arms used have diameters ranging between 1 m and 1.25 m (3.3 and 4.1 ft), the latter being the most usual dimension (fig. XI, 3). The arm material is AU4G high tensile Dural.

With certain arms we have reached peripheral speeds up to 530 m/s (1,750 ft/s), but the measurement of temperature rise of models placed at the extremity of the arm were carried out at speeds up to only 480 m/s (1,600 ft/s). The models consisted of small plates of different metals attached to plexiglass supports (fig. XI, 4). These supports were extensively perforated in order to reduce weight as much as possible and reduce interference of molecules with support. Some experiments were carried out with small cylinders placed on these supports.

The pressure measurements using ionization microgauges of special design were carried out at speeds up to 250 m/s (820 ft/s), gauge failure caused by centrifugal loading having been experienced at higher speeds.

These are the main features of our facility.
A revolving arm has also been built at the Institute of Aerophysics of the University of Toronto, with a diameter of 60 cm (2 ft) placed in a cylindrical vacuum tank of 80 cm (2.6 ft) diameter. The material is chrome molybdenum steel and the maximum rotational speed obtained was 2500 r.p.m., which corresponds to 80 m/s (260 ft/s) peripheral speed. Stagnation pressure probes were tested on this device.

2. Useful Range of the Technique

Theoretically, the revolving arm technique is valid only in free molecule flow regime, i.e., when the mean free path is larger than the transversal dimensions of the arm or the measuring devices.

Measurements carried out by Stalder, Goodwin and Creager (1) and our own tests show the free molecule regime to exist when the Knudsen number is at least equal to 2. This condition is fulfilled, in the case of our device, if the tank pressure is below 1 µHg for air.

Investigations by Dr. Crave in our laboratory show that measurements at higher pressures are still valid if the Knudsen number is higher than 0.22, corresponding to a tank pressure of 9 µHg for air. In this case we operate in the intermediate flow regime with predominance of free molecule effects. (For gases other than air the pressures corresponding to a given Knudsen number are different because of the difference in mean free path.)

Maximum operating speed is conditioned by various factors. The rotating seal is one of the limiting factors, for an inefficient seal will not allow high vacuum to be maintained during high speed operation. We think, however, that the main limitation in rotational speed is due to the arm itself and its support and not to the rotating seal.

The centrifugal loading on the arm and the models must be limited and we think it difficult to exceed a peripheral speed of 600 m/s (2,000 ft/s). With an arm of 1.25 m (4.1 ft) diameter, whatever the material or shape used, at 530 m/s the maximum stress is 8 kg/mm² (12,000 psi) and we work with a considerable margin of safety because the ultimate strength of the dural used is 35 kg/mm² (52,500 psi). At 600 m/s (2,000 ft/s) the stress is close to the elastic limit. Large safety coefficient are used to prevent damage to equipment and personnel (2).

If a given limit is set to the amount of centrifugal loading, it is clear that the maximum peripheral speed increases as the square root of the arm diameter, so that an arm of 2.50 m (8.2 ft) diameter would allow a maximum peripheral speed of 850 m/s (2,800 ft/s).

(1) J.R. Stalder, G. Goodwin, M.O. Creager: A comparison of Theory and Experiment for High Speed Free Molecule Flow, NACA Rept. 1032 (1951)

(2) Statement answering a question raised by M. de l'ESTOILE.
A safety device must of course be provided internally to protect the vacuum tank and the personnel in case of failure of the arm.

Other factors affecting the speed are the design of the supports and the balancing of the arm.

We have built an arm able to reach speeds up to 600 and 700 m/s (2,000 and 2,300 ft/s) but the support was not satisfactory and both support and arm had to be modified to prevent severe vibrations at a certain speed. It is difficult to give general rules about the design of the support, but dynamical balancing of the arm seems required for operation at high r.p.m.

The choice of arm diameter seems mainly limited by the difficulty of obtaining vacuum tanks of large diameter, 2 m (6.5 ft) apparently being an upper limit in most countries. Therefore, effective diameters much larger than 1.60 (5.25 ft) do not seem feasible and the peripheral speed cannot exceed 700 m/s (2,300 ft/s) which appears accordingly as the upper limit for the technique in the present state of the art.

However, by using gases having much higher molecular mass than air, we could obtain much larger Mach numbers or speed ratios $S$, for a given peripheral arm speed. We have done so and have been able to obtain Mach numbers up to 5 in certain cases (the speed ratio $S$, however, is the significant parameter in this flow regime).

With air, it seems to be difficult to operate at a Mach number higher than 2.

3. Advantages of the Technique

The revolving arm technique has several advantages, i.e.

1. Possibility of operation at different, well defined, pressures;

2. Possibility of operation at variable speed, measured with high accuracy.

3. Possibility of using gas mixtures of well defined composition and of studying the influence of composition on the observed phenomena.

4. Possibility of operation at a well defined static pressure, which is not possible in a highly rarefied wind tunnel because of the difficulties in accurate measurement of the static pressure in a rarefied flow.

5. The gas is in equilibrium, which is not always the case at the exit of a very low density nozzle.

6. Possibility of using media which are in liquid or solid state at normal pressure. The vapor of such substances may have very high molecular mass and will lead to much higher values of the parameter $S$ than in the case of air.

7. The technique permits the study of temperature effects by circulation of liquids at various temperatures in screens placed in the vacuum tank.
8. The tests are perfectly reproducible.

9. Possibility to operate in ionized gases, to measure ionization and to study the phenomena on or in the vicinity of the body in motion, which is extremely important.

10. Low cost of the facility. Our own facility totals about $10,000.

4. Limitations of the Technique

The numerous advantages of the method are, unfortunately, coupled with certain limitations, i.e.

1. Limited range of available speed and pressure.

2. Extreme difficulty of force measurement at extremity of arm. It seems, in fact, that only temperature rise and ionization current on moving bodies can be measured. Stagnation pressure measurements seem to be possible only at speeds not exceeding 300 m/s (1,000 ft/s) and by the use of micro gauges at the extremity of the arm or a tube placed inside the arm (UTIA tests).

5. Summary of Experimental Results obtained by the Revolving Arm Technique

As far as we know, the UTIA group only measured stagnation pressure at relatively low speeds (below 100 m/s = 330 ft/s). We have also measured stagnation pressures up to speeds of 250 m/s (820 ft/s), using ionization micro gauges on the arm. In the actual state of the art, it seems possible to go to slightly higher speed and to improve the accuracy of the measurement.

Our own tests also involved the measurement of temperature rise of plates of different metals at various pressures and speeds and the study of influence of speed on the accommodation coefficient.

In the field of ionized gas, we have measured temperature rise and ionic current collected by a moving body as well as phenomena occurring in the vicinity of the trajectory of such a body.

