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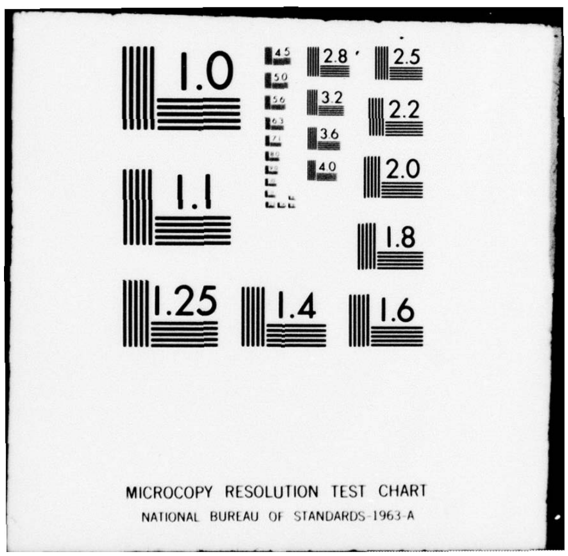
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REPORT NO. DME/NAE 1978(4)

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Conseil national de recherches Canada

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FOREWORD

The Quarterly Bulletin is designed primarily for the information of Canadian industry, universities, and government departments and agencies. It provides a regular review of the interests and current activities of two Divisions of the National Research Council Canada:

Division of Mechanical Engineering
National Aeronautical Establishment

Some of the work of the two Divisions comprises classified projects that may not be freely reported and contractual projects of limited general interest. Other work, not generally reported herein, includes calibrations, routine analyses and the testing of proprietary products.

Comments or enquiries relating to any matter published in this Bulletin should be addressed to: *DME/NAE Bulletin, National Research Council Canada, Ottawa, Ontario, K1A 0R6*, mentioning the number of the Bulletin.

AVANT-PROPOS

Le Bulletin trimestriel est conçu en premier lieu pour l'information de l'industrie Canadienne, des universités, des agences et des départements gouvernementaux. Il fournit une revue régulière des intérêts et des activités actuelles auxquels se consacrent deux Divisions du Conseil national de recherches Canada:

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Établissement aéronautique national

Quelques uns des travaux des deux Divisions comprennent des projets classifiés qu'on ne peut pas rapporter librement et des projets contractuels d'un intérêt général limité. D'autres travaux, non rapportés ci-après dans l'ensemble, incluent des étalonnages, des analyses de routine, et l'essai de produits de spécialité.

Veuillez adresser tout commentaire et toute question ayant rapport à un sujet quelconque publié dans ce Bulletin à: *DME/NAE Bulletin, Conseil national de recherches Canada, Ottawa, Ontario, K1A 0R6*, en faisant mention du numéro du Bulletin.

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ISOTHERMAL FORGING AT THE NATIONAL AERONAUTICAL ESTABLISHMENT

by

R.L. Hewitt, J-P.A. Immarigeon, W. Wallace
Structures and Materials Laboratory

and

A.Kandeil, M.C. de Malherbe
Department of Mechanical and Aeronautical Engineering,
Carleton University

ABSTRACT

The isothermal forging process is briefly described and its importance as a means of forming complex parts from high strength aerospace alloys is discussed. Experimental facilities have been designed and built at the National Aeronautical Establishment for carrying out detailed investigations of the isothermal forging process and its products. The experimental approach is explained with reference to some current research projects and the associated experimental equipment is described.

1.0 INTRODUCTION

The aerospace industry has always sought to use materials with the highest specific strengths available. While such materials offer benefits in service, their high strengths present particular problems to the manufacturing industries which must produce fabricated components. To resolve these problems extensive work has been done to develop improved fabrication processes, and materials that will respond to them favourably.

Isothermal forging is one of the more important processes to have evolved in recent years. In this type of forging the billet and dies are maintained at the forging temperature during deformation. Slower forging rates can therefore be used, and with highly strain rate sensitive materials forging loads may be reduced to as little as 10% of the conventional forging loads (Ref. 1). At the same time chilling at the die-billet interface is avoided (Ref. 2), lubricants become more effective (Ref. 3) and improved die filling is obtained (Refs. 1 to 4). The overall result is improved workability of deformation resistant materials. By combining this process with powder fabrication, highly alloyed casting type alloys can be processed into homogeneous wrought products (Refs. 5, 6). This should allow new strong wrought alloys to be developed which may find uses in a wide range of critical applications.

Isothermal forging has already been exploited commercially, particularly in the United States. For example, the Pratt and Whitney F-100 engine, which powers the General Dynamics F-16 and the McDonnell Douglas F-15 aircraft, contains seven discs in the high pressure compressor and turbine sections, plus some seals and spacers, all of which are produced by isothermal forging of modified IN-100 powder billets (Ref. 5). This is a high strength alloy which until recently has only been used for investment castings. Airframe components such as the nacelle centre beam frame for the B-1, the horizontal stabilizer torque-rib for the F-15 (Ref. 6), and scaled-down nose wheels and other structural shapes (Refs. 2, 7) have been produced in titanium alloys such as Ti-6Al-4V. In addition since close tolerances can be achieved in thin section iso-forgings of Ti-6Al-4V, these can be used to replace more expensive machined parts made from deep hardening alloys such as Ti-6Al-2Sn-4Zr-6Mo (Ref. 5). Complex shaped high performance components such as the cover for the M85 machine gun have been isothermally formed in 4600 and 4620 type steels from pre-alloyed powders (Ref. 8).

2.0 EXPERIMENTAL APPROACH

Although several large scale facilities have been developed, primarily in the United States, they are mainly used for system and component development. Few attempts have been made to characterize and understand the effects of forging temperature, strain rate and prior structure on the flow characteristics, subsequent metallurgical structure and mechanical properties of the forgings. Such work requires versatile equipment and, at NAE, it has been decided that two complementary test systems are most convenient. The hot working and mechanistic studies are performed under rigidly controlled conditions in a subscale system. A larger isothermal forging apparatus is used to produce material at slow controlled rates of deformation for subsequent mechanical property evaluation. A brief description of these two systems is given below.

3.0 EQUIPMENT FOR MECHANISTIC STUDIES

The intrinsic behaviour of metallic systems during forging is conveniently studied using highly sensitive servo-controlled hydraulic testing machines modified for constant temperature, controlled strain rate compression testing. Such equipment has been developed in this laboratory for several years (Refs. 9, 10), and the following notes describe the current system, shown in Figure 1.

Deformation of small cylindrical samples is carried out between flat-faced TZM molybdenum or hot-pressed silicon nitride dies which are housed inside a closed cylindrical steel environmental chamber, Figure 1-B. This can be evacuated or purged with argon to prevent oxidation of the sample and tooling. The dies are mounted on Udimet 720 superalloy supports which are held in turn by water cooled 347 stainless steel columns. These are fixed to the load cell at the top and hydraulic actuator at the bottom, Figure 1-A, with o-rings providing seals with the top and bottom plate of the environmental chamber. The parts are shown schematically in Figure 2. The compression dies and specimen are heated through a susceptor by an induction coil which is powered by a 7½ KW Lepel induction generator operating at 250KHz, Figure 1-E.

Temperatures of the specimen and tooling are measured by either chromel-alumel or platinum-platinum rhodium thermocouples which are embedded in the dies. To maintain constant temperature, the output from a control thermocouple is fed to a proportional controller which in turn provides a DC signal to the power control unit of the Lepel generator. The power control system is shown schematically in Figure 3.

Specimen deformation is followed by measuring the relative displacement of the upper and lower die plates. This displacement is transferred by two concentric probes to a DCDT displacement transducer which is housed in a small cylindrical chamber above the main environmental chamber. The strain measuring system and upper compression tooling are shown in Figure 4.

The deformation tests can be carried out at constant true strain rates as well as isothermally. This is important for materials whose flow properties are highly strain rate sensitive. This can be done by keeping the hydraulic piston velocity proportional to the instantaneous height of the specimen, which is achieved by means of an analogue function generator designed to operate in conjunction with the servo-controller of the test system (Ref. 10). A schematic of the hydraulic piston position control, incorporating the function generator, is shown in Figure 5. The generator produces an exponential voltage decay which is fed to the program input of the servo-controller. The compression gap height decreases exponentially with time accordingly, as required for constant true strain rate.

An important feature of the apparatus is that specimens can be quenched immediately after the deformation cycle is completed. The forged specimen is pushed by a flipper arm down an opening machined into the lower anvil and out at the base into a quenching media. The entire operation takes less than one second. This allows the hot worked microstructure to be retained for subsequent metallographic examinations.

The apparatus is interfaced to a real-time data acquisition system (RDAS). Loads and specimen height (compression gap) are monitored and digitized during testing. The recorded data are processed by the Structures and Materials Laboratory Programmable Remote Job Entry System (PRJES) for later transfer to the NRC computation centre for analysis. The true flow stress and corresponding true strain values are derived from these data. The RDAS-PRJES system data flow chart is shown in Figure 6 (Ref. 11).

The above system has turned out to be a powerful laboratory tool for the phenomenological study of high temperature plastic flow. However, to assess the full potential of isothermal forging, the mechanical properties of processed material must be evaluated. To do so, the forged pancakes must be large enough to provide test samples of standard size.

4.0 LARGE SCALE FORGING SYSTEM

A pilot scale forging system has been designed and built to allow forgings up to 85 mm final diameter to be produced (Ref. 12). This is shown in Figure 7. Since it was intended to forge materials under conditions which might be of commercial interest, it is not as versatile as the smaller equipment described above, nor quite so accurate. It is capable of providing specimen temperatures up to 1150°C and can forge at approximately constant strain rates from 2.7×10^{-2} s^{-1} to 1.4×10^{-4} s^{-1}.

4.1 Heating Source

Cartridge heaters (Ref. 13) were used as the heating source. These consist of swaged tubes containing resistance wire wound onto a magnesium oxide core and separated from the sheath with an electrically insulating powder. They are available ex-stock for applications to 1000°C, but by using boron nitride powder packing, which has a very high thermal conductivity, they can be made for continuous service to 1100°C (measured 12 mm away from the surface of the cartridge). Higher temperatures are possible if a reduced heater life is acceptable. Because of the limited height between the platens of the press, only one row of heaters could be used for each die and thus the heat input to the system was limited to about 5KW.

The centre cartridges in each row were manufactured with a chromel-alumel thermocouple next to the winding, and the outputs from these were used to control the power input via temperature and power controllers in the normal way.

4.2 Insulation

Because of the limited heat input, as much insulation as possible was incorporated in the design, both around the dies and in the load train. The choice of material for use in the load train is a compromise between strength and insulating value, since in general the better the insulating value the lower the strength. Also the material must have a high thermal shock resistance, since one face is in contact with the heater block at 1100°C while the other contacts the cooling block at 50°C. Cast fused silica was chosen for this component; it has a strength of better than 250 MPa at 1000°C (Ref. 12), and an excellent thermal shock resistance while its thermal conductivity is about 0.003 cal cm^{-1} s^{-1} $°K^{-1}$ at 800°C. An as-cast insulating base is shown in Figure 8.

To limit heat loss around the outside of the die and heater block, insulation was provided on the outside of the insulating base, heater block and die as shown schematically in Figure 9. A series of baffles as shown were employed in the region around the specimen to prevent heat loss from this area while providing for relative vertical movement of the dies. Fused silica foam was used for these parts since it has a very low thermal conductivity of 0.0004 cal cm^{-1} s^{-1} $°K^{-1}$, and is easily machinable.

4.3 Die and Heater Plates

The die and heater plates were fabricated by powder metallurgy processing from Mar-M200 powder. As shown later, this powder can be consolidated by hot isostatic pressing at 1250°C and 100 MPa for two hours to produce a coarse-grained deformation-resistant material.

The can for manufacturing the heater block consisted of 12 mm thick steel side plates with a 1 mm thick stainless steel sheet welded to the top and bottom. Mild steel rods were welded in place where the heater holes were required, since these would be easier to machine out after pressing, and an evacuation tube was provided on one side. A photograph of the filled can after pressing is shown in Figure 10.

The die was made in a similar manner with one face of the can made of 38 mm thick steel with the profile of the die plate machined in it. The finished part is shown in Figure 11.

4.4 Atmosphere Control and Specimen Manipulation

To prevent excessive oxidation of the dies and heater blocks the system is operated in an environmental chamber filled with argon under a small positive pressure. The chamber consists of a rectangular box 700 $\times$ 600 $\times$ 420 mm high made from 12 mm thick aluminum plates. A large access hatch 450 mm $\times$ 340 mm is provided at one end and a loading chamber at the other. This chamber, 200 mm diameter by 230 mm long is connected to the main chamber by a sliding door and is vacuum tight so that after inserting a specimen it can be quickly evacuated and back filled with argon.

To transport the specimen to and from the die area, a stainless steel trolley is provided which runs on a track as shown in Figure 12. A schematic of the arrangement is shown in Figure 13.

4.5 Constant Strain Rate Device

The original hydraulic control system could only operate at a constant loading rate. This was achieved by opening a mechanical variable relief valve via a gear box and chain by a control motor. This was modified to provide a constant strain rate by inserting solid state switches in the control motor circuit so that the motor only operated when an increase in load was necessary to maintain the desired strain rate.

The switches are controlled by a device which continuously compares the specimen height with a height provided by a function generator. This is a digital device which generates the height of the specimen from a true strain of 0 to 1.4 in 256 steps. The rate at which these are generated is controlled by a variable frequency clock which provides strain rates from $2.7 \times 10^{-2}\ s^{-1}$ to $1.4 \times 10^{-4}\ s^{-1}$.

To prevent overshoot in the system, caused by the mechanical linkage, a pulsing mechanism was introduced such that every time the device calls for an increase in load, the control motor is only activated for short periods ($\sim$ .1s) with a delay period ($\sim$ .9s) between.

5.0 APPLICATIONS

Over the last few years much information has been gathered on the high temperature flow behaviour of nickel-base superalloy powder compacts (Refs. 14 to 17). In particular, it has been demonstrated that superplastic properties can be obtained in compacts prepared by hot isostatic pressing, by appropriate control of the compaction parameters (Refs. 14, 15). The possibility has been examined that this fine grain superplasticity might be exploited to improve the forging characteristics of tungsten wire reinforced superalloy composites, and forming limit criteria established (Ref. 18).

Typical flow curves are shown in Figure 14 for compacts of Mar-M200, one of the strongest precipitation hardenable high temperature alloys available. Figure 14a demonstrates the importance of considering the prior thermo-mechanical history of materials when evaluating forging behaviour. The figure shows the flow curves for fine grained and coarse grained Mar-M200 compacts pressed below and above the solvus temperature of the intermetallic precipitate (Ref. 15). The coarse grained material is nearly seven times more resistant to plastic flow than the fine grained material under identical forging conditions. This fact was used in preparing the die plates for the pilot scale system described above.

The effects of temperature on flow at a fixed strain rate and those of strain rate at a fixed temperature are shown in Figures 14b and 14c respectively. Both the temperature and the strain rate sensitivities are obviously quite pronounced. The general features of the flow curves in these, and in all the other compacts examined to date are quite similar. An initial transient deformation period, during which the material either flow softens or flow hardens is followed at high strains by a steady state regime where neither the flow stress, nor the microstructure changes.

Transient deformation has been linked to microstructural instabilities and the microstructure that develops as steady state flow is approached has been shown to consist of a microduplex arrangement of ultra-fine equiaxed grains of the two (γ & γ') phases (Refs. 15, 17). It has also been shown that the steady state grain size, and hence flow stress, is a unique function of the forging parameters, thereby suggesting that control of the microstructure and mechanical properties developed during forging is feasible (Refs. 15, 16, 17).

It was to investigate the dependence of mechanical properties on forging parameters that the large system was built. Figure 15 shows a forging of an IN-100 powder billet processed with this pilot system at 1050°C and a strain rate of 10^{-3} s^{-1}. A typical starting billet is also shown. So far no mechanical property evaluations have been carried out on these forgings, but work is progressing in this direction.

In addition to these superalloy projects, work is in progress in several other areas following the experimental approach outlined above. Some of the materials of interest are shown in Figure 16.

a) Powder metallurgy billets of Ti-6Al-4V have been prepared, Figure 16a, which will be evaluated as forging preforms and as forged products. As explained earlier, these are materials which are being evaluated by aircraft manufacturers for the new generation fighter aircraft which are of interest to Canada.

b) Isothermal forging is also being evaluated as a means of forming oxide dispersion strengthened alloys such as the MA-754 alloy shown in Figure 16b. These are extremely expensive alloys which are produced from powders as axially symmetric extrusions. To produce complex airfoils from such alloys requires a great deal of time consuming machining and involves high scrap losses. Isothermal forging may provide a way of reducing some of the high costs, provided the highly elongated grain structure, which is required for high temperature strength, can be retained.

c) Figure 16c shows the microstructure of a cast cobalt-chromium-molybdenum alloy which is often used in the aerospace industry. This alloy has excellent corrosion resistance and high strength, and hence it is also widely used to produce cast surgical implants. This particular photograph was obtained from a hip prosthesis, and it reveals the presence of large intendendritic shrinkage cavities. Wrought forms of this material with more uniform alloy distribution, finer grain size and absence of gross internal defects would be expected to give higher tensile and fatigue strengths without sacrificing corrosion resistance. Isothermal forging of cast or powder fabricated billet may provide a way of producing such material.

6.0 SUMMARY

1. The isothermal forging process has been reviewed and experimental facilities at the National Aeronautical Establishment described.

2. Two test systems are used. The first system provides information on the mechanisms of plastic flow at high temperature, while the second provides forgings for subsequent mechanical property evaluations.

3. Areas of current interest include nickel and titanium base superalloy powder preforms, oxide dispersion strengthened alloys, and cast or powder fabricated cobalt base alloys.

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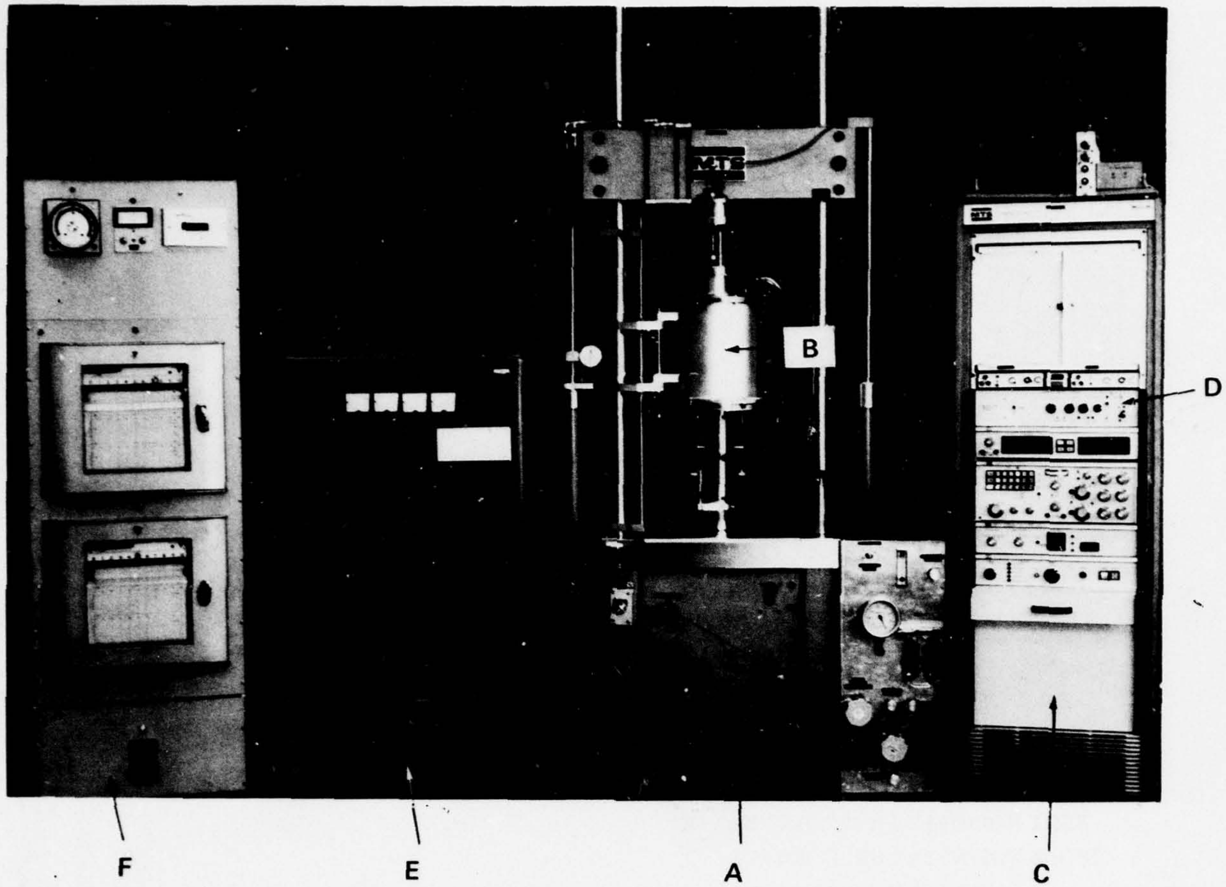
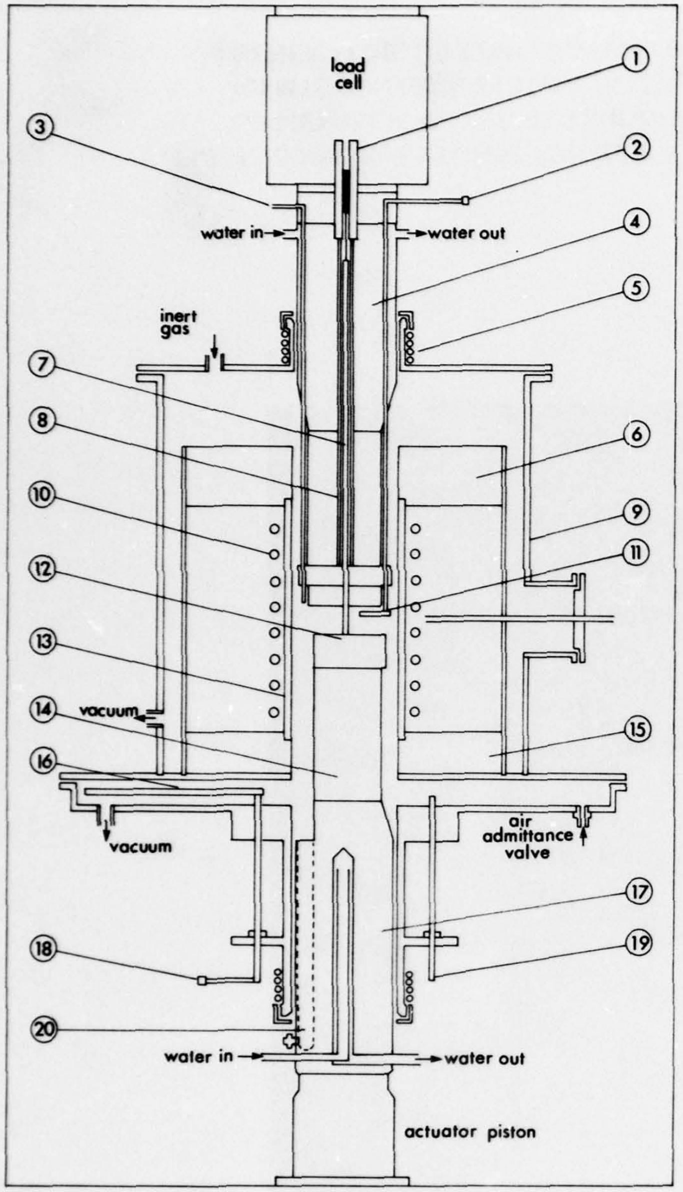


FIG. 1: SUBSCALE SYSTEM FOR CONSTANT TRUE-STRAIN RATE, ISOTHERMAL COMPRESSION TESTING OF METALLIC MATERIALS SHOWING: (A) MTS LOAD FRAME, (B) ENVIRONMENTAL CHAMBER, (C) MTS CONTROL SYSTEM, (D) EXPONENTIAL FUNCTION GENERATOR, (E) LEPEL INDUCTION GENERATOR, (F) TEMPERATURE CONTROLLER, RECORDERS



1. DISPLACEMENT TRANSDUCER
2. FLIPPER SHAFT HANDLE
3. INCONEL SHEATHED THERMOCOUPLE PROBE
4. TOP ANVIL SUPPORT
5. WATER COOLING COIL
6. TOP INSULATING BLOCK
7. TRANSDUCER EXTENSION PROBE
8. TRANSDUCER EXTENSION TUBE
9. COMPRESSION CHAMBER
10. INDUCTION COIL
11. FLIPPER
12. COMPRESSION DIE
13. SUSCEPTOR
14. BOTTOM ANVIL
15. BOTTOM INSULATING BLOCK
16. VACUUM DOOR
17. BOTTOM ANVIL SUPPORT
18. VACUUM DOOR HANDLE
19. VACUUM DOOR CLAMP
20. QUENCHING CHUTE

FIG. 2: SCHEMATIC CROSS-SECTION OF THE INDUCTION HEATING COMPRESSION TRAIN

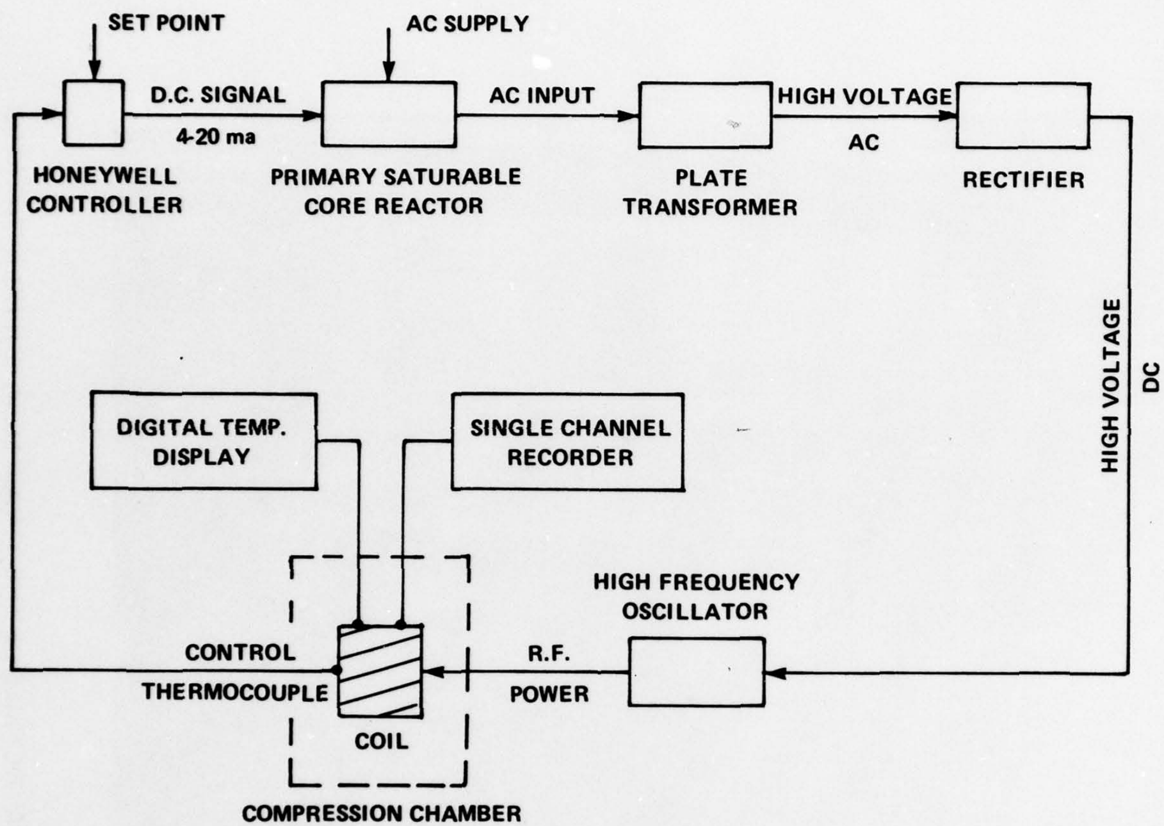


FIG. 3: SCHEMATIC DIAGRAM OF THE TEMPERATURE CONTROL SYSTEM

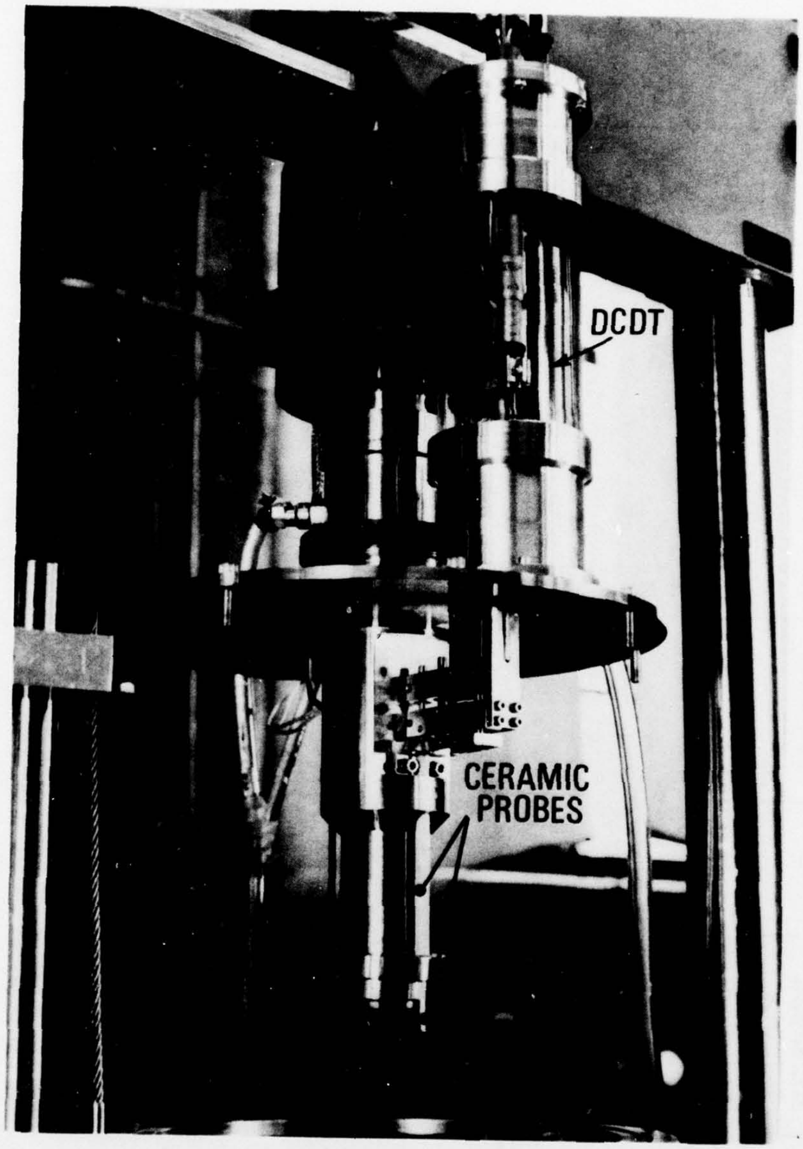


FIG. 4: DETAILS OF THE STRAIN MONITORING APPARATUS AND UPPER ANVIL ASSEMBLY

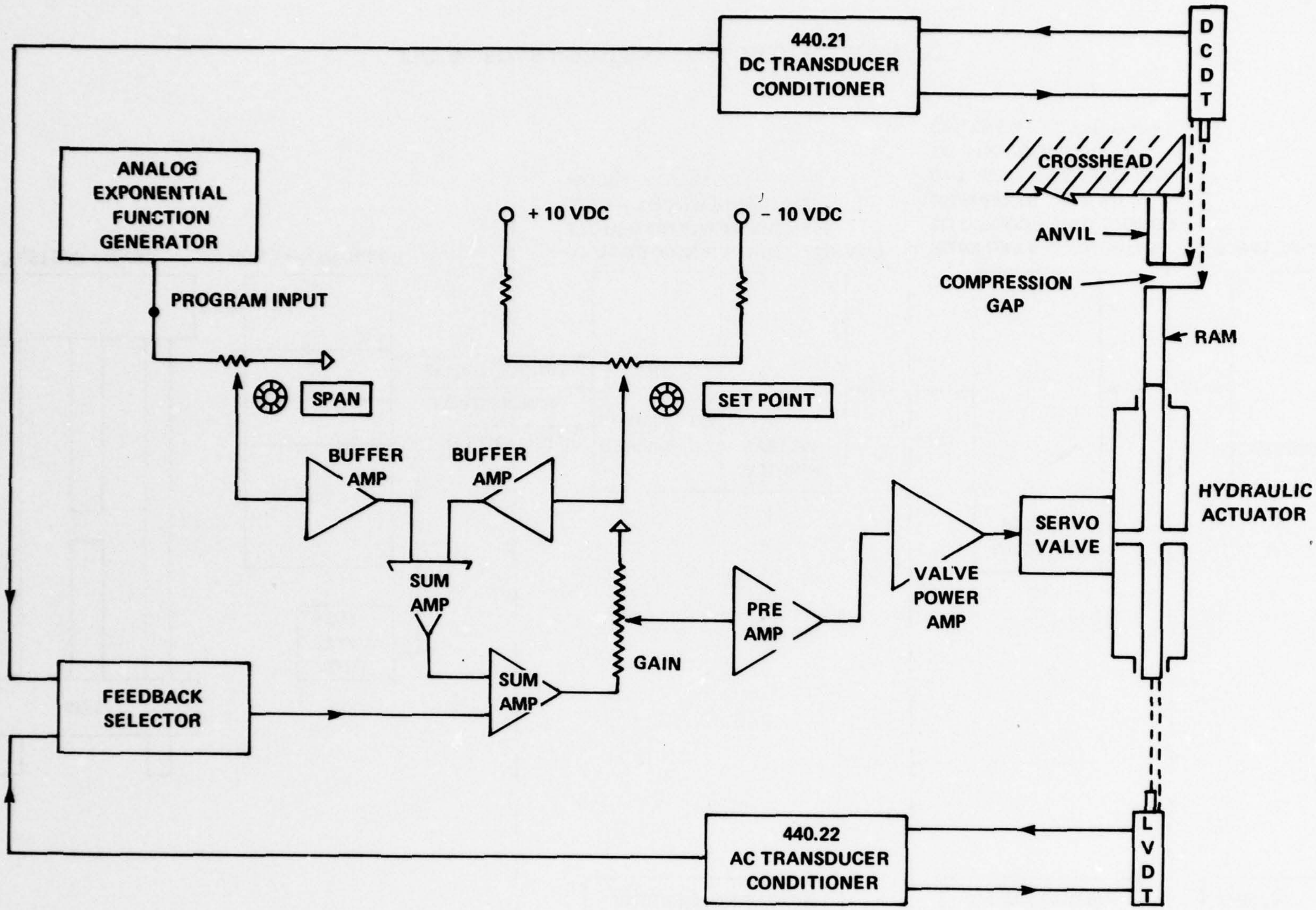


FIG. 5: RAM POSITION CONTROL INCORPORATING THE FUNCTION GENERATOR FOR CONSTANT TRUE STRAIN RATE DURING COMPRESSION

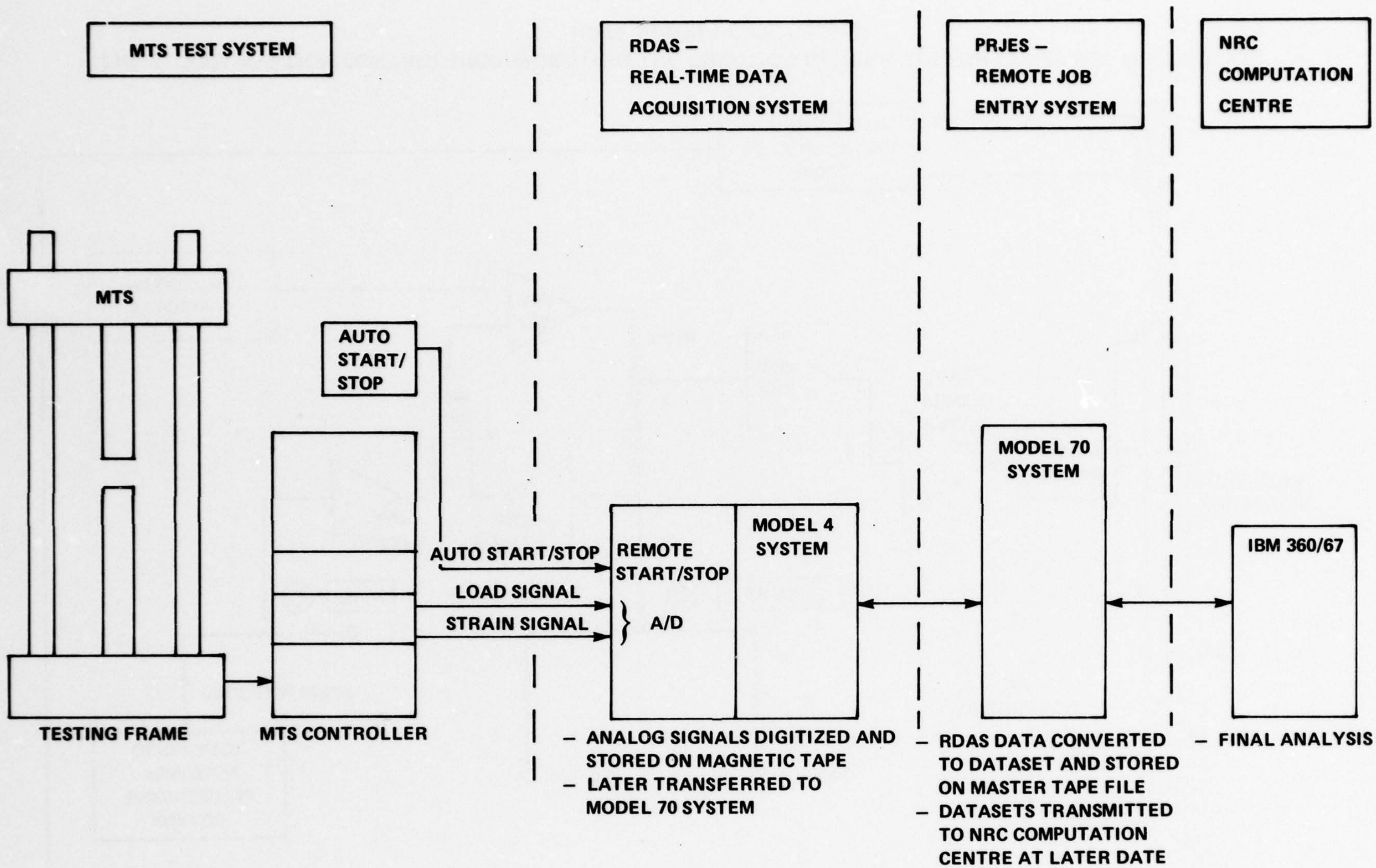


FIG. 6: RDAS – PRJES SYSTEM DATA FLOW CHART

SECOND SYMPOSIUM

ON GAS TURBINE OPERATION AND MAINTENANCE

ASSOCIATE COMMITTEE ON PROPULSION

held in Calgary, Alberta, June 1977

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FIG. 7: PRESS AND CONTROL PANEL