We were able, using the revolving arm technique, to study the influence of various factors, such as speed, pressure, body and probe shapes, degree of ionization on the disturbances observed during the passage of a conducting or insulating body through an ionized atmosphere.

We believe that this research work is a good example of the possibilities of the revolving arm technique.

Cost of equipment

Vacuum pumps and tank, revolving arm, electronic control for speed, total about 12,000 $. The revolving disk costs more.
Conclusion

The revolving arm technique, despite a few limitations, seems to be the most suitable for the study of phenomena in highly rarefied atmosphere, i.e. at pressures of the order of a few microns of mercury and at medium velocities.

For higher pressures, in the same speed range, it is possible to use revolving disks, while for much higher speeds and pressures below 0.1 μHg, the hypervelocity molecular beam seems to be the most interesting technique.

Our present research is based on the latter technique, using an idea suggested to us by Dr. Estermann three years ago, but completely modifying the initial design. We have been able to obtain recently molecular beams, the speed of which were measured to be between 10 and 30 km/s (30,000 and 100,000 ft/s).

DISCUSSION

Dr. Cox: How uniform is your ionization?

Dr. Devienne: This depends on the distance from the ionization generator (high voltage, 48 MC frequency). In order to check the uniformity, the arm is rotated and we measure probe currents at different locations. The maximum difference is of the order of 1%. If the ionization is injected laterally, the difference becomes 5%. The differences are much greater close to the ionizing device.

It may be of interest to mention that it is preferable to inject the gas laterally with respect to the quartz tube energized by the R.F. rather than to inject it through the tube (fig. XI, 5). Tests have shown that an ion beam shoots out of the quartz tube if the first technique (lateral injection) is used.
XII. RESEARCH PROGRAMS IN LOW DENSITY AERODYNAMICS

Introduction

Prof. Brun (co-Chairman): I think it very difficult, and not very useful, to make a clearcut distinction between basic research and applied research.

I consider it however much more important, especially from our point of view, in France, to divide the research problems into the ones that are accessible to the limited means of laboratories in universities or institutions like our Centre National de la Recherche Scientifique (C.N.R.S.) and the problems requiring large scale facilities as are only available in industrial laboratories or in government sponsored applied research institutions.

For instance, the research program that Prof. Malavard and myself have planned at the Paris university and the C.N.R.S. is necessarily based on facilities of modest scale.

There will also be developments of low densities facilities in the government sponsored and industrial laboratories with much more important means.

The main point is not to decide that the small laboratories will concentrate on basic research and the others on applied research and development, but to establish close cooperation between research in small scale facilities (mainly basic) and in large scale facilities (mainly applied).

I don't think that these remarks are original but in France this problem is perhaps more critical than in England and the U.S.A.

In conclusion to these three days of discussions, I wish to say that the meeting has been very useful for the French delegation and complemented harmoniously the BERKELEY Colloquium which was rather more theoretical while the emphasis in this meeting was mainly on the experimental aspects.

We were pleased to see the recent British contributions in the field and appreciated the opportunity of meeting the BERKELEY group, Dr. Estermann, Dr. Chuan and others, who contributed largely by giving us the benefit of their experience in the field.

We ourselves were not able to contribute much because we are rather new in this field, into which we were drawn because of the growing importance of re-entry, orbiting and similar problems, and we hope that in the next meeting we will be more than just listeners.

Dr. Schaaf opens the discussion by summarizing the views of the BERKELEY group on the various aspects of low density aerodynamic research and also the plans for future developments there.
He understands that the emphasis is mainly on wind tunnels in this meeting so that the other research tools, such as molecular beams, rotating disks, etc., will not be discussed extensively.

A detailed bibliography covering the field of low density flow is presented. (1)

References 181 to 208 cover most of the available experimental results (mainly wind tunnel results).

References 209 to 262 describe experimental techniques, most of it applicable to wind tunnel work (particularly useful are ref. 246 by Enkenhus, already quoted, ref. 257, the AGARDograph n° 39 by Maslach and Schaaf, and ref. 259 by Stalder on Low Density Wind Tunnels, a very good summary of the subject). Ref. 108 by Stalder, etc., covers a few of the important experimental results on free molecule flow. This is not complete but represents a good starting point.

Summary of the University of California (BERKELEY) Views on Low Density Research

Dr. Schaaf considers that almost three quarters of the way has been accomplished towards obtaining the fundamental data in basic physics, basic fluid mechanics and basic applications to aeronautical engineering in the low density range available in the existing wind tunnels. In the low density wind tunnels at AMES (NASA), BERKELEY, UTIA (Toronto) and JPL (Caltech), the ranges covered so far are the following:

**Mach number range:** from 0 to 6, most of it supersonic. No tests above M = 6.

**Reynolds number range:** between 1 or 10 to $10^4$ (Reynolds number per inch in test section).

**Knudsen number:** In experiments in which some sort of aerodynamics is studied the Knudsen number has always been smaller than unity. Most of the tests were therefore in slip flow or early transitional regime. Free molecule flow was obtained only for very special models (cross stream cylinders, etc.), with Reynolds number per inch much smaller than one and Knudsen numbers of the order of 100.

**Temperature range:** All these tests were done with cold air (T about 500°R). No test with heating are available.

(1) see appendix I: Bibliography prepared by Dr. Schaaf for his coming article on low density flows in HANDBUCH DER PHYSIK.
Basic Physics of Low Density Gas Dynamics

One deals mostly with simple monatomic gases, or air, or other diatomic gases and mixtures, and no particular problems are encountered except for the question of relaxation times for rotational energy in diatomic gases. A research program has been started in BERKELEY by Talbot and Shermann on this subject.

A simple MAXWELL-BOLTZMANN equation describes the behaviour of monatomic gases.

The equation is more complicated for diatomic gases, because the internal degrees of freedom appear as arguments of the distribution function and effect of collisions on rotation must be included in the collision integral. However, it appears that the ENSKOG expansion procedure can be applied as in the monatomic gas case.

The question of the boundary conditions is in a less satisfactory state and there is a need for further research on surface interaction.

For air in contact with engineering type of surface, it seems that no great improvement can be expected on the description by accommodation coefficients, which is quite satisfactory at low temperatures. It is known that the tangential accommodation coefficient $\sigma$ is always close to unity and that the energy and normal momentum accommodation coefficients $\alpha$ and $\sigma'$ are nearly equal. Usually they have values between 0.7 and 0.8, depending on gas, surface and temperature, and a fair amount of experimental data is available on this.

Fluid Mechanics at Low Densities

A good number of important results have been obtained in this field.

(a) Free Molecule Flow: The experimental work at AMES (Stalder group) UTIA and BERKELEY (Schaaf group) verifies the theoretical calculations in this regime. This work included heat transfer and aerodynamic forces measurements on convex bodies in uniform flow.

It would be surprising, in view of this, if a large departure from free molecule flow theory would ever be observed in experiments.