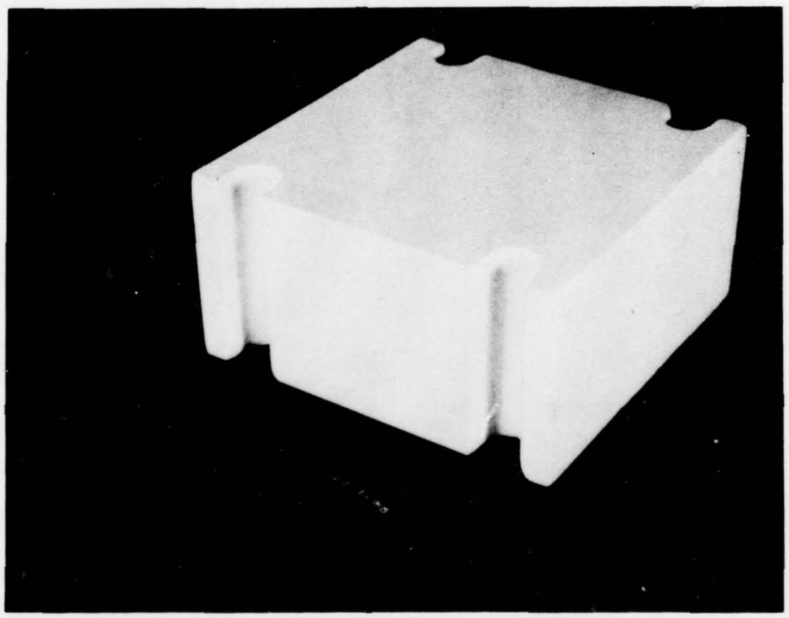

FIG. 8: AS-CAST FUSED SILICA INSULATING BASE

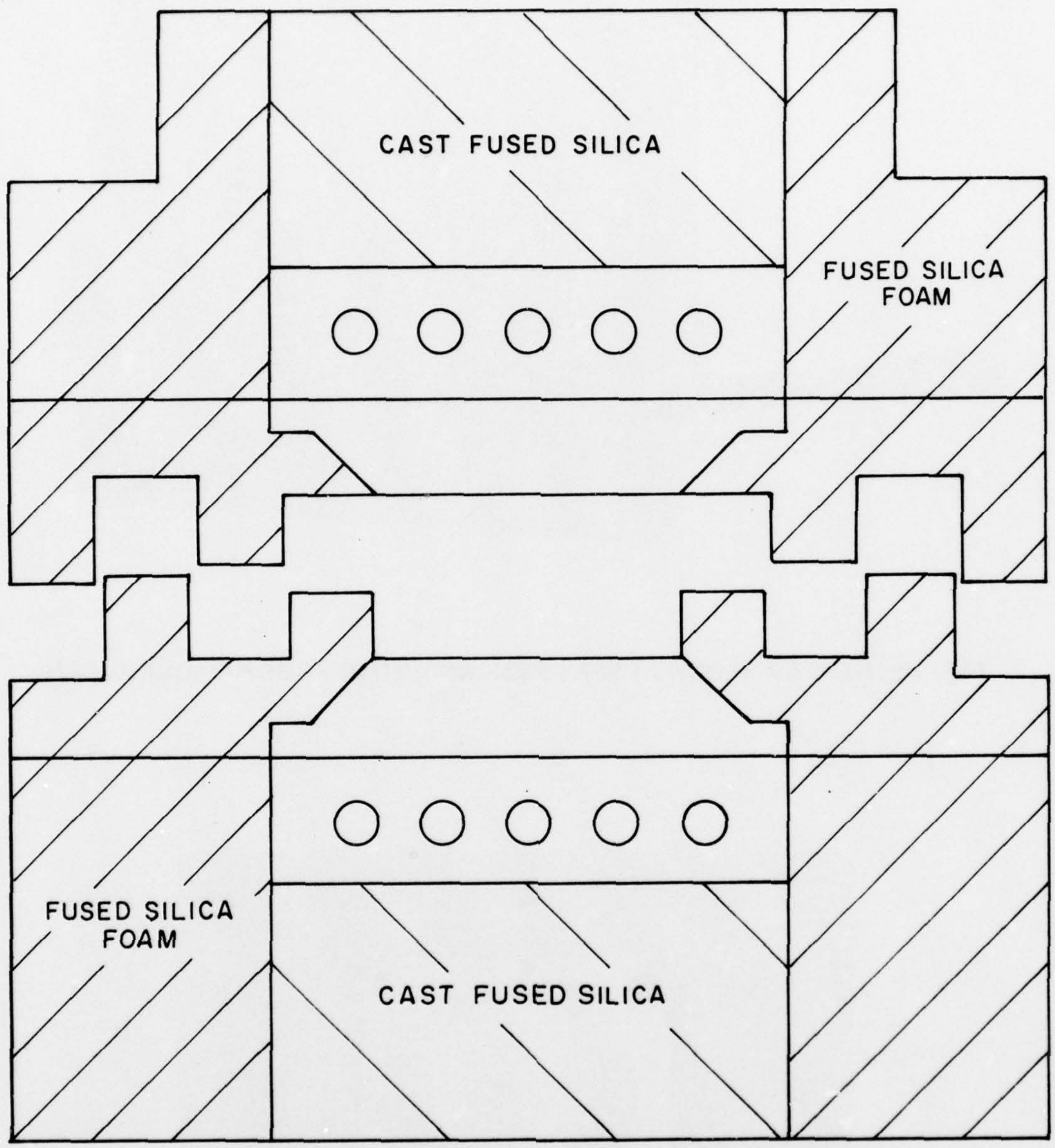

FIG. 9: SCHEMATIC OF TOTAL INSULATION

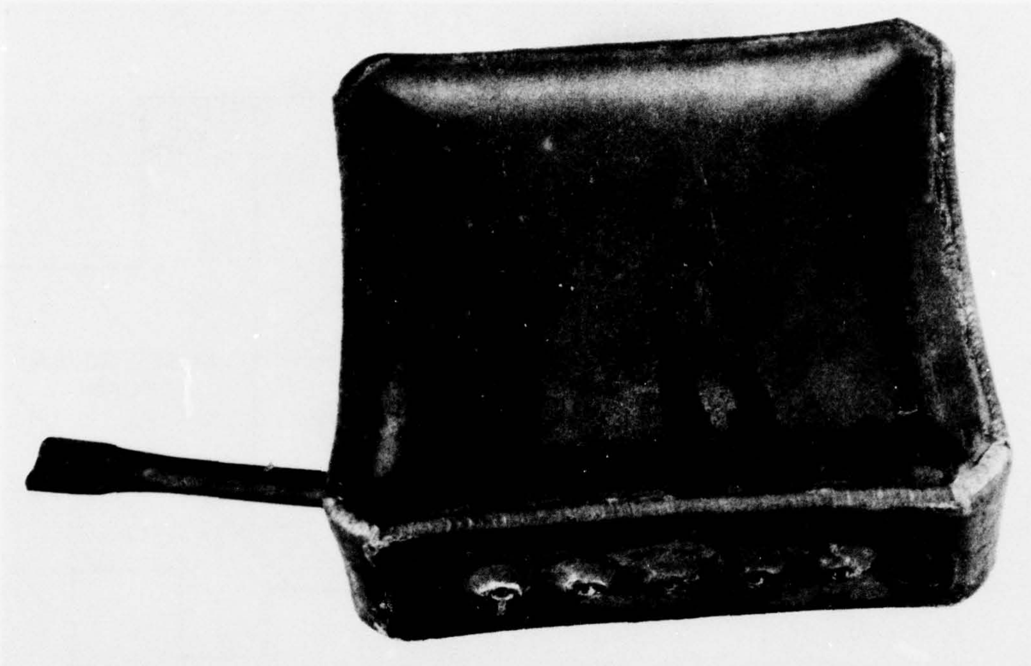

FIG. 10: HEATER BLOCK AFTER PRESSING AND BEFORE REMOVING CAN

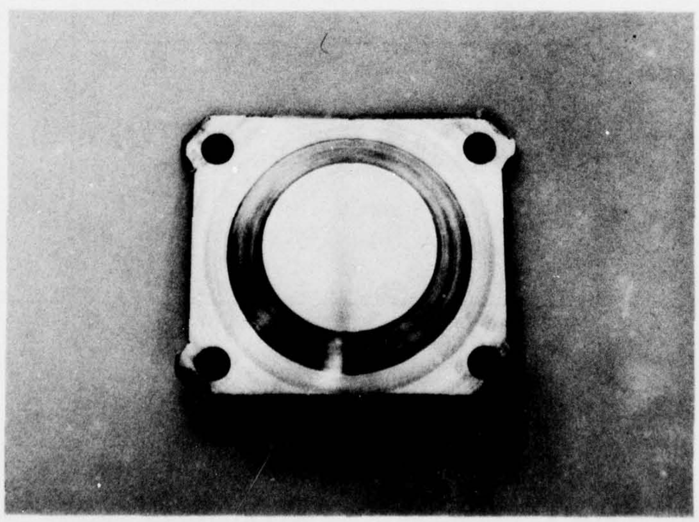

FIG. 11: DIE AFTER MACHINING

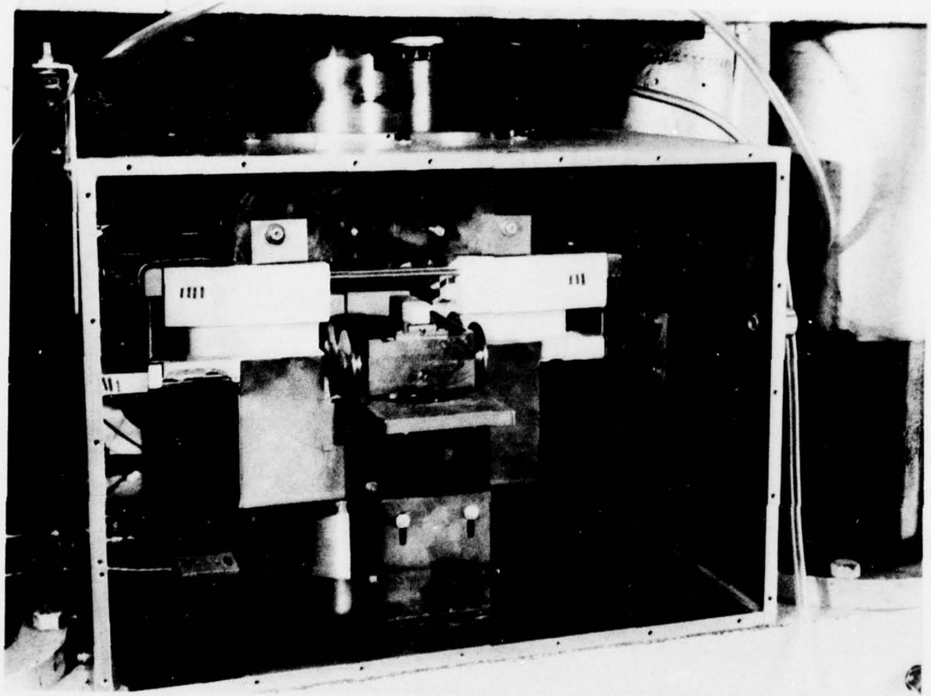

FIG. 12: SPECIMEN INSERTION TROLLEY ON TRACK

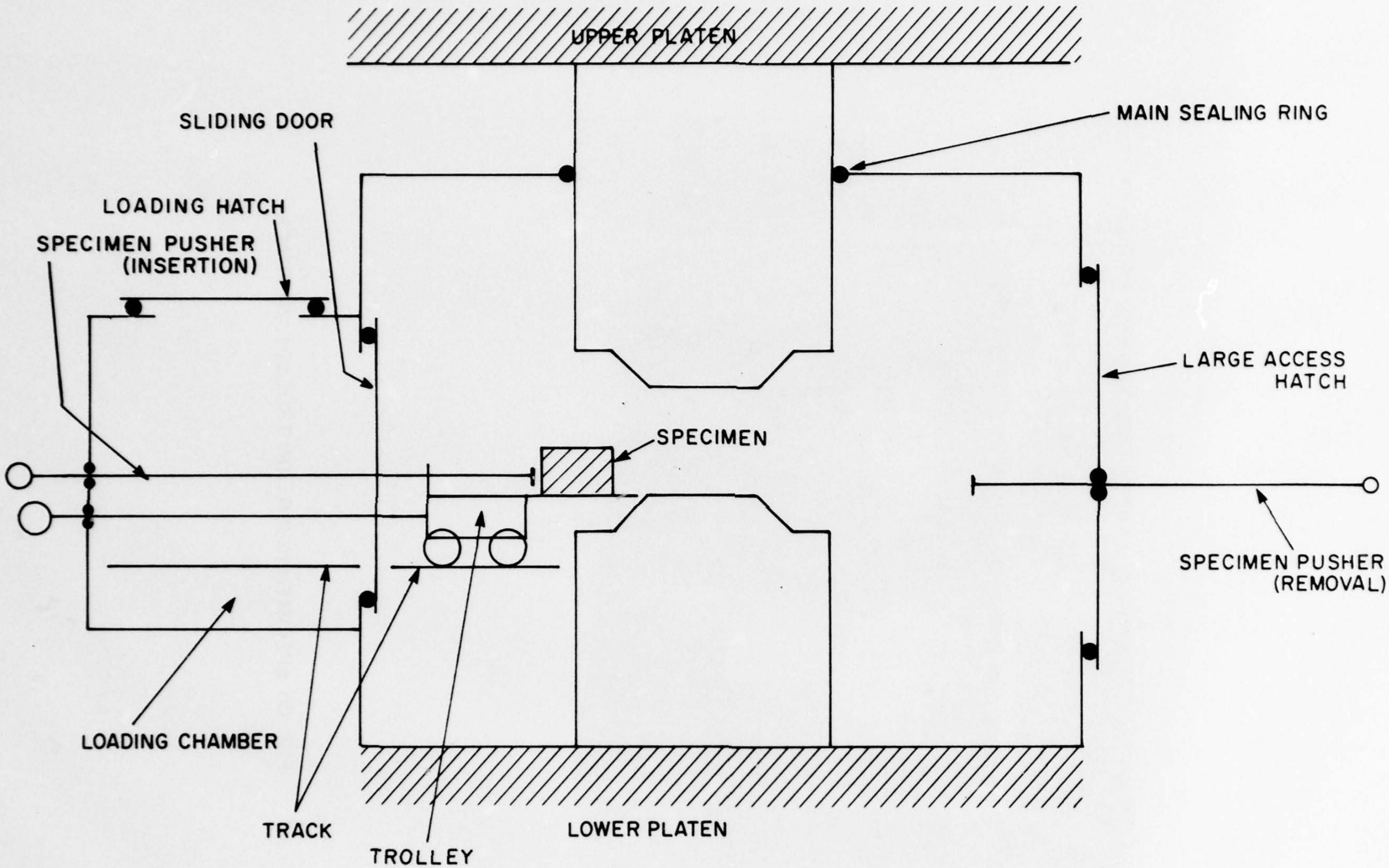

FIG. 13: SCHEMATIC OF ENVIRONMENTAL CHAMBER

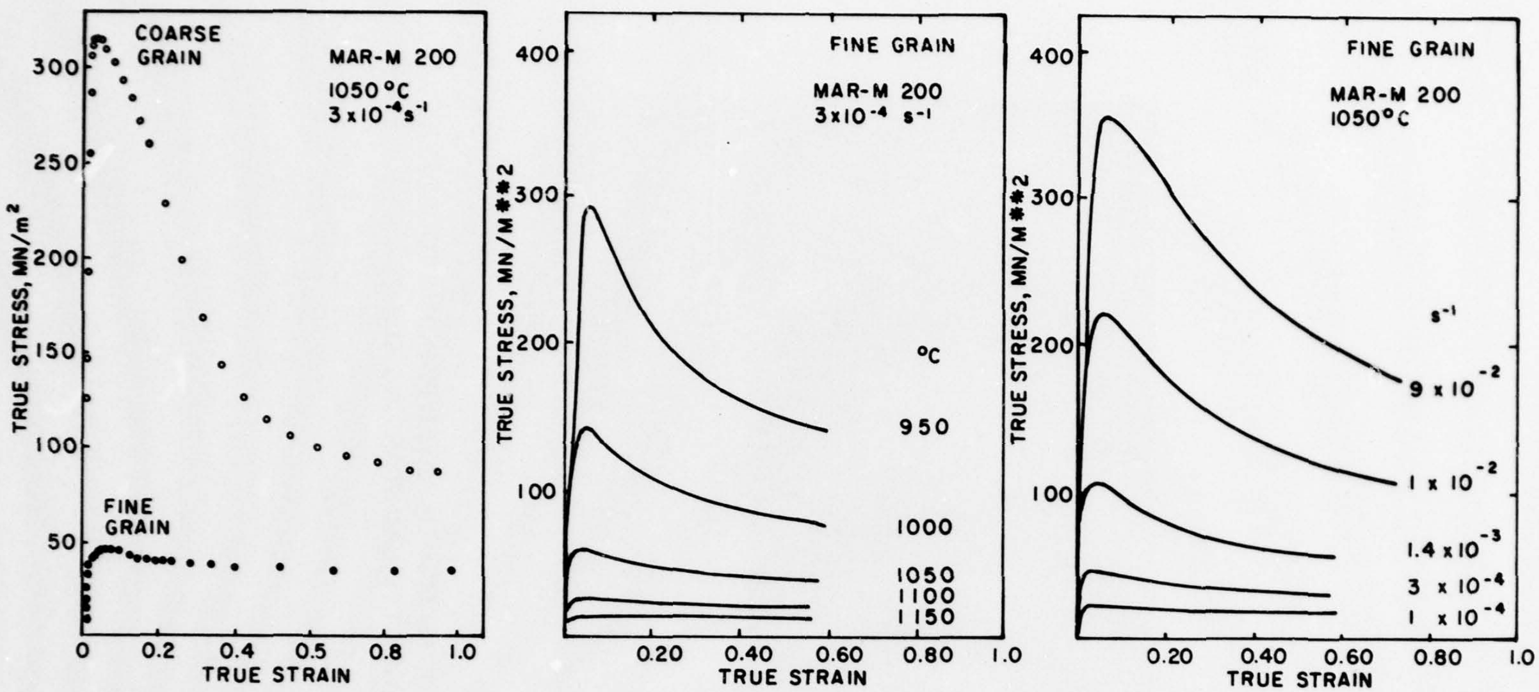

FIG. 14: HIGH TEMPERATURE STRESS STRAIN CURVES FOR MAR-M200 COMPACTS

(a) EFFECTS OF INITIAL MICROSTRUCTURE

(b) EFFECTS OF TEMPERATURE AT A CONSTANT STRAIN RATE OF 3 X 10^{-4} s^{-1}

(c) EFFECTS OF STRAIN RATE AT A CONSTANT TEMPERATURE OF 1050°C

FIG. 15: IN-100 SPECIMEN AFTER FORGING TOGETHER WITH TYPICAL STARTING BILLET

a x200 b x50 c x50

FIG. 16: CANDIDATE MATERIALS FOR ISOTHERMAL FORGING

(a) POWDER METALLURGY COMPACT OF TITANIUM BASE ALLOY (Ti-6Al-4V)
(b) OXIDE DISPERSION STRENGTHENED NICKEL BASE ALLOY (INCO MA754)
(c) CAST COBALT BASE ALLOY (VITALLIUM)

SECTIONAL VERSUS FULL MODEL WIND TUNNEL TESTING OF BRIDGE ROAD DECKS †

R.L. Wardlaw

Low Speed Aerodynamics Laboratory

National Aeronautical Establishment

1.0 INTRODUCTION

Through technological and engineering advances bridge road decks have been made lighter and structural damping has been reduced; consequently the modern intermediate and long span bridge has become more responsive to wind action. Today the avoidance of high stress levels and large amplitude motion as result of dynamic behaviour in wind is, more than ever, a major consideration for the design engineer.

In a presentation to the First Research Progress Review in San Francisco in 1973 the author discussed some of the aerodynamic considerations in bridge design and reviewed the state-of-the-art of wind tunnel investigation (Refs. 1 and 2). It was pointed out, at that time, that we had ". . . . not reached a point where the behaviour (of bridge road decks) as a result of wind action can be satisfactorily predicted by analytical means." Attention was drawn to certain gaps in our knowledge, particularly, the effects of turbulence and terrain. Also stressed was the need for more extensive investigations of the motion of completed structures, in order to obtain more information on structural damping levels and, more importantly, to provide a basis for the comparison of model and full scale measurements.

While these problems have not been entirely resolved it is gratifying to be able to comment that significant progress has been achieved in all areas as a result of both field and laboratory investigations in several countries including Australia, Canada, Japan and the United States. Therefore, it is timely to attempt once more to bring into focus for the practising engineer some of the implications these advances have on our techniques and approaches to wind tunnel investigations. Certainly, the question to which this paper is addressed, sectional versus full model testing, deserves re-examination; however, it should be made clear at the outset that unanswered questions remain and the final chapters cannot yet be written.

The principle contemporary issue in need of discussion is that of the effects of the gustiness or turbulence in the earth's surface wind on the bridge dynamic behaviour. Quite apart from the effects of turbulence on aerodynamic stability the adequacy of the traditional gust factor approach for estimating peak wind loads in turbulent wind must be challenged. Several questions arise:

i) does testing in smooth flow give excessively conservative estimates of aerodynamic stability in the natural wind.

ii) can dynamic behaviour in the natural wind be predicted from results obtained with sectional models in smooth flow using analytical procedures as proposed by Scanlan (Refs. 3 and 4).

iii) can the earth's surface wind be adequately modelled in the wind tunnel.

iv) can the modelling of the bridge itself at reduced scale be carried out with enough precision.

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v) finally, do the advantages of the sectional model approach — low cost, large scale, configuration flexibility, and short lead time for model preparation — have to be sacrificed for the advantages of the full model — simulation of the natural wind, inclusion of three-dimensional aeroelastic effects, and inherent modelling of the bridge modal dynamics.

These and other questions relating to wind tunnel investigations of bridge behaviour will be examined in this paper. A compromise approach between full model and sectional model techniques, the taut-strip approach advocated by Davenport (refs. 5 and 6), will also be discussed. The emphasis throughout the paper will be on dynamic behaviour as opposed to static or mean wind load effects.

The early history of bridge failure in wind and the development of investigative techniques was briefly reviewed in Reference 1. Some of the basic aspects of the relevant aerodynamic fundamentals and testing methods were reviewed in the same paper and in more depth in a review paper prepared by Scanlan for the Federal Highway Administration (Ref. 3); this latter paper also outlined analytical considerations in predicting bridge dynamic behaviour. The literature in the field is quite extensive and, rather than attempt a complete review, the reader is referred to the papers cited in References 1 and 3. It will be worthwhile, however, to re-examine certain aspects of the problem that bear closely on the question of wind tunnel testing technique.

2.0 WIND TUNNEL TESTING TECHNIQUES

2.1 The Full Model

The full model is a reduced scale geometric facsimile of the entire prototype bridge that includes all structural elements, the towers, the suspension cables, the road deck and the road deck hangers. For dynamic studies, it is necessary, as well, to model the mass, the mass distribution and the elastic characteristics of the prototype according to well established scaling principles. The scale ratio for a long span bridge may be very small; for example, the model of a 3000-foot long bridge would have to be constructed at a scale ratio of about 1:400 if it were to be tested in an 8-foot wide wind tunnel test section. Clearly large reductions in size will introduce difficulties in model design. Components become very small and it may become awkward to construct or assemble the model in a replica fashion. Figures 1 and 2 show a 1:110 scale full model in the National Aeronautical Establishment 30-foot × 30 foot wind tunnel of a proposed widened version of the Lions' Gate Bridge that crosses the Burrard Inlet at Vancouver, British Columbia. In the background in Figure 1 can be seen aerodynamic "spires" at the entrance to the test section that are designed to generate the shear and turbulence properties of the earth's surface wind. Depending on the roughness of the terrain at the bridge site the wind layer will be between about 1000 and 2000 feet deep and consequently at a scale of 1:100, the wind layer will be between 10 feet and 20 feet deep in the wind tunnel.

2.2 The Sectional Model

The expression "sectional model" derives from the aeronautical engineers practice of measuring the two-dimensional or sectional properties of aerofoils in wind tunnels by using constant section models that span the test section.

Rather than model the complete bridge, the aerodynamics of the bridge road deck can be studied by constructing a model that represents a short, mid-span section of the deck. The model spans the test section and is supported rigidly at the walls if force measurements are to be made or is mounted on pairs of springs for dynamic measurements (Fig. 3) in which case the mass, the mass distribution and the elastic properties must be modelled according to scaling criteria as is done with the full model. The bending mode natural frequency is controlled by the spring stiffness and the ratio of the bending to torsional mode frequencies is controlled by the spacing between the pairs of springs. If necessary the horizontal stiffness can be modelled by the addition of a spring constraint in the lateral direction. A 1:30 scale sectional model of the Long's Creek Bridge, a cable-stayed bridge on the Trans-Canada Highway in New Brunswick, that was tested in the National Aeronautical Establishment 15-foot diameter vertical wind tunnel is shown in Figure 4. The junction between the ends of the model and the wall introduces three-dimensionality into the flow and in order to minimize this "end effect" it is desirable to have the model as slender as is practicable and a span to chord ratio of 1:4 would be acceptable. The slenderness of the model is limited by it being strong enough to resist significant deformation when in motion and by the desirability of large scale. For testing in an 8-foot wide test section a model chord of 2 feet would be suitable and for a 100-foot wide prototype this would give a scale ratio of 1:50.

The simpler concept of the sectional model and its larger scale result in a much less expensive model than the full model and one that can be built more quickly and can be quickly modified for examining corrective configuration changes. Although the air flow can be made turbulent, by, for example the use of coarse upstream turbulence grids, it is not fundamentally possible to simulate all of the natural wind properties, particularly the physical size of the gusts, the so-called turbulence scale. Research, such as is underway at the Colorado State University, aimed at the development of large longitudinal scale two-dimensional "turbulence" should lead to a useful research and development tool for sectional model studies.

Although the road deck response to natural wind turbulence cannot be obtained directly, the prospect remains of predicting the response by analytical procedures such as those being developed by Scanlan (Refs. 3 and 4) which make use of sectional aerodynamic measurements made in smooth flow. Success with this approach would result in an ideal method for predicting bridge behaviour in natural wind. Formidable hurdles must be overcome before success is realized. For example, one question that must be resolved is the applicability to bridge road decks of the aircraft aerodynamicists classical strip theory, in which an aerofoil is divided into thin chordwise strips that are assumed to behave independently so that the overall aerofoil performance can be calculated by spanwise integration. Some alternative or modification to this technique may have to be devised.

It is quite common for slender elastic structures, as a consequence of their cross-sectional geometry, to be aerodynamically unstable in that energy is extracted from the airstream and oscillatory motion of the structure results. As will be discussed later, there are different aeroelastic mechanisms that may account for the instability. In some cases the phenomenon is amplitude limited and although excessive stress levels may not result, the bridge road deck will still be considered unacceptable from a user point of view (Ref. 7). Other mechanisms can result in dramatic motion that reaches catastrophic levels in a small number of motion cycles.

It has become conventional practice to use the spring-mounted sectional model in smooth flow to establish the susceptability of road decks to aerodynamic instability. For amplitude limited excitations, it must be established that amplitudes will not exceed a prescribed criterion of acceptability. As discussed in Reference 7, the acceptable level of amplitude will depend on the probability of occurrence at the bridge site of the wind speeds at which the motion occurs and upon the natural frequency of the deck mode excited. For the catastrophic category of instabilities it must be established that the motion will only occur at wind speeds above those that can be expected at the site. Experience to date, both in the field and in wind tunnel practice has corroborated the hypothesis that the sectional model approach will be conservative in predicting the occurrence of instabilities on prototype bridges. There have been no observations of unacceptable aerodynamic instability of prototype bridges in those cases where the road decks have been wind tunnel tested in smooth flow in advance of construction. There are several examples, The Golden Gate Bridge (Ref. 8), the original Tacoma Narrows Bridge (Ref. 9) and the Long's Creek Bridge (Ref. 10) that were not tested in advance of construction and turned out to be aerodynamically unstable. In these cases, subsequent wind tunnel studies in smooth flow confirmed the existence of the instabilities and demonstrated that the problems could have been circumvented if the wind tunnel testing had been done in advance.

2.3 The Taut-Strip Model

For this technique, that has been developed by Davenport (Refs. 5 and 6), the road deck model is attached to two parallel taut wires suspended across the wind tunnel test section (Fig. 5). The vertical and horizontal bending mode natural frequencies are controlled by the wire tension while the ratio of the bending mode to torsional mode natural frequencies is controlled by the separation between the wires. Davenport suggests that the wires be at the level of the bridge road deck shear centre (Ref. 5). The dynamic motion of the model will be primarily in the fundamental half-wave modes. As with the other modelling concepts the scaling of the mass and the mass distribution has to be correct.

The advantages sought by this approach over the sectional model are that the model behaviour can be observed in an appropriately simulated wind and the three-dimensionality of the model deformations are inherently included. At the same time the model is simpler in concept than the full model and to some extent retains other advantages of the sectional model.

With the taut-strip concept, the model scale is constrained not so much by the size of the prototype bridge but by how deep a wind layer, and hence how large a turbulence scale can be accommodated in the wind tunnel to be used. It is practical to think in terms of wind layer depths that are about one-half the height of the wind tunnel test section. Therefore, in an 8-foot high test section, a 4-foot deep wind layer could be developed representing a 1000-foot deep full scale layer at a scale ratio of 1:250. If the model were to be installed in an 8-foot wide test section the half-wave could represent as much as 2000 feet of bridge road deck at prototype scale. While the taut-strip model may offer some advantage in scale over the full model it will still be much smaller than the sectional model.

3.0 MODEL SCALING CONSIDERATIONS

3.1 Scaling Parameters

Model scale observations can only be extrapolated with confidence to prototype scale if sound scaling principles have been applied in the design of the model and the experiment. This will ensure that the relative magnitudes of the various forces involved in the bridge dynamics — the gravitational, inertial, aerodynamic, elastic and structural damping forces — will be the same for the model and the prototype and that the motion amplitudes will be in the same proportion as the geometric scale ratio. As will be shown, the scaling of different physical variables will not always be compatible and judicious relaxations of one or more of the dimensionless scaling parameters will be required after careful examination of their relative importance in the behaviour of the bridge.

It has become conventional to express the various forces as ratios of the aerodynamic forces, which gives rise to the following dimensionless scaling parameters.

i) $\frac{U^2}{bg}$ Froude Number

ii) $\frac{E}{\rho U^2}$

iii) $\frac{m}{\rho b^2}, \frac{I}{\rho b^4}$, etc.

iv) $\zeta = \frac{c}{c_c}$

v) $\frac{\rho U b}{\mu}$ Reynolds Number

where
- b bridge width
- c structural damping
- c_c critical structural damping
- E modulus of elasticity
- g acceleration due to gravity
- I mass moment of inertia of structure/unit length

m	mass of structure/unit length
U	wind velocity
ζ	critical damping ratio
μ	viscosity of air
ρ	density of air

3.2 Dynamic Scaling

It is normal to respect parameter (i), the Froude Number in modelling long span bridges since there are significant gravitational forces affecting the bridge static and dynamic behaviour. The requirement for equality of model and prototype Froude Numbers sets the velocity scaling of the experiment. That is:

$$\frac{{U_m}^2}{b_m g} = \frac{{U_p}^2}{b_p g} \quad \text{and consequently} \quad \frac{U_m}{U_p} = \left(\frac{b_m}{b_p}\right)^{1/2}$$

where subscripts m and p refer to model and prototype respectively.

It follows that the time scaling will be $\qquad \dfrac{\tau_m}{\tau_p} = \left(\dfrac{b_m}{b_p}\right)^{1/2}$

For a scale ratio $b_m/b_p = 1/100$, a full scale wind speed of 100 mph would be represented by 10 mph at model scale speed in the wind tunnel.

From parameters (i) and (ii) together we get:

$$\frac{E_m}{E_p} = \left(\frac{U_m}{U_p}\right)^2 = \frac{b_m}{b_p}$$

Therefore if the model is to be made as an exact replica, it would be necessary to use materials having lower values of E than the prototype material in proportion to the geometric scale ratio. Alternatively the scale stiffnesses can be made correct by modifying the material thickness, t, or in the case of cables the cross-sectional area, A, so that

$$\frac{E_m t_m}{E_p t_p} = \frac{b_m}{b_p} \quad \text{or for cables} \quad \frac{E_m A_m}{E_p A_p} = \frac{b_m}{b_p}$$

In modelling cables, this approach can be used to get the stiffness correct; however the mass scaling requirement of parameter (iii) is then violated, and, as well, the cable diameter will no longer be at the correct geometric scale size. The deficiency in mass can be corrected by adding distributed weights to the cables, while the correct aerodynamics can be restored by suitably choosing the geometry of the weights. Similarly, it is possible, for box section road decks to design the model so that its dynamic properties are intrinsically correct. However, for open truss designs the elastically scaled values of component thickness are usually impractically small and some other way of constructing the model has to be devised. This can be done by designing a structural spine for the road deck on which is mounted non-structural modules that give the correct shape aerodynamically. The modules must be carefully made to keep the weight equal to or below that dictated by the mass parameter. Weights can then be added to adjust the mass and moment of inertia. When this approach is used, the elastic and dynamic properties are not intrisically correct and the spine must be designed so that its elastic properties correctly scale those of the prototype. It may be difficult to design a spine that is aerodynamically unobtrusive. For example in the model of the original Lions' Gate Bridge configuration, it was difficult to design a spine to duplicate the prototype that did not, at the same time, modify the aerodynamic characteristics of the section (Ref. 11). The credibility of the final design was established by comparative sectional model tests of a replica model and a model that included the spine.

The sectional and taut-strip modelling concepts pre-suppose that the elasto-dynamic behaviour of the prototype is known or can be adequately predicted. An advantage of the full model is that the need for this assumption is obviated because the correct behaviour is modelled implicitly.

Parameter (iii) must be respected in order that the inertial forces of the bridge mass are in the correct proportion to the other forces. It follows that

$$\frac{m_m}{m_p} = \left(\frac{b_m}{b_p}\right)^2 \quad \text{and} \quad \frac{I_m}{I_p} = \left(\frac{b_m}{b_p}\right)^4$$

The damping parameter (iv) must be modelled in order that the dissipative forces due to structural damping are properly accounted for. Adjustment of this parameter can be precisely controlled with sectional models but not with taut-strip or full models.

3.3 Aerodynamic Scaling

Parameter (v), the Reynolds Number, is a measure of the relative magnitude of the aerodynamic viscous forces and the aerodynamic inertial forces. Reynolds Number scaling is a fundamental requirement for aerodynamic similarity; however there are many problems where the viscous forces are small and relatively unimportant compared to the inertial forces, in which case the requirement for scaling the Reynolds Number is negated. Relaxation of this requirement must be undertaken with care.

Respecting the modelling of the Reynolds Number requires that

$$\frac{U_m}{U_p} = \frac{b_p}{b_m}$$

Clearly, this is incompatible with Froude Number scaling and, furthermore, would lead to model scale wind speeds that are impractical for a variety of reasons. The limitations of assuming that the bridge behaviour is independent of the Reynolds Number must be carefully examined.

An important illustration of the importance of the Reynolds Number to aerodynamic stability is the flow around a circular cylinder. Above a value of the Reynolds Number — based on the cylinder diameter — in the range 3×10^4 to 3×10^5 there is a dramatic change in the flow. The most apparent change is the reduction of the wake width immediately behind the cylinder. There is a corresponding reduction of the drag coefficient, C_D, and an increase in the frequency of formation of vortices, n, in the wake as shown in Figure 6. The wake vortex formations are shown in Figure 7. The value of the Reynolds Number at which the changes occur is dependent on the surface roughness of the cylinder and the turbulence level in the airstream. It is readily apparent that in modelling circular or other curved cross-sections that these effects have to be allowed for. In the case of cables the prototype Reynolds Number will often be above the critical values at which changes occur, whereas the model value will be below. The resulting differences in C_D can be compensated for in the model by increasing the projected area of the cables by appropriately selecting the shape of the added weights referred to earlier.

The change in wake width is a consequence of a rearward shift on the cylinder surface of the so-called "separation points" where the smooth flow on the forward part of the cylinder detaches from the surface of the cylinder. In the case of rectangular cylinders the separation point is fixed at the sharp upstream corner of the cylinder and as a consequence the Reynolds Number dependency disappears — this is not so for rectangles with rounded corners. As a result it is normal to assume that sharp-cornered shapes are insensitive to Reynolds Number effects and in general this premise is acceptable. However at very small scale it becomes difficult to reproduce precisely the prototype geometric shape, particularly the small corner radii of structural components.

There are other Reynolds Number effects. The flow over a square cylinder with a side facing the wind will form a broad wake after separation from the upstream corner; however, for a rectangle where the streamwise dimension is much larger than the lateral dimension the separated flow will reattach to the streamwise surface and consequently the wake will be much narrower (Fig. 8). As with the cylinder this results in a lower value of C_D and a higher value of the dimensionless vortex frequency, the Strouhal Number, S. The length:width ratio at which this change occurs depends on the Reynolds Number, the corner radius and the airstream turbulence level. This should not normally be a problem with road decks because of their slenderness; although caution is warranted where curved fairings or large vertical wind angles are involved. The flow around components may also be affected.

It is difficult to answer the question, how large should the model scale be to avoid Reynolds Number problems. There is some favourable evidence from model-prototype comparisons and from wind tunnel investigations over a range of scales that substantiates the premise that we can neglect Reynolds Number scaling. An example is the Long's Creek Bridge (Fig. 9, Ref. 10) a cable-stayed orthotropic girder bridge. Wind tunnel sectional model measurements at 1:30 scale are shown extrapolated to prototype scale in Figure 10. The peak amplitude of 4.2 in. occurring near 28 mph agrees with several observations at the bridge site and the narrow velocity range over which the excitation has been observed corresponds closely for the model and the prototype. Winds normal to the bridge at velocities above the critical range, that is above 35 mph were measured at the site and no bridge motion was observed. Amplitudes as high as 8 in. were also reported and it is believed that these larger responses were due to snow blockage of the handrails — in the wind tunnel a peak amplitude of 7 in. was recorded with the handrail blocked. No torsional motion was observed in either the model or the prototype. The structural damping in the model was in the range $\zeta = 0.008$ to 0.016. A record of the decay of an impact-induced flexural vibration of the bridge indicated a damping value of $\zeta = 0.010$. Encouraging comparisons have been made for sectional and full models of the Golden Gate Bridge (Ref. 8) and the original Tacoma Narrows Bridge (Ref. 9). Also, further confidence is derived from the absence of unsatisfactory aerodynamic behaviour in prototype bridges whose aerodynamic stability has been demonstrated in wind tunnels in advance of construction.

Dynamic sectional model testing of the Lions' Gate Bridge has been done with two different model scales, 1:110 and 1:24 (Refs. 12 and 13). The velocity scaling for the 1:110 scale model was selected to satisfy Froude Number similarity, whereas the velocity scale for the 1:24 scale was set arbitrarily at about 1:4. (Velocity scaling of sectional models will be discussed later). The Reynolds Numbers, based on bridge chord, and corresponding to a prototype wind speed of 75 mph were 3.5×10^4 and 6.5×10^5 for the 1:110 and 1:24 scales respectively. At the same speed the prototype Reynolds Number would be 3.8×10^7. There were small differences such as a decreased sensitivity to angle of attack at the higher Reynolds Number, but the overall behaviour was similar in both cases. Davenport (Ref. 5) has compared sectional models at 1:40 and 1:320 scale and found "...reasonably good agreement ...." in the behaviour. He has, however, found differences between the behaviour of the full model in smooth flow and the sectional model which he attributes to the modelling concepts rather than the scale. This difference has not been observed by Irwin with the Lions' Gate Bridge models (Refs. 11, 13 and 14), nor by Farquharson and Vincent with the Tacoma Narrows Bridge (Ref. 9) or by Frazer and Scruton with the Severn Bridge (Ref. 15). Sectional model force measurements for the Severn Bridge by Walshe and Rayner (Ref. 16) showed some Reynolds Number dependency below $Re = 2 \times 10^6$ which practically disappeared at higher values.

With the sectional and taut-strip models gravitational forces do not affect the model dynamics and velocity scaling can be selected arbitrarily rather than by respecting the Froude Number. In this case, it is conventional by combining scaling parameters (ii) and (iii) to replace (ii) with a new parameter U/nb where n is the natural frequency of the bridge mode being modelled. The velocity scaling is now

$$\frac{U_m}{U_p} = \frac{n_m}{n_p} \cdot \frac{b_m}{b_p}$$

and we are free to select n_m. From a Reynolds Number point of view, it is desirable to select n_m as large as possible within the limit of speed available in the wind tunnel. Gravitational effects such as the blowback of the cable plane and rotation of the road deck are not intrinsically included with these modelling concepts. Allowance can be made for aerodynamic effects of road deck rotation by setting the model chord plane at an angle to the wind.

For a 1:50 scale sectional model and a velocity scaling $U_m : U_p$ = 1:2 the Reynolds Number ratio would be $Re_m : Re_p$ = 1:100. By comparison, a full model of a 3000-ft. span bridge in an 8-ft. wind tunnel would have a scale ratio of 1:400, and with Froude Number similarity the Reynolds Number ratio would be about $Re_m : Re_p$ = 1:8000. The model scale Reynolds Number would be about 8×10^3 for a 100-ft. wide road deck at 70 mph. At this scale the road deck width would be about 3 in. and components such as cables would of the order 1/32 in. in width. Clearly at these scales model geometric precision becomes difficult and the integrity of the assumption of aerodynamic similarity would have to be seriously questioned.

4.0 EFFECTS OF TURBULENCE

4.1 The Earth's Surface Wind Layer

The planetary winds are retarded near the earth's surface by the resistance to flow introduced by roughness elements on the ground and by fluid friction associated with the air viscosity. As a result of this shearing action, the velocity varies from zero at the surface — the fluid dynamicist's no-slip condition — to the "gradient wind" at about 900 to 2000 ft. above the surface (Fig. 11). At greater altitudes it is assumed that there are no further mechanical effects of the earth's surface. The rate of shear depends on the roughness of the ground and is often described by a power law such that,

$$\frac{U(z)}{U(z_o)} = \left(\frac{z}{z_o}\right)^{\alpha}$$

where the exponent α is in the range 0.15 and 0.5, having the higher values for rougher terrain, z is height above ground and z_o an arbitrary reference height.

The shearing action also causes mechanical agitation of the flow, or turbulence. To an observer fixed on the ground the turbulence manifests itself as gustiness with continuous and sometimes abrupt changes of direction and of magnitude. A measure of the magnitude of the fluctuating component of the wind is its root-mean-square value which is known as the turbulence intensity. At the height of the gradient wind the turbulence intensity is nearly zero but increases toward the surface and the longitudinal or streamwise component can be as high as 30 to 40 percent of the local mean wind speed near ground level (Fig. 12). Peak excursions can be several times the RMS value.

The wind turbulence is characterized by a nearly random distribution of the physical size of the disturbances. In the longitudinal direction the size can vary from near zero to several thousand feet in length. The dimensions of the disturbances in the lateral direction are somewhat less. The random fluctuations in wind velocity, seen by a fixed observer, represent wind energy distributed over a wide range of frequencies. The distribution of frequency, f, can be characterized by the power spectral density function, ϕ. Figure 13 shows the von Karman formula for the power spectrum of the longitudinal component. The position of this curve along the frequency axis can be fixed by adjusting the value of a length constant in the formula that is known as the integral scale and is a measure of the mean size of the disturbances. This curve is in good agreement with observed spectra for an integral scale of 400 ft.

4.2 Modelling the Wind Layer

There are several different methods for simulating the properties of the wind layer in the wind tunnel. A well-established approach that is used in special purpose, long working section wind tunnels is to develop the layer "naturally" by having the wind blow over a long fetch of surface roughness elements. A second method that is suitable for shorter working section aeronautical wind tunnels is to install spires at the entrance to the test section as shown in the background of Figure 1 (Ref. 17). With both of these techniques it is practical to develop wind layer depths approaching one-half the height of the test section.

4.3 Testing in Turbulent Wind

The effects of the turbulence on bridge behaviour depend on the scale of the turbulence relative to the size of the bridge, its intensity and its frequency spectrum. For example, if the lateral scale were large enough that the velocity at any one instant in time was constant along most of the span, one would expect the turbulence to play a different role than if the scale was much smaller and the velocity varied considerably along the span. Similarly, if the natural frequencies of the bridge were in the higher energy part of the spectrum, one would expect a greater response to the turbulence than if they were in a low energy part.

It is important to simulate all of the properties of the turbulence that have been discussed but because of the large scale components this cannot be done with the sectional model. Therefore to fully study the effects of turbulence it must be done with the full model or taut-strip model.

4.4 Buffeting Response

Since there is significant turbulent energy near bridge natural frequencies (Fig. 13), the dynamic buffeting response becomes very important at high wind speeds for light weight, low damping, modern suspended bridges and the gust factor approach to estimating loads may not be satisfactory. An alternative, as demonstrated by Irwin (Ref. 18) is to estimate the stress levels due to the dynamic response from the motion measured using full models in simulated wind. As more experience with full models is being obtained, the goal of being able to adequately predict the response from the sectional model data, as has been proposed by Scanlan (Ref. 3) and Holmes (Ref. 19), or from taut-strip models as has been proposed by Davenport (Ref. 6), should be pursued more vigorously.

4.5 Road Deck Flutter

The term flutter is used to describe an oscillatory instability of the road deck that occurs when a critical wind speed is reached. It is characterized by rapid build-up of amplitude and catastrophic levels may be reached in a few cycles of motion. At higher wind speeds the build-up rates would normally be increased. Typically torsion is the dominant vibration mode but the instability is normally considered to be a consequence of aerodynamic coupling between vertical bending and torsion; although single-degree-of-freedom torsional flutter may occur. Short of having an aerodynamically stable shape it is, of course, essential that critical flutter speeds be well above wind speeds expected at the site.

Flutter stability can be readily assessed using sectional models and it is common practice to assume that such observations provide a conservative approach to design against flutter, on the basis that the stability in turbulent flow will be greater than in the uniform flow of the section model test.

There is now some evidence to support the view that the section model method can be overly conservative. Davenport's investigation of the Halifax Harbour Bridge (Ref. 5) included the first full model test in a simulated natural wind. Like the Lions' Gate Bridge it is an open truss bridge, and for both bridges it has been found that the flutter instability observed with the sectional model was not present for the full model in the turbulent flow, even for velocities well above the sectional model critical speeds. Observations of the response of the Lions' Gate Bridge are shown in Figure 14 (Ref. 14).

For the plate girder and box section road deck structures, the evidence that the sectional model is conservative is less compelling than for the open truss design. Davenport (Ref. 5) observed with his taut-strip model of the original Tacoma Narrows Bridge H-section road deck that turbulence inhibited ". . . . .non-catastrophic (possibly vortex-induced) motion at subcritical windspeeds but only marginally postponed the onset of catastrophic torsional motion." The effects became greater as the turbulence intensity was increased to represent rougher terrain. The box section road deck of the West Gate Bridge was tested by Melbourne in simulated natural wind (Ref. 20); however, the section was aerodynamically stable in smooth flow and therefore does not provide a good assessment of the effects of turbulence. The author is not aware of an example of an aerodynamically unstable box section that has been tested in turbulent flow.

4.6 Vortex Shedding Response

The wake structure behind slender, bluff structures consists of an orderly sequence of vortices as illustrated by flow visualization of the flow behind a circular cylinder in Figure 7. The vortices form alternately on either side of the wake in a regular periodic manner. The frequency of vortex formation (on one side of the wake) can be expressed dimensionlessly as

$$S = \frac{nb}{U}$$

The value of the Strouhal Number, S, depends on the section geometry and in varying degrees on the Reynolds Number. The influence of the Reynolds Number on the Strouhal Number of a circular cylinder, already mentioned in Section 3.3, is shown in Figure 6. The Strouhal Number for sharp-cornered shapes such as rectangular cylinders is insensitive to changes in Reynolds Number.

As the wind speed is increased over a slender, elastic structure, the frequency of vortex formation increases and when this frequency matches a structural natural frequency, quite large crosswind vibration amplitudes can develop. The vertical bending oscillations of the Long's Creek Bridge, shown in Figure 9 (Ref. 10) are caused by the periodic wake vortices. The finite, non-destructive amplitudes and the narrow velocity range over which the motion occurs are characteristic of vortex shedding response. Torsional modes are equally susceptible to this form of excitation. While in the short-term amplitudes are not damaging, they can be large enough to make the bridge unacceptable to the user and may result in long term damage. The critical wind speed range often will be at quite common wind speeds.

Sectional models are well-suited to studying vortex shedding response — the ease with which configuration changes can be made, being a particularly attractive feature for developmental or remedial investigations. Experience with the Long's Creek Bridge demonstrates that the section model result can reliably predict full scale vortex shedding behaviour under certain circumstances. Whether or not it is unduly conservative for more streamlined box sections, for truss bridges or for higher turbulence levels has yet to be established.

5.0 CONCLUSIONS

In the foregoing discussion fundamental aspects of modelling procedures and bridge road deck behaviour have been reviewed with a view to appraising the advantages and disadvantages of the sectional, taut-strip and full model approaches. Is it now possible to draw up the balance sheet in favour of one or the other of these approaches? The answer would appear to be "no". With the present state-of-the-art there is a time and a place for each technique. Which investigative procedure or combination of procedures is used will depend on a variety of considerations — the size of the bridge, the road deck configuration, the lead time available.

It is worthwhile in conclusion to summarize some points that came out in the earlier discussion.

(1) Well-established dimensionless scaling parameters must be respected in wind tunnel modelling of the bridge dynamics. Apart from the aerodynamic similarity parameter, the Reynolds Number, it is possible to satisfy these requirements as long as a large enough wind tunnel is available.

(2) There is little evidence from wind tunnel tests done over a range of Reynolds Number to suggest that aerodynamic similarity is a problem at the small scale of full models; but model to full scale comparisons are not available and caution must still be the watchword.

(3) Satisfactory techniques are available for simulating the earth's surface wind that can be used with full and taut-strip models. For sectional testing it is not possible to reproduce turbulence having the large scale that exists in the natural wind.

(4) Sectional testing is demonstrably reliable in design to avoid vortex shedding excitation and flutter. The question remains as to whether or not it is excessively conservative. Evidence suggests that it is for truss stiffened road decks in view of the suppressive effect of turbulence on flutter. For closed box deck sections and plate girder systems this is likely not the case as the sectional model appears to predict full scale vortex shedding excitation, and there is evidence from wind tunnel studies that turbulence has only a minor effect on critical flutter speeds.