At high Mach numbers, very high values of the KNUDSEN number were found to be required in order to obtain free molecule flow.

It is known, for example, that at $M = 2$, a Knudsen number of 5 will be sufficient, while at $M = 5$ the Knudsen has to reach 30 or 40 to get free molecule flow regime.
This leads to another subject:

(b) Near-free Molecule Flow: This is one of the major remaining areas of research in the moderate temperature range. Very little reliable results are available in this regime.

This subject is especially important and valuable because of the surprising results, established both experimentally and theoretically, that departures from free molecule flow occur, for high Mach numbers, at much lower densities that originally expected. For instance, a KNUDSEN number of 100 is required before the free molecule results are approximated within 5% at satellite speeds.

From the mathematical point of view, the BOLTZMANN equation which describes the basic physics of the gases, presents even a more formidable mathematical challenge than was anticipated, because of the complication of the collision term.

A lot of theoretical work has been published recently (this was one of the main subjects at the recent BERKELEY Colloquium) but there still are no satisfactory solutions available even for problems with very simple geometry or for linearized problems. The best one can do seems to be to translate the BOLTZMANN equation into a system of an infinite number of differential equations for an infinite number of unknown functions.

Various iteration techniques have been tried, such as the CHAPMAN-ENSKOG, BURNETT expansion at high density, and the JAFFE expansion at low density, but they are all probably inapplicable to the near free molecule flow regime.

In view of this, it appears even more useful for the experimenter to help the theoretician especially in the near free molecule flow regime where no correct mathematical approach seems to be available.

Some engineering approaches however are being used, which consist in calculating the effect of certain types of collisions and ignoring others so as to make the computation of a theoretical correction to free molecule flow data possible. No mathematical validation of this procedure, in the sense of an asymptotic expansion, for instance, seems to exist, but the calculations are feasible and the fragmentary results available look promising and indicate that we may be on the right track. A very careful experimental program to check these theoretical predictions for near free molecule flow would be extremely useful.

Transition Region

Available theoretical and experimental data show that the true transition region is very abrupt and narrow in terms of density: the entire transition region covers a range corresponding to a factor of only 3 or 4 in the density. One almost immediately reaches continuum regime when raising the density level from a near free molecule flow. This is so
especially in the case of hypersonic flows but also in the lower speed range (1) (where the change is not so abrupt).

This seems to be a characteristic of low density flows.

**Slip Flow Regime**

At slightly higher density, slip flow regime is encountered, the dominant feature of which is not the slip but the very thick boundary layers. These thick boundary layers determine the pressure distribution on flat plates and skin frictions of the order of the dynamic pressure are encountered.

This is of course a very different situation than experienced at high Reynolds numbers but it is still essentially a continuum flow regime, corrections to the ordinary viscous flow equations due to slip being of secondary importance.

One can immediately conclude from experimental evidence that Mach and Reynolds numbers are not sufficient to define a slip flow because the boundary layer is so strongly influenced by thermal conditions. Even in normal temperature ranges (cold tunnels) stagnation and model temperature must be accurately specified for they influence strongly lift, drag, etc.

The corrections to Newtonian flow coefficients for sharp leading edge aerofoils at rather high Mach numbers, due to boundary layer and temperature effects, are very important and shown on fig. XII, 1 (2). Differences of 100% or even 200% appear in the correction factors for Newtonian flow aerodynamic coefficients at rather high Mach numbers due to change in temperature conditions.

**Future Plans for Research at the BERKELEY laboratory.**

High altitude aerodynamic research is the main subject.

The problems are best situated by reference to altitude and velocity (or Mach number) diagram shown on Fig. XII, 2. The flight corridor is indicated (region where enough lift is available and aerodynamic heating is acceptable). The range covered by the BERKELEY facility is also indicated and it is seen to be rather far removed from the flight corridor. It is planned to extend the tunnel operation region towards higher Mach numbers. The problem here is of course to obtain equilibrium flow in test section when expanding a hot gas. This introduces essential limitations to wind tunnel capabilities (as indicated on fig. XII, 2).

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(1) In answer to a remark from Dr. Cox.

(2) From a presentation at the A.R.S. semi annual meeting, Los Angeles, May 1960.
At higher altitude or for low density flows, one is in general more interested in aerodynamic forces and stability than in heating effects, which are relatively unimportant under these conditions.

At BERKELEY, for example, the following engineering problems have been studied quite extensively in recent years:

(1) Aerodynamic stability and drag of re-entry shapes, a study of importance also outside and above the corridor (preventing tumbling of a re-entry vehicle with single sided heat protection, etc.).

(2) Probes for upper atmosphere exploration (high atmosphere sounding rockets, see fig. XII, 2). Calibration must be carried out and it is important to do this at the correct temperature (impact tubes, static pressure probes, etc.).

(3) Re-entry drag and stability for special type of re-entry trajectories involving very high drag devices and extreme altitudes (high above the flight corridor, fig. XII, 2).

(4) Air intakes and diffuser characteristics for aircraft designed for flight above the corridor but not necessarily at hypervelocities. Operation of such aircraft is very critically dependent on air intakes efficiency.

The plans for further development of facilities at BERKELEY are therefore clear:

Temperature simulation will be improved in the wind tunnel. A heater is available which can now be used up to 2,500° R. Two purposes may then be satisfied: temperature simulation at low Mach numbers and extension of operation towards higher Mach numbers (in excess of 10) with condensation free flow. In addition, lower Reynolds numbers may be obtained at a given Mach number. This will extend the operating region of the facility towards the right and upwards on fig. XII, 2.

The planned research program includes:

(a) Extension of typically aerodynamic measurements (drag, pitching moments, pressure distribution, local skin friction) on calculable bodies (wedges, cones, spheres, etc.) in order to obtain some comparison with theory.

As a part of this, a very careful experimental program will be conducted in the strong interaction region near the leading edge of a flat plate to study the possible effect of slip on the viscous layer. There is no theoretical work available on this problem, even in the incompressible case, because of the mathematical complication of the NAVIER-STOKES equations when gradients are large in both directions.
Great efforts will be spent at BERKELEY to measure the local skin friction near the leading edge to try and identify the effect of slip.

(b) To test real gas effects (all previously quoted work is in moderately cold facility $T_0 \leq 2500^\circ R$), a rarefied plasma jet will be used and Dr. Talbot will describe the program for this facility.

Dr. Talbot: Program for the next few years in the low density plasma jet facility at BERKELEY.

First, an investigation will be made about the type of aerodynamic data that can be obtained in such a facility.

(1) The first question is the nature of the flow obtained. This leads to a problem of instrumentation to measure electron and ion concentrations and partial temperatures of flow constituents. The problem is difficult because of the complicated physical situation even in the case of simple monatomic gases like argon. Confirmation of the results will be valuable and different types of measurement will be developed in view of this (measuring techniques contemplated will be similar to the ones described by Dr. De Leeuw at UTIA and Mr. Clayden at A.R.D.E.).

A study of aerodynamics in low density plasma will then be started. Viscous magnetohydrodynamics is one of the most interesting aspects and one should first measure the conductivity in the fluid to evaluate whether magnetic field will have significant effects.

It is not at all clear, at present, whether available calculations about conductivity levels required to get magnetic effects (AVCO data, etc.) apply to low density flows. This is because, although simple scalar conductivity is assumed, charge separation and, mostly, diffusion and variation of conductivity across the boundary layer are present. These phenomena could radically change the net magnetic effect one might obtain, so that the transport processes in low density flow boundary layers must be considered.

If it can be demonstrated, experimentally or theoretically, that these magnetohydrodynamic effects are of some magnitude in moderately ionized flows, important practical applications may result. If not, the problem is still interesting from a fundamental point of view.

(2) The Transport Properties in partially ionized Gases therefore have to be investigated. Simple experiments, such as measurement of induced pressure on a flat plate with and without magnetic field, are planned. It is not known initially whether this will lead to practical applications.

The effects of magnetic fields on shock detachment and on heat transfer are known to depend strongly on the gas conductivity. These effects can be calculated within an order of magnitude and no better, because of lack of information as to what conductivity should be used in the formulas.
This difficulty must be resolved by comparison between theory and experiment.

Another problem arises in near free molecule flow, because the conductivity shows tensor, rather than scalar, behaviour. There are very few theoretical results available on this and a new, broad field is thereby opened in aerodynamics.

(3) Wake Problem: This is essentially a problem of communication with, or detection of, objects flying in the upper atmosphere. The character of the wake must be studied before radar cross sections can be calculated. Workers in the field claim to be able to compute the wake far away from the object if the wake is known close to the object. The calculation of the near wake seems to be difficult so that an experimental study of the distribution of ionized gas shock layer and laminar wake close to the object would be very useful. This is an interesting experimental aerodynamic problem requiring a lot of ingenuity.

It is also expected that many questions of pure physics will arise in research with plasma jets and there will be opportunities to try and understand these and contribute to the knowledge of the subject.

Dr. De Leeuw: Program at UTIA (Toronto)

The intention is to go on working close to free molecule flow. Some experiments are planned in the range where the first collision theory is applicable.

The work on near free molecule flow around the leading edge of a flat plate will be extended using the new gas temperature measuring technique described, possibly by heating the plate and measuring gas temperatures near the leading edge. A plasma wind tunnel is developed as an intermediate effort to study the new difficulties that arise in ionized flows. This tunnel will also be operated close to free molecule flow. It is hoped that the electron beam can be used for density measurements in dissociated flows and that the degree of dissociation can be controlled (possibly by leaking in molecular gases downstream of the arc chamber). Research planned in near molecule flow of dissociate gases include:

(1) Behaviour of probes, making use of catalytic and no-catalytic effects.

(2) Calibration of probes for high altitude sounding rockets and some supporting research in connection with such projects.

(3) Effect of outgassing flow in near free molecule flow.

For ionized flow, the program includes what everybody else does in this field, i.e.: analyzing the nature of the flow and developing the measuring techniques.
It is hoped that instrumentation designed for free molecule flow regime will be applicable. The Langmuir probe operation in free molecule flow will be investigated, with emphasis on the ion current measurement and its dependence on flow velocity. This might prove useful to provide information about flow velocity.

Ionized flows around some practical configurations will be considered also, as well as studies in magnetohydrodynamics and transport properties at low densities.

**Dr. Stalder:** (answering a question from Dr. Schaaf): The NASA Ames Low density wind tunnel, which has been in operation for some time now, is at present being fitted with huge multi megawatts arcs for full temperature simulation at high Mach numbers.

**Dr. Cox:** Program at A.R.D.E.

A new comer to the field should consider carefully the large number of results already in existence before embarking on a research program in the classical low density field (it has already been mentioned, for instance, that something like three quarters of the work has been accomplished in such important subjects as viscous interactions on a flat plate). There are, however, many new and important aspects of Low Density work coming to the fore.

At A.R.D.E., for instance, it is planned to study the problems of flight in the ionosphere, through which all long range missiles have to pass (see Fig. XII, 2). This was not mentioned in Dr. Schaaf's summary of research subjects.

The ionosphere is characterized by an ionization level of about $10^6$ electrons/cm$^3$, a degree of ionization of $10^{-4}$, and a magnetic field of about 0.5 gauss. The degree of ionization available in plasma jets of the type used at A.R.D.E. is quite comparable to ionosphere values.

The study of flight in the ionosphere is a branch of magnetohydrodynamics which we suggest might be called ionospheric aerodynamics.

Interesting interactions may be expected between a moving object, its wake and the medium.

According to an important recent paper by Lighthill, several types of waves may be set up in the ionosphere: electromagnetic, electrostatic and ALFEN waves, and a wide region for study is available here.

The parameter describing the magnetic effect is the ratio of magnetic pressure ($B^2/8\pi$) (1) to the gas pressure and this is much larger

\[ \text{(1) } \text{Dr. Froood remarked later that, as } B = \mu E \text{ and as } \mu \text{, being dependent on atomic radius, can be very small for excited atoms, } B^2/8\pi \text{ could be a very small quantity in a plasma, for a given magnetic field.} \]
than unity in the ionosphere so that a big magnetic influence on the wave systems may be expected. The same value of the parameter would be obtained in a typical plasma wind tunnel with a field of about 500 gauss.

In a wind tunnel, one cannot hope to simulate all the actual wave systems because if a magnetic field is set up in a wind tunnel, the air is in motion with respect to this field, while in the ionosphere the field is locked to the plasma. To get over this, some experiments are being made at A.R.D.E. in which a model is fired into an ionized range section with a magnetic field.

However, many useful investigations may be carried out in a plasma jet because of the correct order of magnitude of ionization. For instance, significant effects are observed in microwave propagation (a test setup had been shown at A.R.D.E. to study the propagation of 3 cm waves into the plasma jet).

Of course, as in other types of wind tunnels, one has to know the detailed nature of the plasma jet flow. Mr. Clayden will describe the efforts of A.R.D.E.

Much theoretical work on ionized gases is also required and Dr. Frood, who recently joined A.R.D.E., will describe the theoretical program.

Mr. Clayden: Preliminary calibration work has already been carried out using microwaves, pitot tubes and Langmuir probes. Pitot pressure can be measured readily in the test section. It is hoped to use mass flow probes (giving $\rho u$), heat transfer probes, etc.

The use of the Hall effect is considered to get informations on electron density and velocity (a magnetic field will be applied across the plasma and the voltage difference appearing perpendicularly to the field will be measured by two probes). There are, however, some theoretical objections to this method. It seems however possible to obtain reasonable results from a plasma jet without an extremely accurate knowledge of the flow characteristics. Dr. Boyd (of University College, London) has done some work on the calibration of Langmuir probes for free molecule flow.