(5) Bridge buffeting is an important design consideration for long, slender, lightweight spans. Stress levels can be computed analytically from motion response observed in full model studies in simulated natural wind. Another attractive approach is the prediction of prototype behaviour based on sectional model data. Development of these procedures should continue to be pursued at the research level, including analytical studies, and laboratory and full scale experimental investigations.

As stated at the outset the advantages of the sectional model are:

- low cost
- large scale
- short lead time
- provides data for prediction procedures now under development.

The advantages of the full model technique are:

- the test can be done in a complete simulation of the earth's surface wind so that the turbulence response is obtained directly and the effects of turbulence on flutter and vortex shedding are intrinsic
- All three-dimensional aeroelastic effects are modelled implicitly.

The taut-strip model can also be tested in simulated natural wind, but is simpler and less costly than the full model. Within the limits of this simplified model, some of the three-dimensional aeroelastic effects are included. To a certain extent it shares the advantages of the sectional model of low cost and short lead time. Analytical procedures for predicting prototype behaviour from taut-strip measurements have been described in the literature.

For a large bridge, extensive aerodynamic investigations are justified and can include in their scope a full model wind tunnel program. It can be advantageous to precede the full model program with sectional investigations so that stable aerodynamic deck shapes, free from vortex shedding excitation are developed using this cheaper, quicker approach. This will also permit the assessment of Reynolds Number effects for the small scale full model. With smaller bridges it may be difficult to justify the full model experiment, in which case, the sectional model, or the sectional model plus taut-strip model can be used.

Finally, all things considered, in making the choice of testing procedure it should be remembered that the cost of the aerodynamic investigation will be a fraction of one percent of that of the full scale structure. Bearing in mind the important implication of the aerodynamic behaviour on the final design, undue restriction of the investigation on cost grounds should be avoided.

It is apparent that our knowledge of the phenomena and of investigative procedures has improved, but that there are still gaps to fill, particularly concerning turbulence and three-dimensional effects, and with analytical prediction procedures. Emphasis is needed on model to full scale comparison to further validate all prediction procedures.

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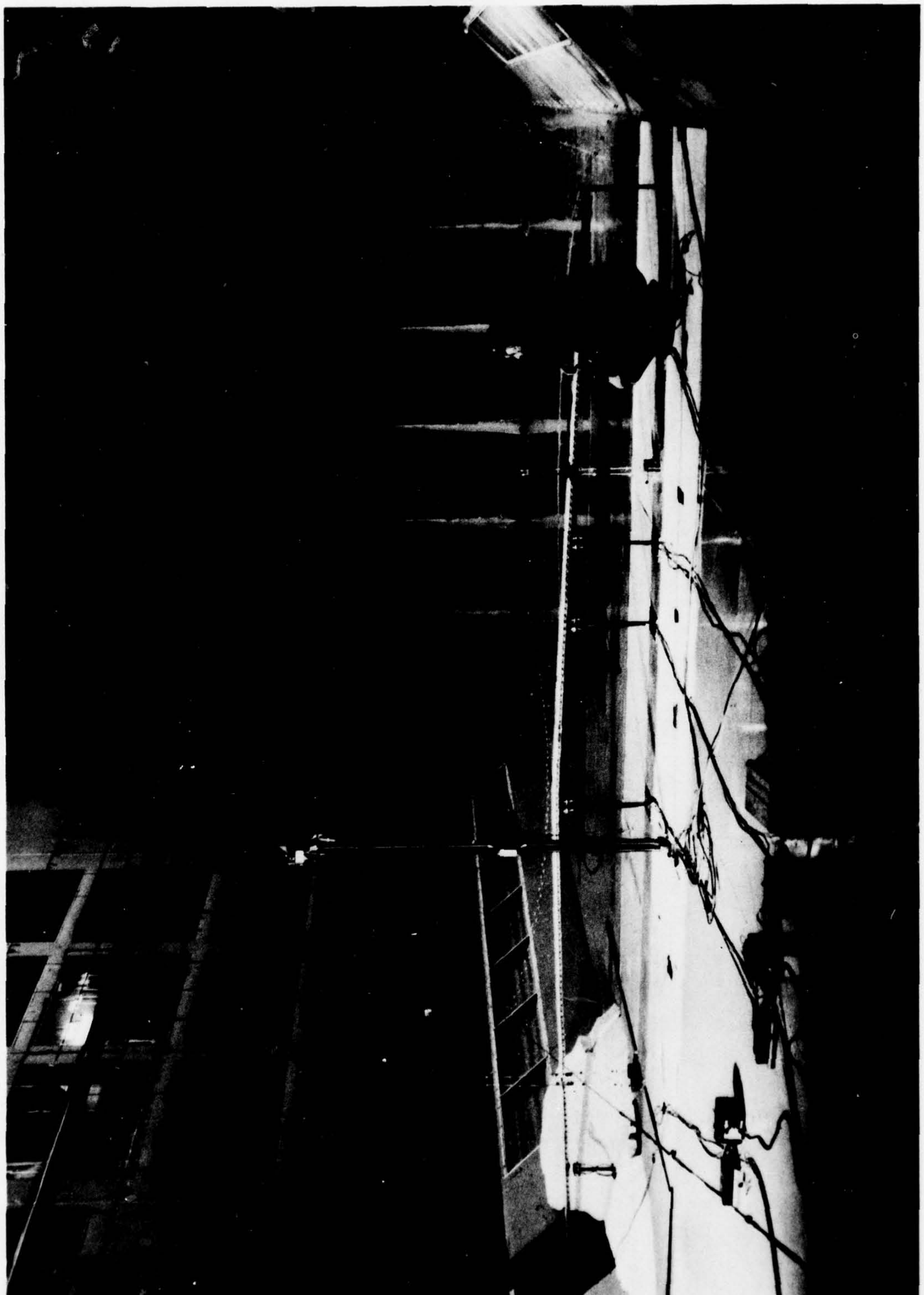


FIG. 1: THE 1:110 SCALE FULL MODEL OF THE LIONS' GATE BRIDGE IN THE NATIONAL AERONAUTICAL ESTABLISHMENT 30 FT. × 30 FT. WIND TUNNEL

FIG. 2: THE 1:110 SCALE FULL MODEL OF THE LIONS' GATE BRIDGE

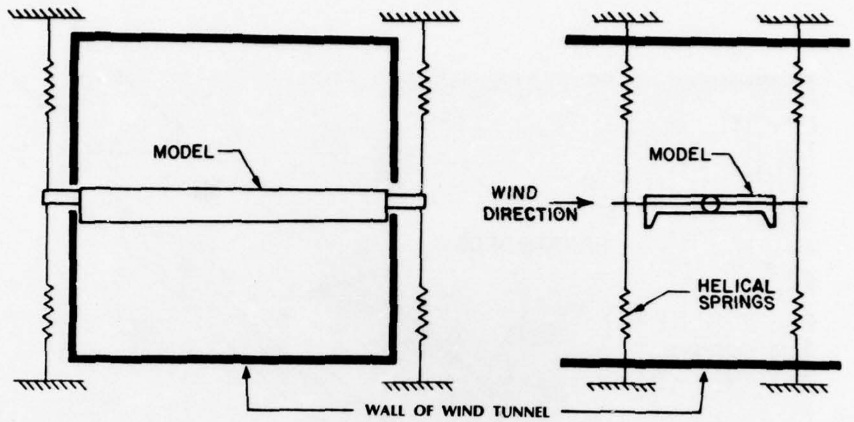


FIG. 3: SECTION MODEL SUSPENSION SYSTEM

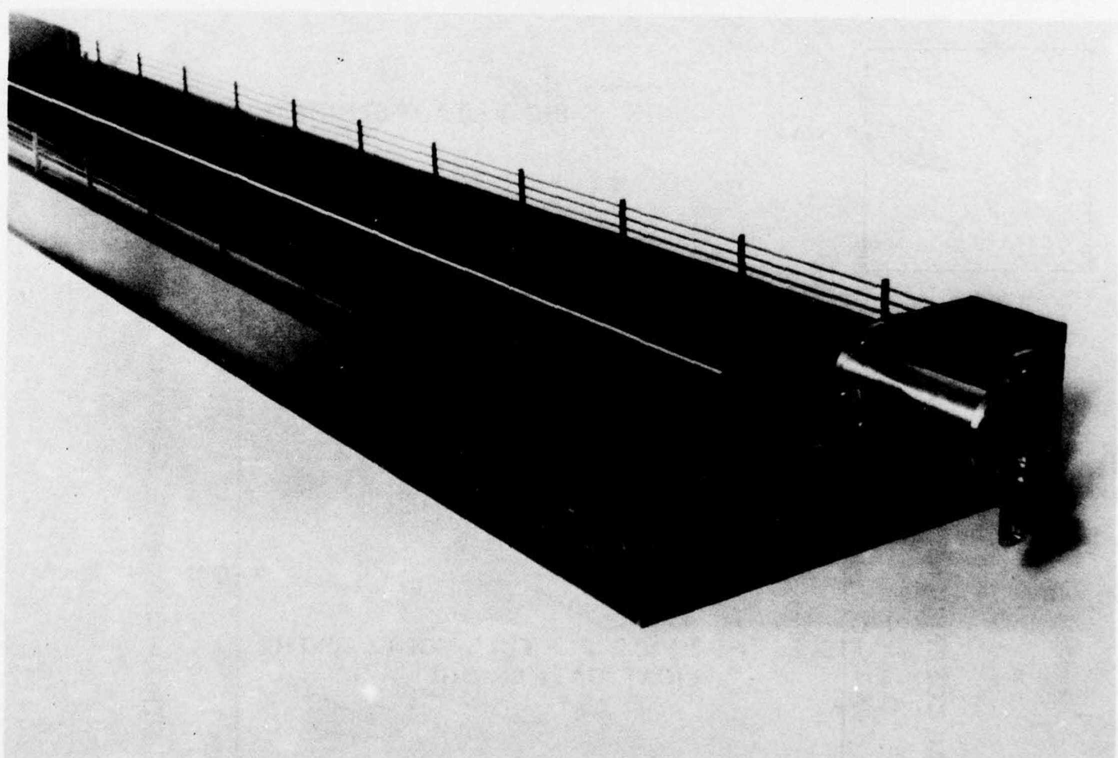


FIG. 4: 1:30 SCALE SECTIONAL MODEL OF THE LONG'S CREEK BRIDGE – ORIGINAL ROAD DECK CONFIGURATION

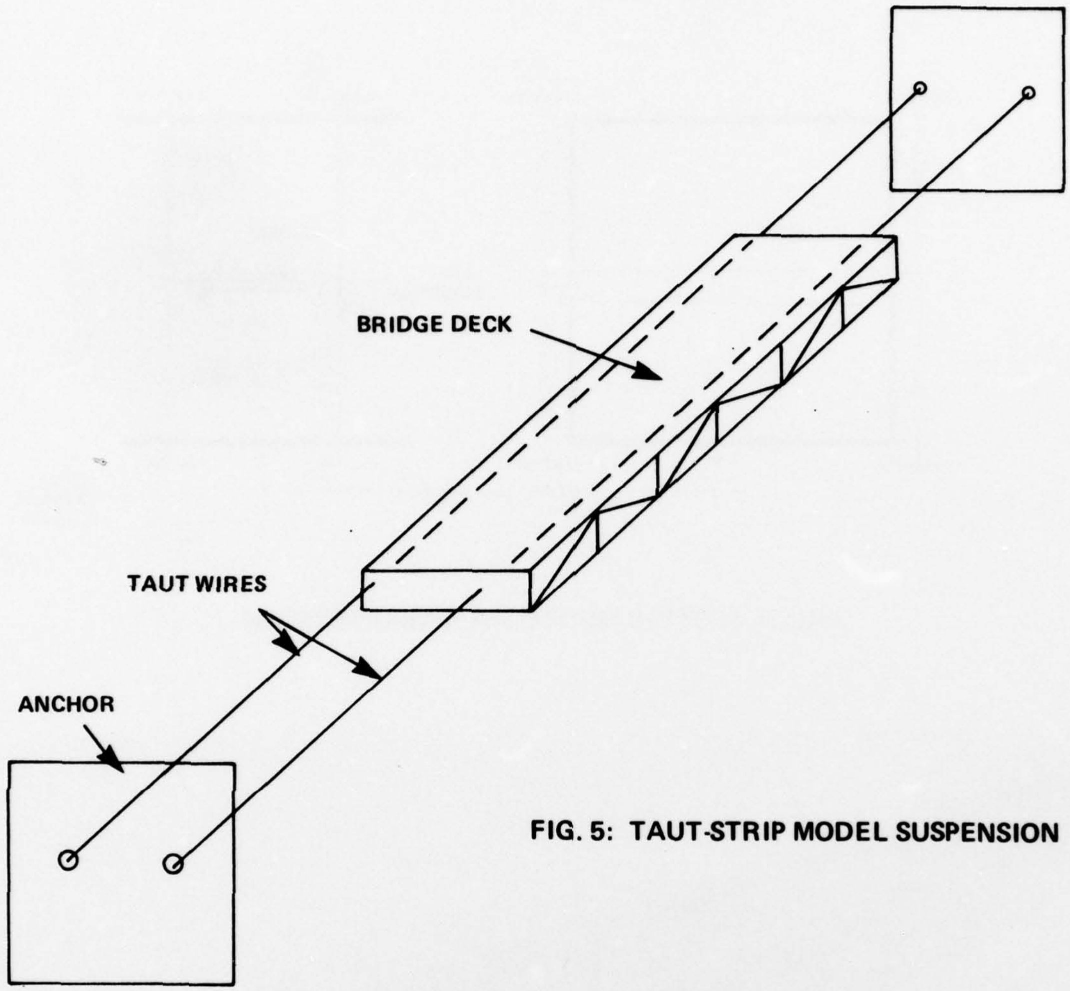


FIG. 5: TAUT-STRIP MODEL SUSPENSION

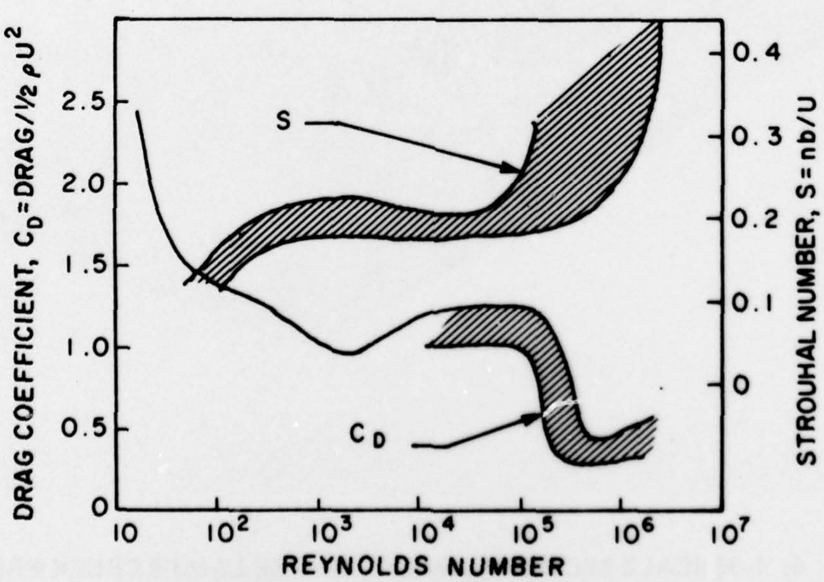


FIG. 6: DRAG COEFFICIENT AND STROUHAL NUMBER OF A CIRCULAR CYLINDER — ADAPTED FROM FUNG (REF. 21)