It is intended to calibrate these probes in the wind tunnel and it is hoped that this will prove useful for sounding rockets.

**DISCUSSION ON LANGMUIR PROBE CALIBRATION**

Dr. Devienne: My opinion is that it is impossible to extrapolate data obtained on Langmuir probes in a low density wind tunnel at a static pressure level of 10 $\mu$ Hg to pressure levels below 1 $\mu$ Hg because of the sheath effect and the adsorption on the probe which completely modifies its response.

We have tested, in our tank for rotating arm, probes which had been immersed during a certain time in a particular atmosphere, and others
which had been heated just before the test and the results were totally different so that contamination plays a very important role here.

Mr. Clayden: Our probes are cleaned by applying a high voltage across the electrodes and "flashing" them.

Dr. Devienne: I just wanted to emphasize this point.

Dr. Talbot: Contamination also occurs at higher pressures. The relevant parameter here is the probe Knudsen number, not the pressure. In free molecule regime, no sheath exists and ion trajectories have to be considered, and in the continuum regime the sheath has to be considered. The analysis is different for both cases and the transition occurs in a given Knudsen number range.

Dr. Devienne does not agree: The effect depends, in his opinion, only on surface accommodation which is dependent only on pressure and crystal structure. Many tests were carried out in his laboratory on this subject and were not published so far because of the high scattering in the results. The cause of these discrepancies has been found since a year.

Dr. Schaaf thinks that all difficulties originate in the important role played at very low densities by molecule surface interaction and therefore contamination, whether the gas is charged or not. The characteristics of the surface are therefore all important.

Dr. Frood: Theoretical Research on Ionized Gases at A.R.D.E.

The only specific things to mention about the theoretical work on ionized gases carried out at A.R.D.E., are the difficulties encountered in treating the collision term in the BOLTZMANN equation for ionized gas (considered as a perturbation to the non interacting case).

The limitation to two particles interactions is probably not correct so that more than two particles should be considered in interactions and this leads to a very complicated problem.

Several attempts were made (mostly in the U.S.A.), and with some success in the very simple case of a free electron gas neutralized by a background of uniformly distributed positive charge.

As an example, consider the quantum mechanical system of two particles.

The stationary states are well known for a system of two non interacting particles (electron and positive ion, for instance). If a COULOMB interaction between these particles is introduced, as a small disturbance to the system, perturbation theory can be applied and two different approaches are possible:
(a) Treating the perturbation as causing transitions between stationary quantum states of non interacting electron and ion.

(b) Treating the perturbations as leading to new stationary states. In the general case, both aspects are present and there is no way of choosing between them, except in particular cases.

For example, in the case of a single electron in interaction with a great number of neutral particles, it is felt to be better to consider the interaction as leading to perturbations of stationary states than as leading to transition (1).

This problem of how to separate the interaction effect into the part leading to transition and the part leading to new stationary states is particularly difficult in the case of Coulomb interaction which is important for the theory of transport phenomenon in ionized gases.

Dr. Devienne: Research Program at the Laboratoire Méditerranéen de Recherches Thermodynamiques (Nice).

Our research program may be summarized in three points:

(1) Develop new research tools and diversify the instrumentation.
(2) Improve the measuring methods.
(3) Increase the accuracy of measurements. The necessity for this has already been stressed by Drs. Schaaf and Talbot.

It must be emphasized that our field is molecular physics and not aerodynamics. We operate in the free molecule flow regime.

Our main subject of research is the study of interactions between gas molecules and solid surfaces which was started since several years in our laboratory. This must include two aspects, which have not yet been sufficiently developed or treated with satisfactory accuracy, in our opinion:

(a) Measurement of accommodation coefficients for momentum, energy, etc. This is the most important aspect in the field and these coefficients should be measured with very high accuracy.

(b) Measurement of surface phenomenon accompanying the collision of a molecule with a solid wall (modification of surface properties due to adsorption, stripping, etc.).

(1) If an electron moves through a polar crystal, the electron effective mass is found to increase, and the optical and lattice oscillator levels are displaced (pertubations to stationary states). If one tries to treat this by the transition aspect, a difficulty is immediately encountered in that the electron must emit or absorb the fundamental crystal frequency or ionization frequency \((h \nu = \text{ionization energy})\) which it cannot do because its energy is too small.
We have developed a high speed molecular beam apparatus, based on an idea suggested by Dr. Estermann and developed and extensively modified during the last two years.

This apparatus is now built and a molecular beam with speeds ranging between 5 and 30 km/s has been obtained.

The main problems encountered in this field have been the measurement of speed, in which we have now succeeded, and the production of a monokinetic beam.

This molecular beam apparatus will be used to study the surface interaction phenomenon.

For the lower speed range, a revolving disk has been built to measure exchange of momentum with a low speed molecular beam.

Ionized gases (argon, neon, air) have also been studied but great difficulties were initially encountered in measurements. These difficulties have to be studied very carefully for they often hide the principal phenomenon.

Dr. Schaaf mentions that surface interaction phenomenon are very important in free molecule flow but do not play such an important role in wind tunnels.

Dr. Holder: Program of Research at the N.P.L.

A number of low density wind tunnels are developed but none is actually operating.

The field of this laboratory is pure aerodynamics and the problems contemplated are, on the whole, more conventional than those mentioned so far.

A lot of work will be in low Reynolds number aerodynamics. Dr. Holder doubts whether 75% of knowledge is available in the field. The problems are identified but not as far solved that prediction is possible and that practical data can be obtained (situation similar to that of supersonic aerodynamics in, say, 1945).

A fairly strong boundary layer research group is working at the N.P.L.

Low density flow can, of course, easily be obtained by means of shock tubes and one should therefore identify the problems requiring long running times which have to be carried out in wind tunnels. In our case, they will consist in detailed analysis of the flow. The subjects treated will be:

(1) Boundary layer behaviour at low Reynolds number (separation, secondary flow, etc.).
(2) Magnetohydrodynamics. (We are worried, on the basis of early design studies, whether the electron density will be sufficient in a plasma jet. A plasma generator has been built to check this).

(3) Decay of ionized wakes, problem similar to the one quoted by Dr. Talbot. It is hoped to extend earlier microwave work in shock tunnel to this field and ionization measurement will be attempted.

Dr. Schaaf: The problem of separation of low density flows is very intriguing because of the enormous pressure gradients occurring in separated regions. We have made some experiments on this.

Prof. Brun: In our laboratory, we hope to go on with our boundary layer explorations but at lower densities.

This meeting was therefore of great value to us. I was struck by the similarity of Dr. Chuan's program and our own, namely in the study of the flow field around the flat plate.

Dr. Chuan: Program of research at U.S.C.E.C.

A general observation that can be made about aerodynamics, especially for high temperature, low density flows is that one is faced with two categories of dilemmas.

(a) In some cases, one has problems (theoretical or experimental), and no tools.

(b) In other cases, one has tools but one does not know what to do with them.

The problem of flow near the leading edge of a flat plate illustrates the first category of dilemma. So far, the Navier-Stokes solutions were always obtained with the assumption of large gradients either across the flow (boundary layer case), or parallel to the flow (shockwave case) but both these effects are present simultaneously in the present case. Some attempts at the solution have been made (see, for instance, the recent contribution by OGUCHI, at BROWN UNIVERSITY (1)).

At U.S.C.E.C., divergent laminar flow in conical channel at high speed where high gradients appear in all directions, have been calculated by the rather rough method of polynomial fitting.

Anyway, there is a clear and urgent necessity for the theoreticians to attack this problem of flow with strong gradients in all directions.

An example for the second type of dilemma is the plasma jet.

However, the situation has improved lately and the problem is approached in a more reasonable manner.

Research Program at U.S.C.E.C.

(a) The experimental work on flat plate is going to be started in the wind tunnel. The plate has a thickness of only $3 \times 10^{-3}$. Pressure plotting and, later, probing of the flow field are planned.

(b) Experimental work on low density strong shock wave structure is planned. This will be an exact duplication of the tests of SHERMAN and TALBOT at BERKELEY. Argon will be used instead of nitrogen. The available experimental results so far cover only the low Mach, moderate density case, where no violent departure between the different theories proposed is to be expected or one is still close to equilibrium. It is hoped that theoreticians will, in the meantime, come up with a theory for strong shocks in low density. The bimodal approximation for the distribution function would seem very well suited to this case (it requires the determination of two parameters, function of the coordinate normal to the shock). However, as pointed out by Willis at the BERKELEY meeting, the comparison of such theories with experiment are not useful if the calculations are based on inaccurate molecular models, because of the impossibility to decide whether a discrepancy is due to inappropriate approximation used to deal with the BOLTZMANN equation or to inaccuracy in the molecular model. It would be valuable therefore if the theoreticians could explore a situation where the nature of the approximations on the distribution function plays a dominant role and that the results are not too strongly depending on the choice of a molecular model. Special experiments could then be planned to check the validity of approximation techniques for the molecular distribution function.

(c) The interaction between electromagnetic field and gas dynamic field at low ionization level is another important problem. Here, one is not really dealing with a magnetohydrodynamic system as encountered in the field of fusion and power generation. For instance, the problem of communications with re-entry vehicles or satellites has to be studied (or the wake problem). We think this is possible in a wind tunnel and have been working on the scaling problems. It is an interesting problem involving many disciplines such as physics, gas dynamics, electronics, etc.

Some grounds support work, theoretical and experimental; will be carried out for the SCOUT flight investigation program. This deals with transmission of radio signal from the vehicle.

The theoretical work in interaction between electromagnetic waves and ionized gases follows fairly clear steps. A lot of literature is available on the subject (MARGENAU and others) but this usually treats the

(1) This statement answers Dr. STALDER's objection that such a study does not appear to be feasible in wind tunnels from the scaling point of view.
case where the frequency of electron-neutral collisions is low compared with field frequency or plasma frequency. This is not valid in the situation we are dealing with and electron-neutral collisions have to be considered in a plasma. This, we now realize, make the (still scalar) conductivity a non-linear function of the electrical field, which is a significant factor in the interaction problem.

The experimental problems we encounter in our plasma work are similar to those of other workers in the field. Instrumentation is studied and we consider that the plasma jet will not be very useful if no method for local electron density measurement is available.

We are mostly working with a medium which is not electrically neutral near the probes or in the center of a plasma jet (1).

(d) Theoretical work on surface interaction with regard to momentum, energy, mass and charge (another example for the first type dilemma, no appropriate tool being available). It is doubtful whether one can hope to obtain a thorough understanding of the phenomenon by doing simple tests (this would be analogous to trying to understand turbulence by measuring pressure drops in tubes, for instance). A detailed microscopic study seems to be required, and building stones have to be gathered before the phenomenon can be understood.

Only two theoretical papers, based on quantum mechanics, were found in the literature. These were the LENNARD JONES and DEVONSHIRE contributions which were rather successful at predicting condensation coefficients.

We intend to study the behaviour of a crystal plus a monolayer of absorbed gas (contaminated surfaced problem, where the crystal potential will be perturbed by the layer). A few research workers at USC are now studying quantum physics for this purpose.

(e) Upper air sounding problem. This may be considered an aerodynamic problem or not. A somewhat different approach is contemplated, whereby the density would be measured by a device flying at a speed determined by tracking. The device will use a supercritical collector similar to a ram jet scoop and a cryopump to sample the air. Experiments have already been conducted in a supersonic jet of alcohol vapor in order to investigate whether this could be collected and condensed on the cryopump.

It is hoped that the combination of ram jet intake and cryopump will provide an ideal sink in supersonic flow and no boundary layer interaction problems are to be expected (2). An analytic study has been undertaken and

(1) Answer to a question of Dr. Stalder about the neutrality of the gas.

(2) Answer to a point raised by Dr. Cox.
it is hoped to do wind tunnel tests later. No diffuser will be used but just a straightthrough pipe. For the external flow, this will behave as an opening without longitudinal thickness (1). A free molecule flow sink is then obtained (term suggested by Dr. Schaaf).

Several other groups are working on the same problem but with a different approach.

---

(1) Answer to a remark from Dr. Schaaf on the non-existence of critical conditions in intakes at very low pressures.
RESEARCH ACTIVITIES OF OTHER GROUPS CURRENTLY OPERATING LOW DENSITY WIND TUNNELS

Jet Propulsion Laboratory (Caltech)

Dr. Wegener has used a low density unheated tunnel somewhat smaller than the BERKELEY tunnel. There are plans for moderate heating in order to reach Mach numbers up to 8 or 10 (without air condensation) as in BERKELEY.

The low density wind tunnel has been in operation for one year now. Results on sphere drag have been obtained using pendulum balance and agree nicely with the BERKELEY results.

Ionized gas flows have been investigated by injecting ions in a cold stream (seeding, no plasma jet).

Cornell Aeronautical Laboratory

A shock tunnel is used giving a Mach number range from 10 to 15 at low density, which leads to low Reynolds numbers, from 10 to 100.

Stagnation point heat transfers in cylinders were measured and no departure up or down from conventional boundary layer theory was observed taking into account experimental uncertainties and no evidence of interaction effects or temperature jump effects has been obtained. An ambitious program for future research in the field is planned.

Rand Corporation

A hot shot has been developed in collaboration with the BLOXSOM and RHODES Co. (Los Angeles) (2).