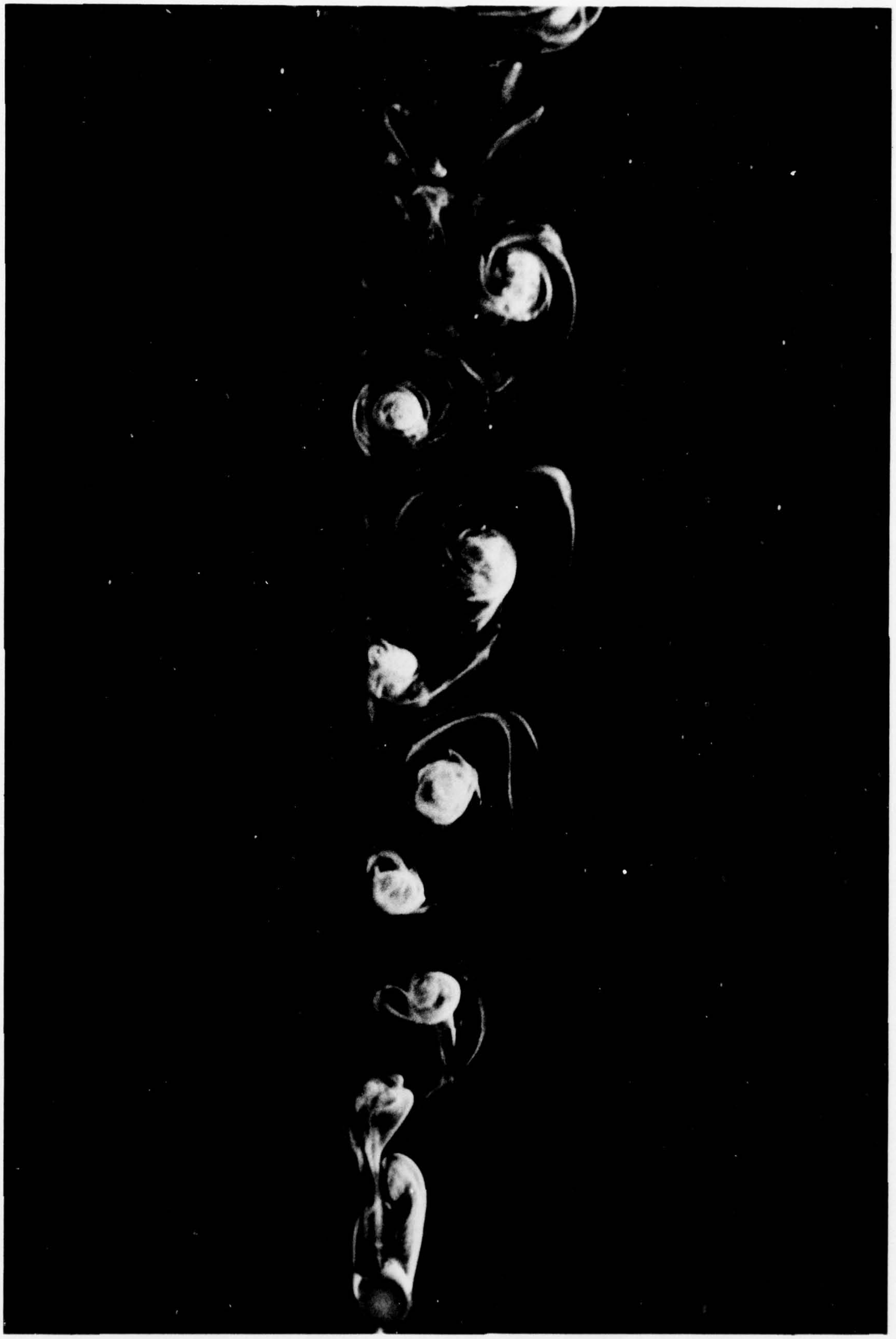


FIG. 7: THE VORTEX WAKE BEHIND A CIRCULAR CYLINDER

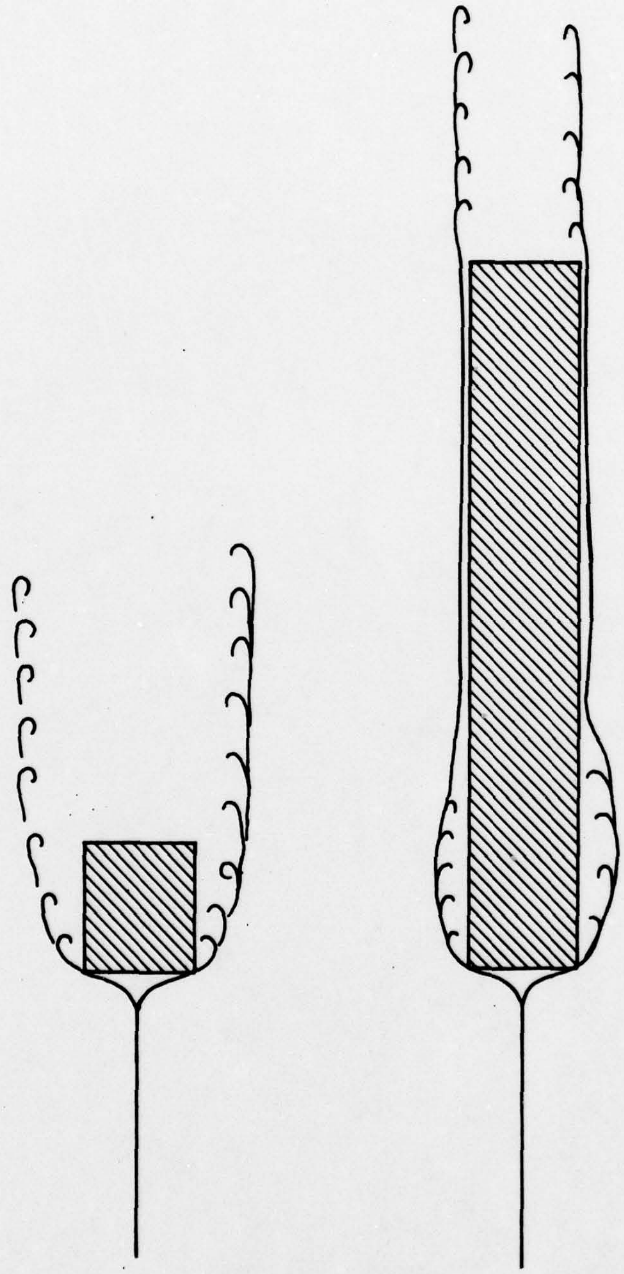


FIG. 8: FLOW OVER SQUARE AND RECTANGULAR CYLINDERS

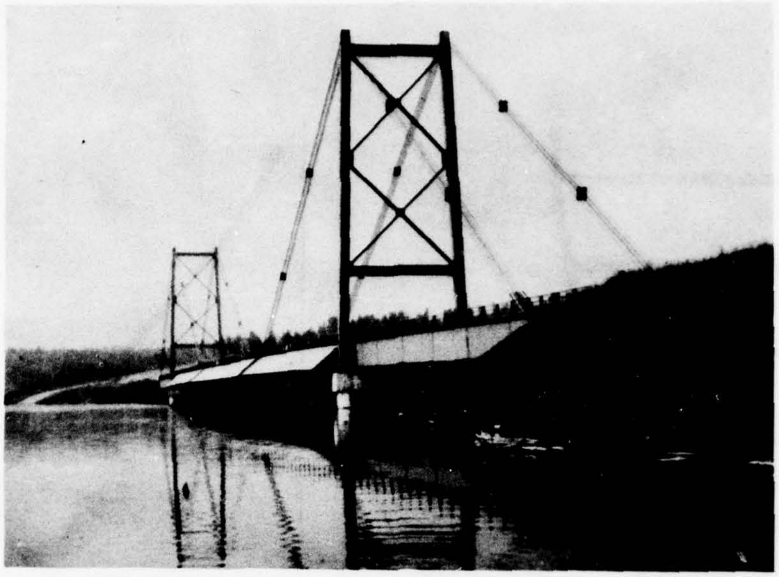


FIG. 9: THE MODIFIED LONG'S CREEK BRIDGE

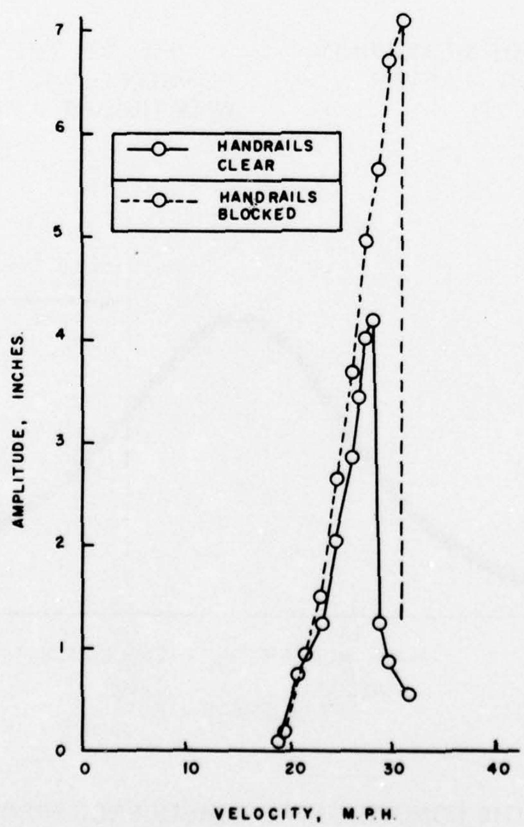


FIG. 10: SECTIONAL MODEL RESPONSE OF THE UNMODIFIED LONG'S CREEK BRIDGE EXTRAPOLATED TO FULL SCALE

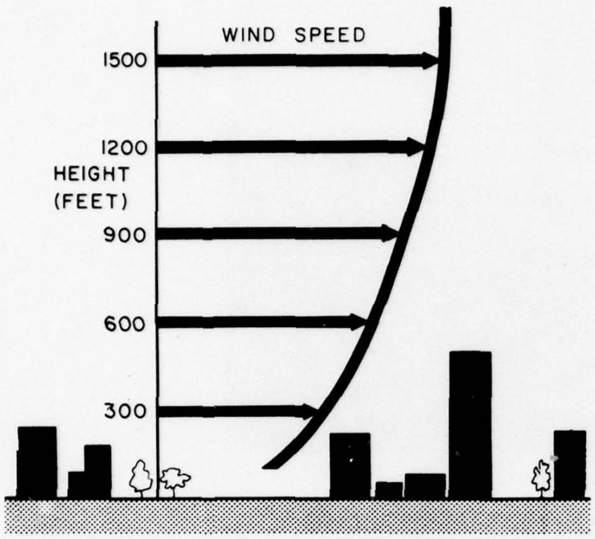


FIG. 11: THE VARIATION OF MEAN WIND VELOCITY WITH HEIGHT – AFTER TEMPLIN (REF. 22)

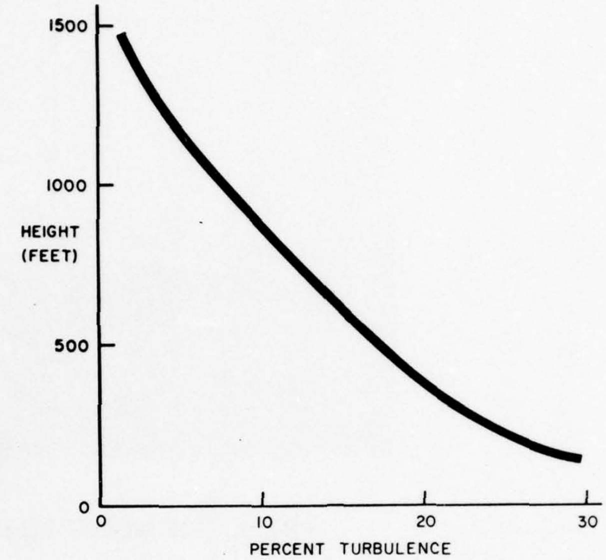


FIG. 12: THE VARIATION OF THE LONGITUDINAL TURBULENCE INTENSITY WITH HEIGHT – AFTER TEMPLIN (REF. 22)

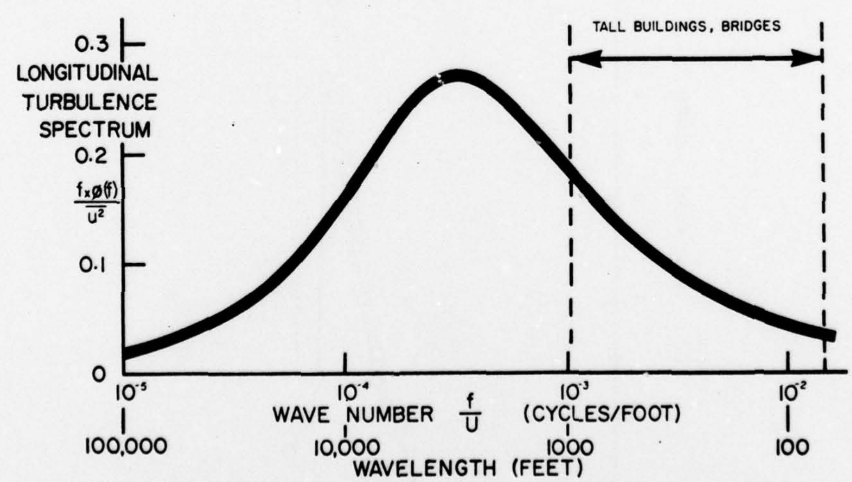


FIG. 13: THE LONGITUDINAL TURBULENCE SPECTRUM – AFTER TEMPLIN (REF. 22)

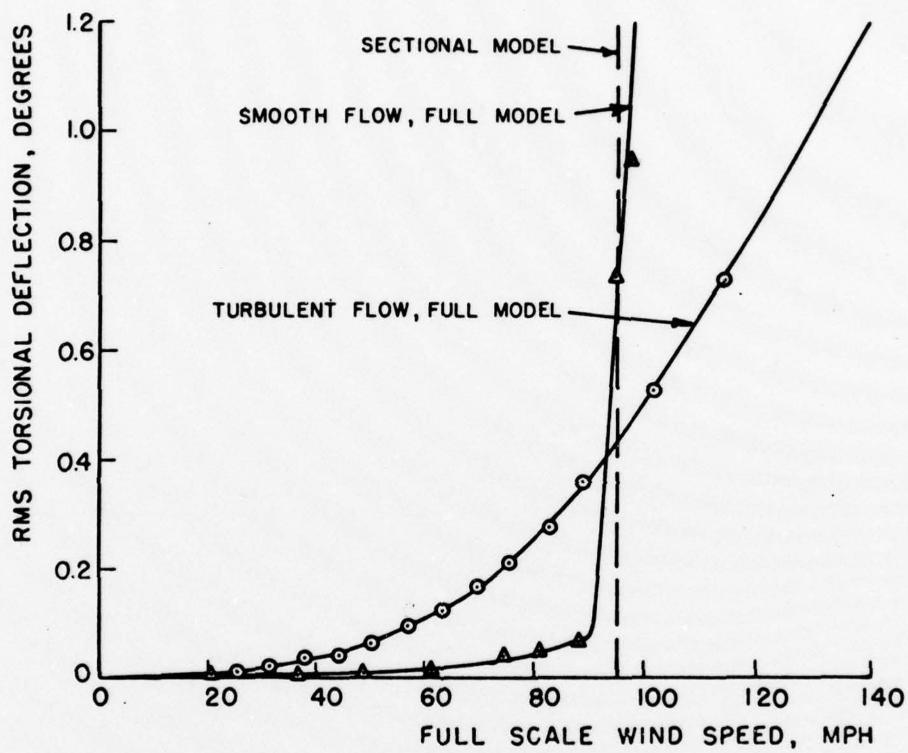


FIG. 14: THE LIONS' GATE BRIDGE TORSIONAL RESPONSE AT THE 1/10TH SPAN POSITION IN SMOOTH AND TURBULENT FLOW

CURRENT PROJECTS

Much of the work in progress in the laboratories of the National Aeronautical Establishment and the Division of Mechanical Engineering includes calibrations, routine analyses and the testing of proprietary products; in addition, a substantial volume of the work is devoted to applied research or investigations carried out under contract and on behalf of private industrial companies.

None of this work is reported in the following pages.

ANALYSIS LABORATORY

AVAILABLE FACILITIES

This laboratory has analysis and simulation facilities available on an open-shop basis. Enquiries are especially encouraged from industry for projects that may utilize the facilities in a novel and/or particularly effective manner. Such projects are given priority and are fully supported with assistance from laboratory personnel. The facilities are especially suited to system design studies and scientific data processing. Information is available upon request.

EQUIPMENT

An Electronic Associates 690 HYBRID COMPUTER consisting of the following:

(a) PACER 100 digital computer

- 32K memory
- card reader
- high speed printer
- disc
- digital plotter
- Lektromedia interactive terminal

(b) Two EAI 680 analogue computer consoles

- 200 amplifiers including 60 integrators
- 100 digitally set attenuators
- non-linear elements
- x-y pen recorders
- strip chart recorders
- large screen oscilloscope

(c) EAI 693 interface

- 24 digital-to-analogue converters
- 48 analogue-to-digital converters
- interrupts, sense lines, control lines

GENERAL STUDIES

A microprocessor-based function generator for the hybrid computer is being designed. A TI 9900 development system has been obtained to be used for the project.

A study is being made on the use of topological methods to describe and analyse complex systems.

APPLICATION STUDIES

In collaboration with Aviation Electric Ltd., modeling work is continuing in support of their advanced control concepts for both the small business jet engine and the helicopter engine. At present, the detailed model of a twin engine helicopter is being used for checkout of a prototype microprocessor-based fuel controller.

In collaboration with Canadian Westinghouse Ltd., a study is being made of the fuel controller requirements for a new family of industrial gas turbines. A hybrid computer model is being used to evaluate control system hardware.

In collaboration with Kendall Consultants Ltd., and SPAR Aerospace Products Ltd., a hybrid computer model of the remote manipulator arm for the space shuttle is being assembled. The model includes all allowable motions in three dimensions as well as arm flexibility effects. The three dimensional model is complete and arm control algorithms are being evaluated.

In collaboration with the Railway Laboratory, a pilot hybrid computer model of the NRC roller rig for railway vehicle testing is being used as an aid in the design of the roller rig and its controls.

In collaboration with the Control Systems and Human Engineering Laboratory and the International Nickel Co., Ontario Division, an interactive computer model of a copper-nickel smelter is being developed to study material handling and scheduling in the plant.

In collaboration with Engine Laboratory a study is being made to develop a computer model of air cushion vehicles.

In collaboration with the Geological Survey of Canada a computer package for seismic data reduction in the field is being written. A Commodore PET computer has been obtained for this project.

In collaboration with Manitoba Rolling Mills and the Control Systems and Human Engineering Laboratory a digital computer model has been used to study proposed increases in melt shop capacity.

In collaboration with Northern Telecom Ltd., an interactive computer program is being developed to schedule orders on cable stranding machines.

In collaboration with R.L. Crain Ltd., the interactive program for computer-aided paint shop scheduling is being extended to examine alternative order streaming and press allocation strategies. Further program development is underway with a view to incorporating the scheduling programs in the company's computer system.

In co-operation with Carleton University and Engine Laboratory a preliminary study is underway of a heavy equipment propulsion system using a co-rotating compressor.

In co-operation with Concordia University, a model of a heavy railroad freight vehicle is being assembled. Simulations of vehicle response to periodic and random excitations are to be conducted.

In collaboration with Stephens-Adamson of Belleville a hybrid computer model of long conveyor belts is being assembled.

In collaboration with Davis Eryou and Associates a hybrid computer model of an automobile is being assembled.

A joint project with ARCTEC Canada and Davis Eryou and Associates for reduction and analysis of oceanographic and ice breaking ship trials data is being carried out on the hybrid computer.

SYSTEM SOFTWARE STUDIES

A preprocessor for hybrid computer model digital programs.

Character string manipulation routines to be used in a Fortran environment.

CONTROL SYSTEMS AND HUMAN ENGINEERING LABORATORY

INDUSTRIAL CONTROL PROBLEMS

Fluid sensor and control component research and development.

Interactive computer modeling applied to operations scheduling of large scale industrial plants and processes.

Development of CAMAC instrumentation for industrial control applications.

Engineering support to specific firms for the implementation of schemes for control and mechanization.

ADVANCED TRANSPORTATION CONCEPTS

The conceptual design for a high speed intercity magnetically levitated and linear synchronous motor propelled vehicle plus elevated guideway system as based on the results of a basic Maglev research program jointly conducted by Queen's University, University of Toronto and McGill University has been carried out in collaboration with Transport Canada. Ongoing study includes computer modeling for ride quality assessment, vehicle dynamic behaviour prediction and engineering design consideration of the magnets.

HUMAN ENGINEERING – BEHAVIOURAL STUDIES

Investigation of the control characteristics of the human operator and the basic phenomena underlying tracking performance.

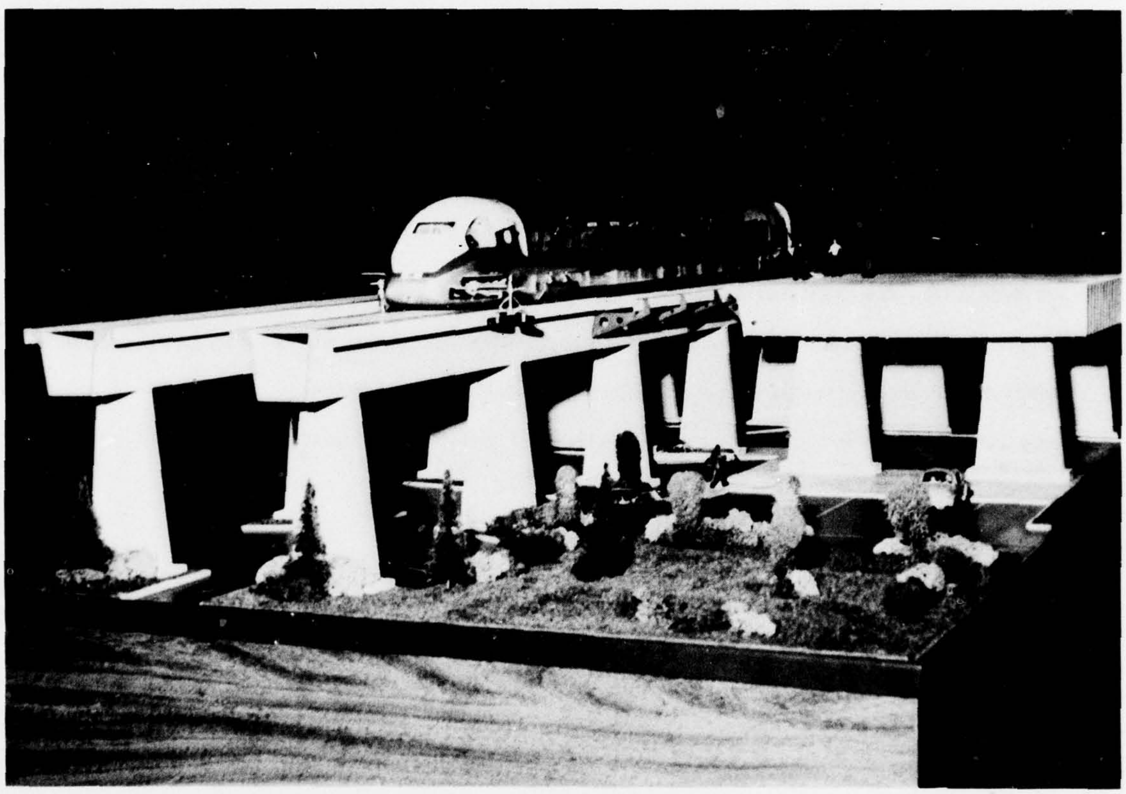
Investigation of the nature of sensory interaction in human perceptual-motor performance.

Investigation of the factors involved in the presentation and processing of information, particularly in air traffic control displays and simulator design.

HUMAN ENGINEERING – MEDICAL AND SURGICAL

Development of systems for localized cooling of the spinal cord at operation.

Measurement in-vivo of the mechanical impedance characteristics of skin and healed wounds.



SCALE MODEL OF A PROPOSED INTERCITY MAGNETICALLY LEVITATED GUIDED GROUND TRANSPORT SYSTEM

ENGINE LABORATORY

HOSPITAL AIR BED

The laboratory is continuing the support and direction of a clinical field trial and evaluation of the air bed principle. The objectives of the clinical investigation are to study the effectiveness of the air bed, and the comfort provided by it, in the treatment of burns. The effects of reduced shear and support pressure, and a carefully conditioned micro-climate on wound healing are being studied in particular.

A special experimental air bed, the NRC Cairbed Mark I, was designed and built by NRC to allow a hospital in Kingston, Ontario to conduct a funded clinical study with the support of bio-medical engineering help from Queen's University.

The project has been highly successful with respect to demonstrating considerable advantage over other more conventional support methods, and to better defining the performance requirements necessary for improving epithelium thickness recovery. A new concept of support air bag structure was tested with complete success.

Arrangements are underway to have four of a more advanced air bed type, the Mark II Cairbed version manufactured under contract. The Mark II beds will feature performance optima and will have the realness of commercial products. Clinical evaluations of these prototypes are being planned in order to demonstrate both performance and usefulness, and in order to verify the design.

GAS TURBINE OPERATIONS

The Engine Laboratory has a test cell equipped with a high speed, computer controlled data acquisition facility that enables gas turbine testing to be carried out. This system is currently connected to a J85-CAN-15 turbojet and is used to define engine parameters during transient operation. This interactive system produces a variety of results, including printouts, report quality time plots, or any variation of cross-plots.

GAS TURBINE ICING INVESTIGATIONS

Preparations are being made for the evaluation of the anti-icing protection of an MHI aircraft engine nacelle. The nacelle houses a Pratt & Whitney of Canada JT15D turbofan engine. The test installation will permit the simulation of forward velocities at sea-level pressures. The icing environment will consist of super-cooled water droplets.

AEROACOUSTICS

A study of the noise characteristics of centrifugal fans and blowers is in progress. The experiments to study the effect of impeller blade shape and casing geometry on the aerodynamic performance and noise generation are being carried out in a 5-horsepower fan test rig.

Methods are being developed to compute the propagating modes in ducts by measurements of sound pressure level around the circumference of the duct using cross spectral density and phase locked methods.

ENGINE COOLING SYSTEM PERFORMANCE

The role of an engine-driven centrifugal fan as a mover of cooling air is being examined experimentally with special reference to energy conservation, air flow distribution, and noise. The centrifugal fan may be a more attractive engine-driven cooling fan choice for transverse mounted engine arrangements than the conventional electrically-driven axial fan.

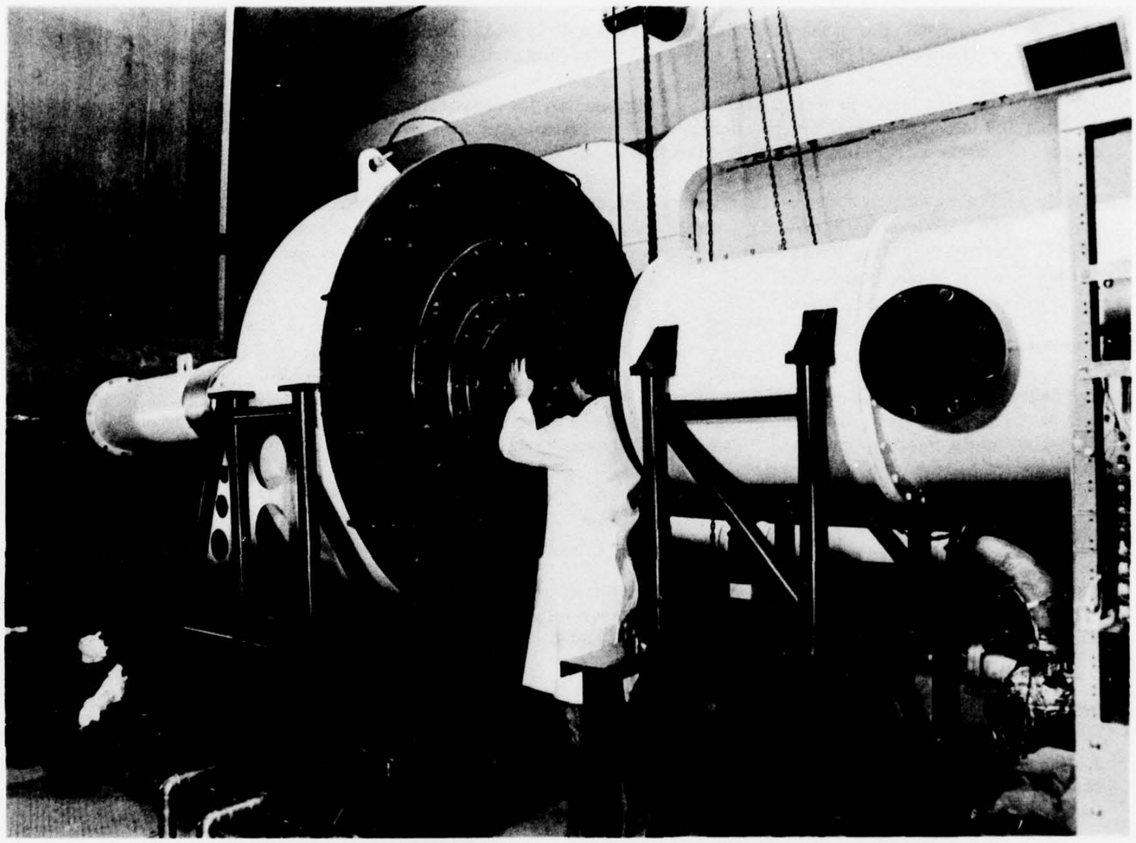
The study, which is being made in collaboration with Canadian industry and is being funded through Transport Canada, is to involve both road tests and wind tunnel experiments in the 10-ft. X 20-ft. propulsion wind tunnel of the Division of Mechanical Engineering. A 1976 Ford Granada, used during an earlier engine cooling system study and provided by industry, is being used as the test vehicle.