An ambitious re-entry research program about sphere drag in low density has been started in this facility, for a Mach number range from 10 to 15 or even almost 20. Reynolds number range reaches down to KNUDSEN flow. Both air and monatomic gases are used. Preliminary work has already been published, giving $C_D$ in function of the KNUDSEN number for a given Mach number.

(1) Described by Dr. Schaaf.

(2) Hot shot specialists and manufacturers of the A.E.D.C., Tullahoma, hot shot facility.
It is understood that this corporation is starting research in the low density field using a group of 300 people.

A low density wind tunnel has been designed (assuming better than normal shock recovery (1)).

University of Bristol

A small low density wind tunnel, using diffusion pumps, is in operation (2).

Dr. Lobb: Program at the Naval Ordnance Laboratory

Large facilities are planned and a feasibility study is underway. The mission of this U.S. Navy establishment involves basic research and development testing for Navy systems.

Hot shot and shock tunnel facilities are available now and complement one another but much longer running times are required for development testing (angle of attack ranges, etc.) The present long running time tunnels reach only M = 2, so that a demand exists for a continuous hypersonic facility.

A feasibility study is carried out for a wind tunnel with the following approximative characteristics. This tunnel could be built in a few years, if financial support is granted.

Mach number range from 10 to 20, without condensation
Stagnation pressure 1000 atm. Maximum.
Stagnation temperature 4,500°R (for flow free of air condensation).
Arc heater.
Isentropic core cross section 2 sq. ft.
Straight through diffuser (it is not known at what density level this diffuser will cut off: 100 or 200 Hg, for instance.
At high Mach numbers, the boundary layer will be turbulent).

Our experience is that users want simulation of Mach number and Reynolds numbers but don't know what to do with temperature simulation.

Mach number simulation is required because no similarity rule exists for detailed data (stability parameters, for instance, vary as M^2).

(1) Information from Dr. Stalder, Dr. Schaaf, and Dr. Chuan.

(2) Information from Dr. Holder.
Capability exists for true temperature simulation up to $M = 14$ (cooling pumps and other equipment being available) if a suitable heater becomes available, which is possible in view of recent developments in the field of clean, high pressure arcs (1,500 to 2,000 psi). The stability problem for such arcs will be studied and it is hoped that it will be possible to operate them at 200 atm.

**Research program planned for Continuous Hypersonic Wind Tunnel.**

*Separation problem at high Mach numbers and effect of heat transfer on separation (extensive information is available on separation in supersonic flow, but very little, in our knowledge, in the hypersonic range).*

*Turbulent boundary layer and skin friction studies at high Mach numbers.*

**Dr. Heyser:** Low Density Aerodynamic Research in Germany

No facility is available at present in Germany and we came here to get information in view of future developments.

A hypersonic blow down wind tunnel is operating in Aachen. It goes up to $M = 7$ with a stagnation pressure of 50 atm maximum and a stagnation temperature of 560°C.

Future plans include a gun tunnel (ARDE type) and a low pressure wind tunnel using the plasma jet developed by Dr. Peters (this is similar to the ARDE plasma jet).

**Dr. Groenig:** A shock tunnel is operating in Prof. SCHULTZ GRUNOW's department at Aachen, but has not yet been used at very low pressures. Diffusion pumps will become available within a few months. It is hoped to get facilities for low density tests (a third type of dilemma is also met: problems but no financial support !).
APPENDIX I

BIBLIOGRAPHY ON LOW DENSITY FLUID MECHANICS

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APPENDIX II

ROUND TABLE CONFERENCE ON LOW PRESSURE AERODYNAMIC FACILITIES
LONDON, 25 - 27 OCTOBER 1960

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PARTICIPANTS AT THE ROUND TABLE CONFERENCE ON LOW PRESSURE AERODYNAMIC FACILITIES.
Fig. 1.1
DIFFUSION PUMP (schematic)

Fig. 1.2
VALVE SYSTEM
SPEED VARIES WITH VAPOUR PRESSURE OF PUMP FLUID. SPEED INDEPENDENT & TEMPERATURE OF COOLING WATER OF OPERATING CONDITIONS AND PUMP FLUID.

**FIGURE 1.3**

TYPICAL CHARACTERISTICS OF DIFFUSION PUMPS.

<table>
<thead>
<tr>
<th>No.</th>
<th>HEATER INPUT Kw</th>
<th>BACKING PUMP DISPLACEMENT CFM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.4</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>5.2</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td>20</td>
</tr>
</tbody>
</table>
BACKING PUMPS
(2-3 mm.hg)

COOLING TUBES

OIL JETS

BOILER 15-40 mm hg

OIL

HEATER

COOLED
CONDENSER
RING

FIGURE 1.4

BOOSTER PUMP (schematic)

FIGURE 1.5

FORE PRESSURE TOLERANCE,
i.e. HIGHEST PRESSURE AGAINST WHICH PUMP WILL OPERATE.

PUMP SPEED

PERFORMANCE VARIATION WITH HEAT INPUT
**FIGURE 1.6**

<table>
<thead>
<tr>
<th>HEATER INPUT Kw</th>
<th>LITRES/SEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 22.5</td>
<td>10000</td>
</tr>
<tr>
<td>2 22.5</td>
<td></td>
</tr>
<tr>
<td>3 6.4</td>
<td></td>
</tr>
<tr>
<td>4 6.4</td>
<td></td>
</tr>
</tbody>
</table>

5 of these pumps used by N.P.L. Low Density Tunnel (Mach 2 nozzle 7" dia.)

6 of these pumps used by A.R.E. and UTIA Low Density Tunnels (Mach 2 nozzles 5.0" dia.)

**FIGURE 1.7**

Typical characteristics of booster pumps

Capital cost and power consumption for complete pumping system

Typical diffusion pump

Typical booster pump

Typical steam ejector plant (Berkeley)

Typical cryopump (usc)
**FIGURE II.1**

Steam Ejector System (schematic)

**FIGURE II.2**

Typical Steam Ejector System Performance Curve

**FIGURE II.3**

Oil Ejector Performance Curve (KS 16000)
Fig. IV - 1.  CALCIUM FLUORIDE OPTICAL SYSTEM - SCHEMATIC

LENS  FOCAL LENGTH
1  8.42 CM.
2  13.43
3  13.43
4  10.96
5  13.14
6  23.30
7  11.69

ALL LENS DIAMETERS - 2.9 CM.
EDGE THICKNESS - 0.1 CM
60° PRISM - 3.2 CM PER SIDE
2.4 CM THICK
Fig. IV-2. SPECTROGRAPH - MONOCHROMATOR WITH COVERS REMOVED.
Fig. IV-3. Shock waves in oxygen in front of 90° cone at Mach number $\sim 3.9$. 

165x67
Fig. IV-4. SCHEMATIC OF ELECTRON BEAM APPARATUS.
Fig. IV_6. AXIAL POSITION COORDINATES
(LAST FIGURE = 0.001 INCH)

Fig. IV_7. FLOW OVER 70° WEDGE AT MACH 2
(LINES OF CONSTANT DENSITY RATIO)
Fig. IV-8. SCHEMATIC OF WIND TUNNEL GLOW FLOW VISUALIZATION INSTALLATION
Fig. IV-9. AIR GLOW OVER SPHERE
AT MACH 3.8
Fig. IV-10. ARGON GLOW OVER SPHERE AT MACH 1.7.
X-RAY SCATTERING TECHNIQUE FOR LOCAL DENSITY MEASUREMENT

FIG. IV, 12

ELECTRON BEAM TECHNIQUE FOR LOCAL DENSITY MEASUREMENT

FIG. IV, 13
FREE MOLECULE FLOW THEORY

SLIP FLOW THEORY

TRANSITION FLOW THEORY FROM KNUDSEN

FIG. VI, 1

KNUDSEN NUMBER, K_r
FIG. VII.1

LANGMUIR PROBE CHARACTERISTIC
Fig. VII.2. MACH DISC CONFIGURATION IN A WATER PLASMA JET OF ABOUT 6000 m/sec and 8000 °K (enlarged)
Fig. VIII.1
CORRECTION FACTORS FOR TYPICAL IMPACT PROBE IN
LOW REYNOLDS NUMBER SUPersonic FLOW

Fig. VIII.2
STATIC PRESSURE ON CONE IN FUNCTION OF
INTERACTION PARAMETER FOR VARIOUS
WALL TEMPERATURES $T_w$. 
Fig. VIII. 3

LINES OF CONSTANT TEMPERATURE RATIO $T_w/T_{w_1}$ FOR FLOW OVER FLAT PLATE
Fig. IX - 1. CUTAWAY VIEW OF AMES POROUS NOZZLE

Fig. IX - 2. VARIATION OF MACH NUMBER WITH AND WITHOUT THE BOUNDARY-LAYER SUCTION IN AMES LOW DENSITY TUNNEL
Fig. IX-3. CUTCAY VIEW OF NOZZLE AT UNIVERSITY OF SOUTHERN CALIFORNIA

Fig. IX-4.

BOUNDARY LAYER THICKNESS VS. WALL TEMPERATURE

SYMBOLS:
- $S$ Boundary-Layer Thickness
- $S_{ad}$ Boundary-Layer Thickness For Zero Heat Transfer
- $S^*$ Boundary-Layer Displacement Thickness
- $T_W$ Wall Temperature
- $T_0$ Stagnation Temperature
Fig. IX-5. REAL GAS MACH 15 NOZZLE (TRUE TEMPERATURE OPERATION)

\[ P_0 = 500 \text{ ATM.} \]
\[ T_0 = 10,800 \text{°R} \]

\[ \text{length} = 16.68 \text{ ft.}, \text{ exit dia.} = 3.774 \text{ ft.} \]
\[ \text{max. expansion angle (of core)} = 10.79° \]
\[ \text{core dia at exit} = 1.5958 \text{ ft.} \]
\[ \text{throat dia} = 9.16 \times 10^{-3} \text{ ft.} \]
\[ \text{turb. b.l.:} \delta_{\text{exit}} = 1.369 \text{ ft.}, \delta^*_{\text{exit}} = 1.089 \text{ ft.} \]

Fig. IX-6. LAMINAR BOUNDARY LAYER MOMENTUM THICKNESS REYNOLDS NUMBER IN MACH 15 NOZZLE

\[ P_0 = 10 \text{ ATM} \]
\[ T_w = 1500 \text{°R} \]

\[ 5,000 \text{°R} \]
\[ 9,000 \text{°R} \]

\[ \text{THROAT} \]
\[ \text{EXIT} \]

\[ \text{NOZZLE} \]

\[ x \text{ FEET} \]
HEAT TRANSFER IN THE THROAT REGION FOR TURBULENT BOUNDARY-LAYER

\[ q = \frac{3.1 \times 10^{-3} P_o^{.75} T_o^{2.5}}{r_e^{.5}} (T_o - T_w) \]

SYMBOLS:
- \( P_o \): Stagnation Pressure
- \( T_o \): Stagnation Temperature
- \( T_w \): Wall Temperature
- \( r_e \): Throat Radius
- \( q \): Heat Transfer Rate

\( \beta = \frac{P_o^{.75} r_e^{.5}}{(ATM)^{.75} ("R")^{2.5}} \)
Fig. IX - 9. OXYGEN RECOMBINATION IN A CONICAL MACH 15 NOZZLE WITH SUPPLY TEMPERATURE OF 9000°C

\[ \begin{align*}
X & = \text{FRACTION BY WT. OF OXYGEN IN ATOMIC FORM} \\
X_e & = \text{DITTO FOR EQUILIBRIUM FLOW}
\end{align*} \]

Fig. IX - 10. EFFECT OF NON-EQUILIBRIUM FLOW ON MACH NO. MACH 15 NOZZLE 16.7 FT. LONG

\[ \begin{align*}
T_e & = 5000^\circ \text{K} \\
p_e & = 200 \text{ ATM}
\end{align*} \]
**Fig. IX, 11**  
THE EFFECT OF STAGNATION TEMPERATURE AND PRESSURE AND NOZZLE GEOMETRY FOR A HYPERBOLIC AXISYMMETRIC NOZZLE ON THE FROZEN DEGREE OF OXYGEN DISSOCIATION FOR A SIMPLIFIED AIR MODEL.

\[ \alpha_f = \frac{(0)}{(0)+(NO)+2(O_2)} \]

**Fig IX, 12** - EFFECT OF CHEMICAL FREEZING ON NOZZLE AIRFLOW MACH AND REYNOLDS NUMBERS. HYPERBOLIC AXISYMMETRIC NOZZLE L/a = 1 cm.
Fig IX, 13 - ELECTRON CONCENTRATION PROFILES IN FIRST STAGE OF HYPERSONIC SHOCK TUNNEL NOZZLE
Fig X, 1
PISTON COMPRESSION HEATER (SCHEMATIC)

Fig X, 2
HOT SHOT (SCHEMATIC)

Fig X, 3
ELECTRIC ARC TUNNEL (SCHEMATIC)
Fig X. 4
NASA SPINNING ARC HEATER (SCHEMATIC)

Fig X. 5
GIANNINI PLASMA JET (SCHEMATIC)

Fig X. 6
FORSCHUNGSINSTITUT FUR STRAHLANTRIEBE
PLASMA JET (SCHEMATIC).
Fig. X.7 - NITROGEN PLASMA JET OF ABOUT 3000 m/sec and 10000 °K.
Fig XI,5 Ionizing devices
FIG. XII. 1

VISCOUS EFFECT ON THE AXIAL FORCES OF A WEDGE AT ZERO ANGLE OF ATTACK

FIG. XII. 2

ALTITUDE MACH NUMBER DIAGRAM