AIR CUSHION VEHICLES

The study of ACV lift-air requirements has been completed for the time being, and was reported at the September CASI Symposium on ACVs. Vegetation porosity measurements have been completed, and are being analysed.

Low-speed drag experiments over water have been discontinued until spring 1979.

A test rig for the study of vertical instability in ACVs has been designed, and manufacture is about to commence.



NRC/PRATT & WHITNEY AIRCRAFT CO-OPERATIVE PROGRAM ON THE HIGHLY-LOADED TURBINE; FINAL ALIGNMENT OF THE TEST RIG NOZZLE RING

ENGINE LABORATORY

DIVISION OF MECHANICAL ENGINEERING

FLIGHT RESEARCH LABORATORY

AIRBORNE MAGNETICS PROGRAM

Experimental and theoretical studies relating to the further development of airborne magnetometer equipment and its application to submarine detection and geological survey, are currently in progress. The North Star flying laboratory has now been retired but analysis of magnetic data taken over east, west and Arctic coasts of Canada will continue for some time to come. Studies are continuing in very low frequency (VLF) and other navigation methods to support long range geophysical surveys. A Convair 580 aircraft to replace the North Star is currently being equipped with new magnetometer and computing systems.

INVESTIGATION OF PROBLEMS ASSOCIATED WITH STOL AND V/STOL AIRCRAFT OPERATIONS

The Laboratory's Airborne V/STOL Simulator is being employed in programs to investigate STOL and V/STOL aircraft flying qualities and terminal area operational problems. Areas of research include a general investigation of flight path control and stability characteristics required to compensate for single engine failure in twin or multi-engine powered-lift aircraft, and the identification of minimum acceptable flying qualities for civil helicopters operating under instrument flight rules.

INVESTIGATION OF ATMOSPHERIC TURBULENCE

A T-33 aircraft, equipped to measure wind gust velocities, air temperature, wind speed, and other parameters of interest in turbulence research, is used for measurements at very low altitude, in clear air above the tropopause, in the neighbourhood of mountain wave activity, and near storms. Records are obtained on magnetic tape to facilitate data analysis. The aircraft also participates in co-operative experiments with other research agencies, in particular, the Summer Cumulus Investigation (see below). A second T-33 aircraft is used in a supporting role for these and other projects.

AIRCRAFT OPERATIONS

The Flight Recorder Playback Centre is engaged in the recovery and analysis of information from the various flight data recorders and cockpit voice recorders used on Canadian military and civil transport aircraft. The military systems are being monitored on a routine basis. Civil aircraft recorders are being replayed to investigate incidents or accidents at the request of the Ministry of Transport. Technical assistance is being provided during incident and accident investigations and relevant aircraft operational problems studied.

INDUSTRIAL ASSISTANCE

Assistance is given to aircraft manufacturers and other companies requiring the use of specialized flight test equipment or techniques.

INVESTIGATION OF SPRAY DROPLET RELEASE FROM AIRCRAFT

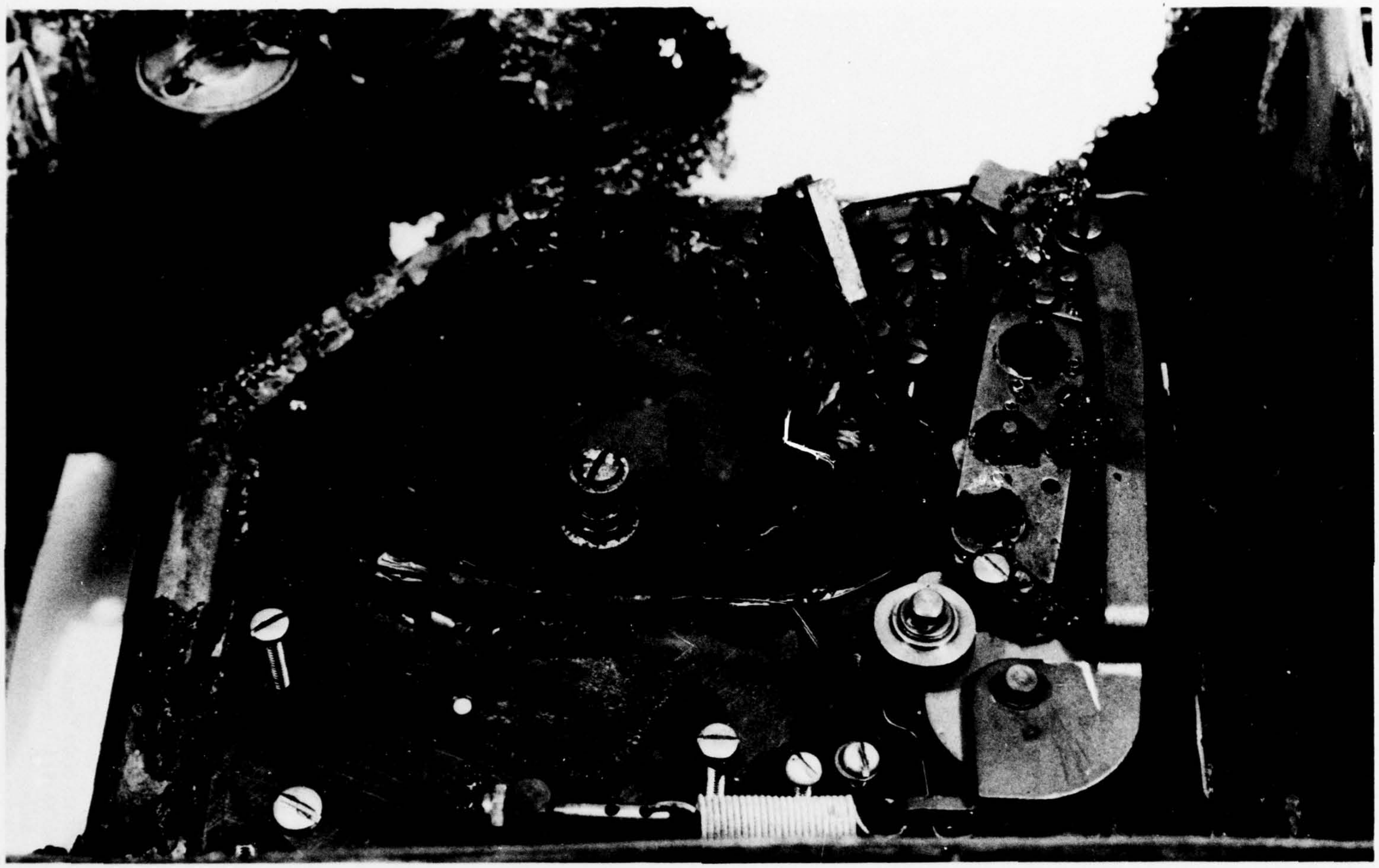
Theoretical and experimental studies of spray droplet formation from a high speed rotating disc have been conducted. Flight experiments utilize a Harvard aircraft modified to carry external spray tanks. Automatic flying spot droplet and particle analysis equipment is in operation for processing samples obtained in the laboratory and in the field by various agencies. The equipment has potentialities for the analysis of many unusual configurations provided that these may be photographed with sufficient contrast.

AUTOMOBILE CRASH DETECTOR

There is a need for a sensing device to activate automobile passenger restraint systems in incipient crash situations. Investigations are in progress to determine the applicability of C.P.I. technology to this problem.

SUMMER CUMULUS INVESTIGATION

At the request of the Department of the Environment flight studies of Cumulus cloud formations over Quebec and Ontario were instituted during the Summer of 1974. Instrumented T-33 and Twin Otter aircraft with a Beech 18 are being used to determine the properties of Cumulus clouds which extend appreciably above the freezing level. The measurements are being made to assess the feasibility of inducing precipitation over forest fire areas by seeding large cumulus formations. During 1975 a variety of cloud physics instruments were added to the Twin Otter, and special pods for burning silver iodide flares were attached beneath the wing of the T-33 turbulence research aircraft. The effects of seeding on the microstructure of individual cumulus clouds were studied in the Yellowknife area during the summers of 1975 and 1976 and in Thunder Bay in 1977 and 1978. This project is planned to continue for several years.



DIGITAL FLIGHT DATA RECORDER

AT THE FLIGHT RESEARCH LABORATORY, 17 SECONDS OF CRITICAL INFORMATION WAS RECOVERED VISUALLY FROM THE CHARRED REMAINS OF THE MAGNETIC TAPE OF THE DIGITAL FLIGHT DATA RECORDER ILLUSTRATED THAT WAS SEVERELY DAMAGED BY FIRE FOLLOWING THE ACCIDENT TO A BOEING 737 AIRCRAFT AT CRANBROOK, B.C. IN FEBRUARY 1978.

FLIGHT RESEARCH LABORATORY

NATIONAL AERONAUTICAL ESTABLISHMENT

FUELS AND LUBRICANTS LABORATORY

COMBUSTION RESEARCH

Experiments on fuel spray evaporation.

Investigation of handling and combustion problems involved in using hydrogen as a fuel for mobile prime movers.

Co-operative studies with Advisory Group for Aerospace Research and Development (AGARD) Working Group 11 to produce a report on aircraft fire safety.

EXTENSION AND DEVELOPMENT OF LABORATORY EVALUATION

Development of new laboratory procedures for the determination of the load carrying capacity of hypoid gear oils under high speed conditions and under low speed high torque conditions.

Evaluation of filter/coalescer elements for aviation turbine fuels.

Evaluation of longlife filter/coalescer elements from aviation turbine fuel service.

Water separation characteristics of aviation turbine fuels.

PERFORMANCE ASPECTS OF FUELS, OILS, GREASES, AND BRAKE FLUID

Investigation of laboratory methods for predicting flow properties of engine and gear oils under low temperature operating conditions.

Evaluation of static dissipator additives for distillate fuels.

Evaluation of properties of re-refined oils and by-product sludges.

Investigation of the use of anti-icing additive in aviation gasoline.

Investigation of hydrogen content as a means of estimating the combustion characteristics of aviation turbine fuels.

MISCELLANEOUS STUDIES

The preparation and cataloguing of infra-red spectra of compounds related to fuels, lubricants, and associated products.

The application of Atomic Absorption spectroscopy to the determination of metals in petroleum products.

Investigation of the stability of highly compressed fuel gases.

Analytical techniques for analysis of engine exhaust emissions.

Participation in the Canadian (CGSB), American (ASTM) and International (ISO) bodies to develop standards for petroleum products and lubricants.

The design and development of an internal combustion engine/hydraulic transmission hybrid power plant for the energy conserving car.

Further developments of specialized pressure transducers for engine health diagnosis and the development of diagnostic techniques and consultation with licencee in developing production methods for patented transducers.

Evaluation of various products, fuels, lubricants and hardware in respect of their effects upon overall vehicle fuel economy and energy conservation properties.

Preliminary studies have started on an air cushion transporter for heavy concentrated loads, such as transformers, pressure vessels, etc. It is anticipated that this program will involve very close co-operation with the A.C. industry and haulage groups.

AUTOMOTIVE FUEL ECONOMY

The preliminary series of float car tests have been completed in Toronto. A second series will begin in January with improved recording and playback procedures. Changes to the traffic light sequencing are to be made and studied in this test series.

NRC–PRATT & WHITNEY HIGHLY LOADED TURBINE

Trial assembly of the test rig has been completed and a hot start will be attempted early in the next quarter. Test instrumentation is being parallel-coupled to a minicomputer which will allow complete data acquisition and partial experiment control.

ROTOR DYNAMICS

The rotor dynamics test rig has undergone initial testing using a simple rotor supported in rolling element bearings. Laboratory-generated computer programs to predict critical speeds and mode shapes of the test shafts have been revised and improved for easier comparison with the experimental rotors and the initial tests have shown good agreement between experimental and computer predictions. Work is currently aimed at the acquisition of a fluid film bearing analytical capability. Rotor balancing for external users as well as in-house projects is continuing under steady demand.

HYDROSTATIC BEARINGS

This laboratory continues to provide assistance and design service to other potential gas and fluid film bearing users both within NRC and in other government laboratories.

VIBRATION MONITORING

An experimental rig has been assembled to allow the testing of rolling element bearings to failure. This rig is now being used to compare current methods of vibration detection and their ability to discover incipient faults in rolling element bearings. Because of the nature of fault generation in rolling element bearings the result gathering process is of a rather long-term nature.

A co-operative program with the Defence Research Establishment Pacific in Victoria will look at the combined merits of oil analysis and vibration monitoring as tools for helicopter transmission gear box monitoring.

This laboratory continues to provide vibration measurement and analysis assistance to both industry and government.

GAS DYNAMICS LABORATORY

V/STOL PROPULSION SYSTEMS

A general study of V/STOL propulsion system methods with particular reference to requirements of economy and safety.

INTERNAL AERODYNAMICS OF DUCTS, DIFFUSERS AND NOZZLES

An experimental study of the internal aerodynamics of ducts, bends, diffusers and nozzles with particular reference to the effect of entry flow distortion is geometries involving changes of cross-sectional area, shape, and axial direction.

SHOCK PRODUCED PLASMA STUDIES

A general theoretical and experimental investigation of the production of high temperature plasma by means of shock waves generated by electromagnetic and gas dynamic means, and the development of diagnostic techniques suitable for a variety of shock geometries and the study of physical properties of such plasmas.

NON-DESTRUCTIVE SURFACE FLAW DETECTION IN HOT STEEL BILLETS

A flaw detection system for metal bars is being tested. Eight inductive bridge circuits, spaced around the bar and sequentially sampled, detect the flaw through a change in coil inductance. The system lends itself to easy elimination of stand-off and eccentricity errors and is currently being adapted to industrial use. Interpretation of test results via microprocessors is in hand. A rugged, heat-resistant circuit is being designed for in-plant application.

HIGH PRESSURE LIQUID JETS

High speed water jets generated by pressures in the range of 1000 to 60,000 psi can be used for cutting a wide variety of materials, e.g. paper, lumber, plastics, meat, leather, rock, etc., and for cleaning surfaces such as masonry, tubular heat exchangers, etc. Nozzle sizes, depending on the application, are in the range from 0.002 to 0.15 in. diameter. A technique for manufacturing small nozzles in the range 0.002 to 0.015 has been developed using standard sapphire jewels available from industry. Larger orifices are manufactured and polished using standard shop procedures.

At present, the following investigations are active in the laboratory:

1. Drilling of rocks of various types, including granite, using a high pressure rotating seal and single and dual orifice nozzles specially developed for this purpose.

2. Study of the effects produced by cavitating jets, how best to produce them and where they may be usefully applied.

3. Experiments on the application of colliding jets.

4. Collaborative experimental work, in collaboration with the Low Temperature Laboratory, on the breaking and cutting of ice.

HEAT TRANSFER STUDIES

An investigation of methods of increasing boiling and condensing heat transfer coefficients by treatment of the heat transfer surface is in progress.

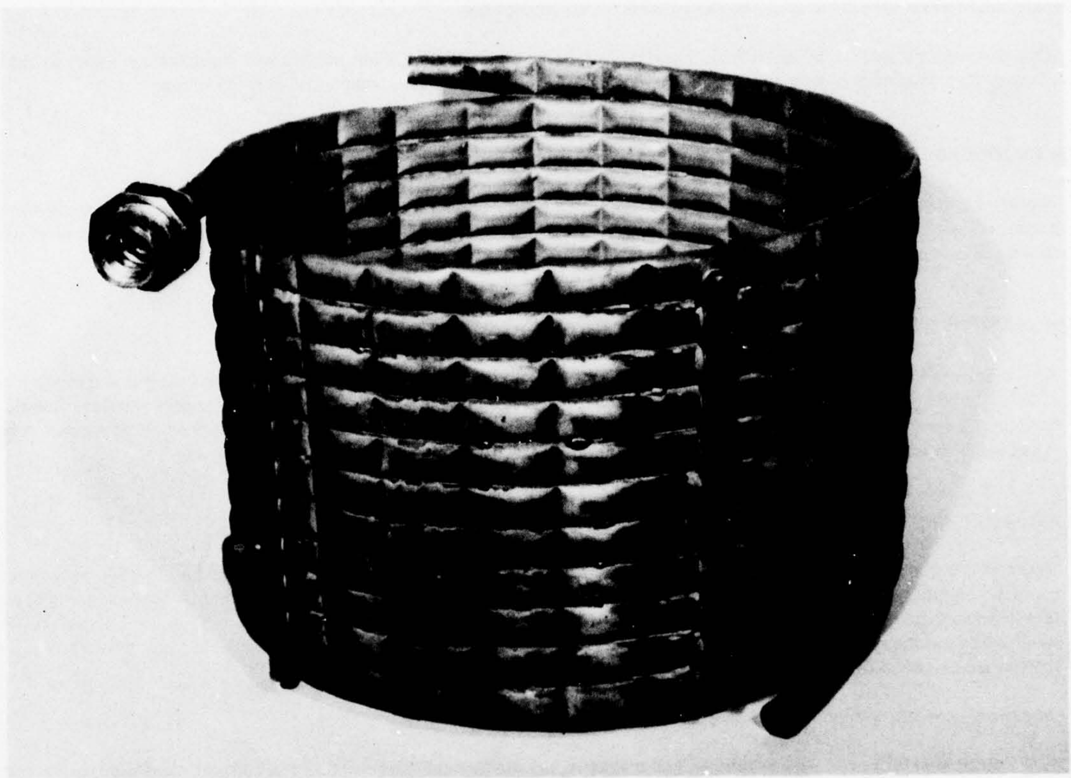
A co-operative project with the Division of Building Research will determine the usefulness of the thermosiphon as a ground heat source for a heat pump.

Experiments continue on the use of steam as a heating method for soldering tubing to thin sheet, as in flat plate solar collectors.

An inexpensive, leakproof heat exchanger has been developed for use in solar energy systems. Fabrication is simple and it is suitable for production in small batches.

Work has started on a new type of temperature control thermosiphon. Previous types have been designed to control the temperature of a heat source; this design controls the temperature of a heat sink.

An experiment is in progress to determine the optimum filling for a thermosiphon that will be used to transfer ground heat to electronic equipment, preventing low temperature damage during the Arctic winter.



HEAT EXCHANGER FOR SOLAR ENERGY SYSTEMS

IN SOLAR ENERGY SYSTEMS FOR HEATING HOT WATER A HEAT EXCHANGER IS REQUIRED TO TRANSFER HEAT INTO THE HOT WATER SYSTEM FROM THE ANTIFREEZE CIRCUIT THROUGH THE COLLECTORS. IT MUST BE LEAKPROOF, SIMPLE AND INEXPENSIVE. THE PICTURE SHOWS A HEAT EXCHANGER DEVELOPED IN THE GAS DYNAMICS LABORATORY. IT CONSISTS OF 40 FT. OF 5/8 IN. O.D. TUBING SOLDERED INTO A DOUBLE HELIX. WITH A FLOW OF WATER OF 2 GPM THROUGH EACH SIDE AND A TEMPERATURE DIFFERENCE OF 10°F IT WILL TRANSFER 10,000 BTU/HR.

GAS DYNAMICS LABORATORY
DIVISION OF MECHANICAL ENGINEERING

COMPUTATIONAL FLUID DYNAMICS

Numerical simulations are carried out in connection with projects initiated internally or as collaborations with outside organizations. At present the field of greatest interest concerns the problems of absorption of laser energy by plasmas and three topics are currently being pursued:

1. A study of the mechanism of re-entry waves occurring when beam intensity is reduced below the level at which laser-supported detonation can exist.

2. Absorption of laser energy by hydrogen plasma confined by a magnetic field (laser heated solenoid).

3. A study of the fluid mechanics accompanying continuous discharge of laser energy into a spot fixed in space.

GAS TURBINE BLADING STUDIES

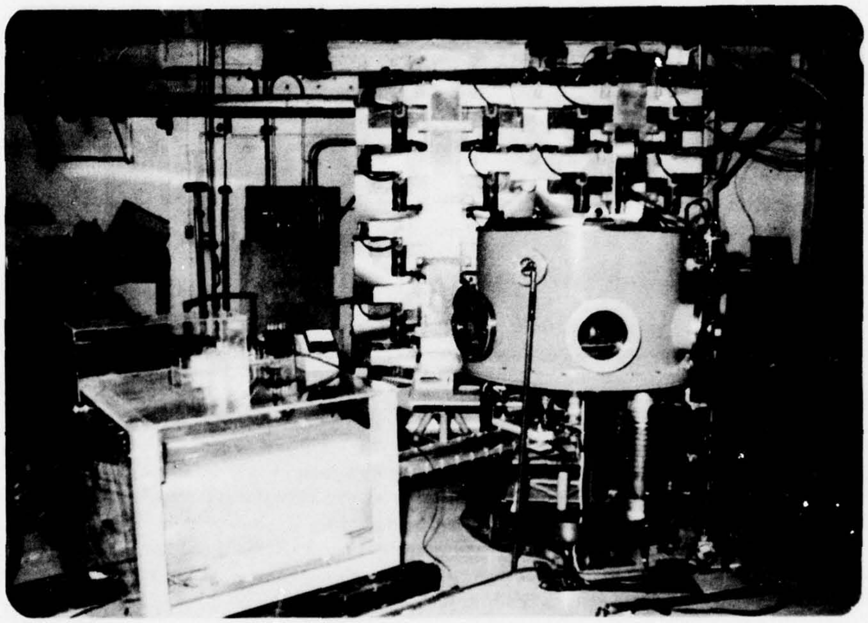
A program on the theoretical and experimental study of the performance of highly loaded gas turbine blading has been undertaken as a collaborative program with industry and universities.

INDUSTRIAL PROCESS, APPARATUS, AND INSTRUMENTATION

There is an appreciable effort, on a continuing basis, directed towards industrial assistance. This work is of an extremely varied nature and, in general, requires the special facilities and capabilities available in the laboratory.

Current and recent co-operative projects with manufacturers and users include:

(a) Flow problems associated with industrial gas turbine exhaust systems (Foster Wheeler).
(b) Combustion studies for industrial gas turbine applications (Westinghouse and Rolls-Royce).
(c) Application of thermosiphon as an energy conserving device in industrial applications (Dept. of Agriculture, Ministry of Transport, Farinon Electric, Chromalox Canada Ltd).
(d) Scaled model studies on steel and copper converters to establish relative performance and ceramic liner deterioration rates (Canadian Liquid Air and Noranda).
(e) High pressure water jet applications in industry (High Pressure Systems Ltd.).
(f) Scaled model studies to establish the performance of complex industrial flue systems with a view to establishing specific design and performance criteria. (Noranda and Inco Canada Ltd.).
(g) Model studies of internal flows in reactor hood and waste heat boiler (Noranda and Kennecott Copper Corp.).
(h) Altitude test chamber for small gas turbines (Pratt & Whitney Aircraft of Canada Ltd.).
(i) Experimental study of a novel fan design (Rolls-Royce).



HIGH-TEMPERATURE PLASMA COMPRESSION EXPERIMENT

GAS DYNAMICS LABORATORY
DIVISION OF MECHANICAL ENGINEERING

HIGH SPEED AERODYNAMICS LABORATORY

CALIBRATION OF THE 5-FT. X 5-FT. WIND TUNNEL'S TRANSONIC TEST SECTION

Further measurements, involving the use of a new centre-line probe and the NLR "Kulite" cone, are planned. Tests are scheduled for early 1979.

DATA SYSTEM IMPROVEMENTS ON 5-FT. X 5-FT. WIND TUNNEL

Modernizing and upgrading of the data system on the 5-ft. tunnel has been progressing slowly towards the new PDP 11/55 system under RSX11-M.

New amplifiers have been installed, increasing the number of channels available to 40 of high quality and 40 of lower quality. These amplifiers have gains ranging from 1 to 5000 and switchable front end filters with cutoffs from 3 Hz to 10 kHz. Self-checking remote calibration and remote switch readouts are built in and will be used when the new system is installed, early 1979.

At that time, improved direct digital I/10 will be installed (for "status" type information) and a table-driven external multiple condition interrupt system should unload the processor significantly. This in turn should make possible on-line data reduction, which will be only partly available initially. Work is now proceeding on an A/D system based on 3, 15-bit, 180 kHz A/D converter with a 96 channel multiplexer. Interfacing between the A/D system and I/D controllers is nearing completion and operation up to 200 kHz has been demonstrated. Plans are proceeding for installation during a springtime servicing period. As part of the upgrading, a remote site capability will also be available at that time.

Software has been developed for "on-line" plotting of aerodynamic coefficients, such as $C_p(X/C)$, $C_L(\alpha)$, $C_D(C_L)$, $C_L/C_D(\alpha)$ etc.

TRANSONIC EQUIVALENCE RULE INVOLVING LIFT

The classical area rule is well known and its application to wing-body design and drag reduction is demonstrated on many existing aircraft. Recent advances in transonic aerodynamic theroy show that the classical area rule requires a modification to account for lift. A series of experiments is being prepared in order to investigate these new concepts. The results of these experimental studies will provide criteria for wing-body design with emphasis on drag reduction for aircraft cruising at transonic speeds.

TWO-DIMENSIONAL TRANSONIC FLOW STUDIES

The 2-D wall correction method of Mokry has been extended to determine the upper and lower wall porosities which will give the best agreement between theoretical and experimental wall pressures for each scan. These optimum porosities are then used to determine the Mach number and angle of attack corrections. A new finite difference method has been developed, which allows for variable porosity along the upper or lower walls. Some improvements in the theoretical model are thus expected since inflow and outflow along the same wall can now be accounted for.

Supplementary Investigation of the BGK No. 1 Airfoil

Earlier NAE investigations of this airfoil have been supplemented with measurements of wall boundary conditions. The "static rails" normally used were replaced by "static tubes" that extended through the whole 2-D section into the inlet contraction. In addition, measurements were made of the boundary layer on the floor and ceiling. Various wall porosity schemes were investigated. Also, recovery and model temperature were recorded to determine if significant heat transfer effects were present during the early part of a run.

STUDIES OF WING BUFFETING

A theoretical study of the transient response of a wing to non-stationary buffet loads is in progress. Various forms of the power spectral density of the aerodynamic loading on the wing have been considered for a number of load versus time history during buffet manoeuvres. A wind tunnel investigation of the surface pressure and normal force fluctuations associated with buffeting has been carried out on the BGK No. 1 airfoil.

REYNOLDS NUMBER EFFECTS ON TWO-DIMENSIONAL AEROFOILS WITH MECHANICAL HIGH LIFT DEVICES

Under a joint NRC/DeHavilland enterprise administered under the PILP programme an extensive set of low-speed aerodynamic measurements were made in the 2-D insert in the period September 26 – November 30, 1978, on a multi-component aerofoil model.

During the first phase of the work several trailing-edge flap geometries (with and without a leading-edge slat) were optimised at a chord Reynolds number of 6×10^6; subsequently their performance at lower and high Reynolds numbers were checked.

In a second phase of tests with this aerofoil some boundary layer measurements were made near the trailing-edge of the main element, utilising a new boundary-layer traversing rig. These latter measurements were primarily directed at checkout of the traversing rig in its simplest form, with the objective of developing reliable gear for more extensive boundary layer measurements on high lift multi-component aerofoils in the near future.

Work on an iterative solution of the compressible boundary layer flows about multi-element airfoil is continuing at the University of Manitoba.

AERODYNAMIC MEASUREMENTS ON A MULTI-ELEMENT AEROFOIL

Some re-testing of a doubly-slotted aerofoil, with and without a leading edge slot, has been made for $0.12 < M < 0.2$ and $1.8 \times 10^6 < Re \leq 9 \times 10^6$.

This recent work stemmed from previous testing of this aerofoil equipped with a trailing-edge boundary layer total pressure rake. In those tests it appeared that a considerably adverse effect was introduced by the presence of the rake when the aerofoil was operated near $C_{L_{MAX}}$.

An analysis of the data from the recent work exposed a significant non-repeatability in the balance output. This has been traced to a combination of, primarily, balance flexure heating during start-up and, secondly, small flow angle changes during the run.

HOLE ERROR INVESTIGATION

An experimental study has been completed, in collaboration with Professor J.C. Menneron, of the University of Sherbrooke, of the effect of orifice size on the measurement of pressure on the surface of an aerofoil at subsonic free-stream velocities. Speeds up to $M = 0.7$ and chord Reynolds number from 6×10^6 to 33×10^6 were used. Orifice diameters range from 0.006 in. to 0.016 in. Analysis of the data is in progress.

MEASUREMENT OF SKIN FRICTION ON TWO-DIMENSIONAL AIRFOILS IN SUBSONIC FLOW

Measurements reported in the previous issue of Q.B. are still being analysed. It was hoped that the obstacle blocks could be used to detect transition. Apparently, the block height was too large compared to the momentum thickness, even through the smallest practical height (0.0145 in.) was used. The data did not even show a qualitative difference between the laminar of turbulent portions of the boundary layer. Measurements of the turbulent skin friction will be compared with theoretical predictions in the near future.

FLOW ANGLE MEASUREMENTS IN THE NAE 15-IN. X 60-IN. TEST FACILITY

Flow angle measurements, as reported in the previous issue of Q.B., have been analysed. For the Mach number range $0.3 < M_\infty < 0.7$, the flow angle is about −0.05 deg. for all values of control valve position. This value is about one-sixth of that found prior to the recent tunnel refurbishment.

Some more recent results, using the same technique referred to above, with a different model, indicate that at $M \approx 0.1$ the flow angle is about 0.35 deg.

SUPERCRITICAL AIRFOIL DEVELOPMENT

Under an on-going joint NAE-DeHavilland program, two 16% thick airfoil designs have been tested in the NAE 15-in. X 60-in. test facility, and their performance compared. The second airfoil, which incorporated design improvements over the first, generally displayed drag values which were higher than those observed for the first. A complete analysis of this investigation will be presented in March 1979 at the Atlantic Aeronautical Conference in Williamsburg, Va.

TESTS FOR OUTSIDE ORGANIZATIONS

DeHavilland Aircraft of Canada Ltd.

(See Reynolds Number Effects on Two-Dimensional Aerofoils with Mechanical High Lift Devices.)

HYDRAULICS LABORATORY

ST. LAWRENCE SHIP CHANNEL

Under the sponsorship of the Ministry of Transport, a study to improve navigation along the St. Lawrence River, using hydraulic and numerical modeling techniques.

NUMERICAL SIMULATION OF RIVER AND ESTUARY SYSTEMS

Mathematical models have been developed to simulate tidal propagation in estuaries, wave refraction in shallow water and littoral drift processes. The feasibility of using array processors to solve the hydrodynamic equations is presently under study.

WAVE FORCES ON OFF-SHORE STRUCTURES

Wave flume study to determine design criteria for off-shore structures, such as cooling water intakes or outfalls, mooring dolphins, drilling rigs, etc.

RANDOM WAVE GENERATION

A study of random waves generated in a laboratory wave flume by signals from a computer. Special attention is paid to the simulation of wave groups.

STABILITY OF RUBBLE MOUND BREAKWATERS

A flume study for the Department of Public Works to determine stability coefficients of armour units and the effect of a number of wave parameters on the stability of rubble mound breakwaters, including the effect of wave grouping.

WAVE LOADS ON CAISSON TYPE BREAKWATERS

A flume study for the Department of Public Works to determine the overall loading, as well as the pressure distribution on various Caisson-type breakwaters.

WAVE POWER AS AN ENERGY SOURCE

A general study to assess the wave power available around Canada's coast and to evaluate various proposed schemes to extract this energy. International co-operation is taking place through the International Energy Agency of OECD.

MOTIONS OF LARGE FLOATING STRUCTURES, MOORED IN SHALLOW WATER

A mathematical and hydraulic modeling program will be carried out to develop techniques and methods to forecast motions of, and mooring forces on large structures moored in shallow water.

CALIBRATION OF FLOW MEASURING DEVICES

Facilities to calibrate various types of low meters up to a maximum capacity of 5,000 gpm are regularly used for/or by private industry and other government departments.

KINCARDINE HARBOUR MODEL STUDY

A hydraulic model study for Public Works, Canada of Kincardine Harbour on Lake Huron, to investigate changes in the layout of the present breakwaters to reduce the level of wave agitation inside the harbour basin.

TRANSPORT OF SAND ON BEACHES

A method has been developed for calculating rates of sand transport in the presence of waves, a modification of the Ackers and White method for river flows. A new flume was recently constructed in which the method can be tested.

LOW HEAD WATER TURBINES

A research program has been started to investigate the feasibility of extracting power from water currents, by using low head turbines.

HYBRID MODELING TECHNIQUES USING ARRAY PROCESSORS

Estuaries where tidal power can be developed require the use of large physical models of the area. The laboratory has demonstrated that a "hybrid model" can dynamically couple together a mathematical model to the physical model at the boundaries, therefore the physical model need not be very large in extent. An array processor will be used to realize the mathematical portion of the hybrid model.

FEASIBILITY STUDY FOR THE EXTRACTION OF POWER FROM THE STRAIT OF BELLE-ISLE

A contract is to be let to study the energy availability and exploration of the temperature differential between the Gulf of St. Lawrence and the Labrador current.

MULTI-DIRECTIONAL PUMPING SCHEMES FOR TIDAL MODELS

To supply and withdraw water at many boundary locations on large tidal models, a development of a sophisticated bi-directional pump and flow controller is to be started this year.

LOW SPEED AERODYNAMICS LABORATORY

WIND TUNNEL OPERATIONS

The three major wind tunnels of the laboratory are: the 15-ft. diameter open jet vertical tunnel, the 6-ft. X 9-ft. closed jet horizontal tunnel, and the 30-ft. V/STOL tunnel. During the quarter, a number of test programs were carried out for groups both within and outside of the government. Within the government, test programs included studies on building aerodynamics and ship-hull flow visualization. Studies for non-government groups included the aerodynamics of a road vehicle, an aircraft, a building, a vertical-axis wind turbine, an aircraft insecticide spray-boom system and downhill skiers.

The contract for the new data acquisition, reduction and control system for the 6-ft. X 9-ft. wind tunnel was awarded in early October with final installation at the site about the first of March 1979. Operations in the 6-ft. X 9-ft. wind tunnel ceased on 4 December 1978 in preparation for the installation of new balance equipment and the data system.

WIND ENGINEERING

In collaboration with the Division of Building Research, an aerodynamic investigation of Commerce Court, Toronto is being undertaken. The purpose is to obtain wind tunnel comparisons with full-scale measurements of surface pressures and building movements. A second program of pressure measurements was carried out on a 1:200 scale model in the 30-ft. X 30-ft. wind tunnel. An aeroelastic model has been designed and will now be constructed for testing.

Investigations into the aerodynamics of the removable roof of the Olympic Stadium were completed in the 30-ft. X 30-ft. wind tunnel using a 1:100 scale model of the entire stadium. A procedure for manufacturing a lightweight roof material was devised so that the dynamic behaviour of the full-scale roof was correctly modelled.

A series of six 1:10 scale truck models are being designed and constructed to continue NRC's program in truck energy conservation through aerodynamic drag reduction and in support of a joint NRC/Transport Canada – DOT/SAE (U.S.A.) wind tunnel testing program.

Measurements of wind properties are being continued on the Lions' Gate Bridge, Vancouver as part of an aerodynamic investigation of the bridge. Outputs from five anemometers and two accelerometers that measure bridge motion are recorded by an automated system. Site assistance is being provided by Buckland and Taylor Limited, Vancouver.

An investigation for Dow Canada was completed in the 30-ft. X 30-ft. wind tunnel into the wind-induced movement of stones, tiles and insulation material used in loose-applied roofing systems.

An investigation into the aerodynamic stability of an ore conveyer bridge was begun in the 15-ft. vertical wind tunnel using a 1:12 scale sectional model. The proposed suspension bridge will cross the Similkameen river valley and will be 1350-ft. between towers. A program of wind measurements is underway at the site. The work is being done for Buckland and Taylor Ltd., Vancouver, Canada.

In collaboration with the Department of National Defence, Defence Research Establishment Atlantic, an investigation was undertaken in the 6-ft. X 9-ft. wind tunnel for a proposed design for a coastal patrol frigate. Using a 1:35 scale below water-line model, the aerodynamic forces on roll stabilizer fins were measured. Flow visualization was also undertaken to locate the fin trailing vortex with respect to the propellers as part of a study of the noise signature.

FLUIDICS

Co-operative studies with D.G. Instruments of a 3-axis air velocity sensor are continuing using both NRC and industry developed concepts. Studies of vortex excitation of velocity sensor probes have been carried out in co-operation with Fluidynamics Devices Ltd. A program of applications of laminar flow in thin passages is being carried out in co-operation with the Control Systems and Human Engineering Laboratory of DME.

VERTICAL AXIS WIND TURBINE

In July, the rotor of the 230-kW demonstration wind turbine on the Magdalen Islands collapsed while the drive train was undergoing maintenance. An investigation of the causes of the accident has uncovered no basic flaws in its design or construction and a decision has been made to rebuild it. Two 50-kW plants are now in operation, directly connected to local power networks in Newfoundland and Saskatchewan.

AERIAL SPRAYING OF PESTICIDES

A new spray boom, designed in co-operation with CONAIR Aviation Ltd., has been used on the spraying operations in Newfoundland, this past summer. The performance of the new boom configuration is satisfactory with regard to both aerodynamic drag, and spray characteristics. It was the opinion of DC-6 flight crews that the aircraft performance with streamline booms installed was essentially that of the clean aircraft, and that a saving of 400 hp was realized at a flight speed of 185 kts.

Research into the behaviour of spray droplets emitted into the aircraft vortex wake is continuing. A wind tunnel model of a Grumman Avenger has been tested with spraying from various parts along the span.

LOW TEMPERATURE LABORATORY

THERMAL PROTECTION OF TRACK SWITCHES

The use of heat to eliminate switch failures from snow and ice is a standard approach to this problem. Work has been carried out on improving the efficiency of forced convection combustion heaters and the means of distributing heat to the critical areas of a switch.

HORIZONTAL AIR CURTAIN SWITCH PROTECTOR

A non-thermal method of protecting a switch from failure due to snow has been undergoing development and evaluation. This method consists of high velocity horizontal air curtains designed to prevent the deposit of snow in critical areas of a switch. The tests conducted to date are especially encouraging with respect to yards and terminals. Additional evaluation is required for the line service application.

NEW RAILWAY SWITCH DEVELOPMENT

The ultimate solution to the existing problem of snow and ice failure of the point switch would appear to be replacement by a new design that is not subject to failure in this way. A switch has been designed, fabricated, laboratory tested and has now completed one winter season of field trials. The design involves only shear loading from snow and ice.

MISCELLANEOUS ICING INVESTIGATIONS

Analytical and experimental investigations of a non-routine nature, and the investigation of certain aspects of icing simulation and measurement.

TRAWLER ICING

In collaboration with Department of Transport, an investigation of the icing of fishing trawlers and other vessels under conditions of freezing sea spray, and of methods of combatting the problem.

AIRBORNE SNOW CONCENTRATION

To provide statistical data on the airborne mass concentration of falling snow in order to define suitable design and qualification criteria for flight through snow, measurements of concentration and related meteorological parameters are being made.

SEA ICE DYNAMICS

Analytical and experimental work on the techniques of forming low-strength ice from saline solutions is being carried out in connection with proposed modeling studies of icebreaking ships and arctic port facilities.

An investigation is being made into the modeling of sea ice based on the freezing of aqueous solutions. The objective of the investigation is to improve the dynamic similarity in model testing in simulated sea ice.

LOCOMOTIVE TRACTION MOTORS

An investigation into the failure of locomotive traction motor support bearings due to winter service has been undertaken. The presence of moisture either as water or ice in the oil reservoirs is suspected to be a contributing cause of the failures.

HIGH PRESSURE CUTTING OF ICE

Experimental work is being carried out in collaboration with Gas Dynamics personnel on the cutting of ice with high pressure water jets. One phase of this work has been concerned with the removal of ice from a substrate such as concrete. The other work on ice cutting has been for possible application to ice breaking ships.

MARINE DYNAMICS AND SHIP LABORATORY

HIGH SPEED CRAFT

Several models in a systematic series have been studied and others are being prepared to determine their performance in still water and in waves.

COMBINATION FISHING VESSEL

Model tests have been completed on a new design of 70 ft. West Coast combination salmon and herring fishing vessel.

The basic hydrodynamic efficiency of the design was investigated through resistance and self-propulsion experiments in calm water and studies were made of the performance of the vessel and its safety against capsize in waves. These experiments were carried out in the 130 m. X 65 m. X 3.5 m. seakeeping and manoeuvring basin using a radio-controlled free-running model.

65 FT. EAST COAST FISHING VESSEL

The laboratory is currently investigating whether increase in the beam of small fishing vessels, which has advantages for deck working, leads to any deterioration in seakeeping qualities.

Beam wave rolling experiments, both with and without passive anti-rolling tank stabilization, have been completed. Empirical coefficients obtained from these model experiments are being used to continue the study with the laboratory's five degrees of freedom ship motion program.

LOCK MODEL STUDY – EXTENSION

The second series of model tests for the St. Lawrence Seaway Authority into the effect of vessel size and lock geometry on lock transit times in the Welland Canal is nearing completion. These tests are in direct support of a prototype marine shunter trials program.

The marine shunters are small tugs which would attach to the bow and stern of vessels and provide the motive power and control to manoeuvre them through the canal and locks. The experiment data would allow the Authority to extrapolate from full scale trials data and predict the value of the marine shunter concept for a much wider range of vessel size and type than it is practical to test full scale.

ANTI-PITCHING

Reduction of ship motions is of major importance in the design of small fast warships. While roll stabilization is common, it is generally believed that pitch stabilization is not practical because of the large forces involved.

The laboratory is engaged in experiments in which hydrofoil technology is being applied to anti-pitching fins. In a first series two models, fitted with fins, have been run in calm water to determine the forces and moments acting for a range of attitudes of the hull.

M.V. "ARCTIC"

The laboratory will shortly be participating in dedicated icebreaking trials aboard the M.V. Arctic. This is Canada's first icebreaking bulk cargo vessel and has been built to meet the Arctic Waters Pollution Prevention Regulations as a Class 2 ship. The laboratory has advised in the design and installation of a sophisticated data system with which the vessel has been equipped to measure ice loadings, using 160 strain gauges mounted on the hull, as well as ship motions and propulsion parameters. The data from these trials should be extremely valuable for the design of future Arctic bulk carriers.

NAVIGATIONAL BUOY

A 1/8 scale model of a prototype aluminum navigational buoy was constructed in the laboratory and extensive studies made of its mooring characteristics in waves.

RAILWAY LABORATORY

YARD AND ROAD EXPERIMENTS

In conjunction with CP Rail and the Transport Canada Research and Development Centre, experiments have been completed on the evaluation of a variety of novel and standard 100-ton trucks with respect to stability and curving. Results have been analyzed and a report has been issued.

At the request of CP Container Service and CP Rail, impact strength tests have been conducted on a new series of container and flat car combinations. Results have been analyzed and a report is being issued.

At the request of the Department of National Defence, impact tests have been conducted on a series of steel structures secured to a flat car to simulate classification yard conditions.

LABORATORY FACILITIES FOR RAILWAY RESEARCH

The curve position control lever system design for the track simulator has been completed and these control levers will be constructed by the Manufacturing and Technology Centre. Various electronic, hydraulic and mechanical components for the railway track simulator and the car shaker system are also in the process of being designed. Interior walkways are being built and the cable trays for the instrumentation and control wires have been installed in the Dynamics Laboratory. The electrical wiring for control of the track simulator and car shaker system between the master control room and the main operational bay of the Dynamics Laboratory is being installed.

The wheel-roller interaction phenomenon in roller-rig simulation is being studied to develop a general purpose Fortran digital computer program based on a mathematical model.

Instrument Car 62 has been fitted with heat, power, and internal partitions, and a floor to absorb longitudinal shocks has been designed for the Car's instrumentation compartment.

GENERAL INSTRUMENTATION

The Laboratory, in co-operation with the Marine Dynamics and Ship Laboratory, have built a micro-processor based ship's motion analyser. Development of the digital programs for computation and control, including laboratory checks of the instrument, using field data, are presently being carried out by the Marine Dynamics and Ship Laboratory.

A non-contacting transducer is being developed to measure speed and displacement of ferro-magnetic surfaces by correlating two magnetic noise signals.

An instrumented locomotive wheelset for measuring vertical and lateral rail/wheel forces in service is being developed for Transport Canada Research and Development Centre. Preliminary tests to determine the optimum position of the measuring gauges have been completed.

TECHNICAL PHOTOGRAPHY

The Photo Group is now set up to resume their former services to the Mechanical Division and others.

STRUCTURES AND MATERIALS LABORATORY

FATIGUE OF METALS

Studies of the basic fatigue characteristics of materials under constant and variable amplitude loading; fatigue tests on components to obtain basic design data; fatigue tests on components for validation of design; studies of the statistics of fatigue failures; development of techniques to simulate service fatigue loading.

RESPONSE OF STRUCTURES TO HIGH INTENSITY NOISE

Study of excitation and structure response mechanisms; study of panel damping characteristics and critical response modes; investigation of fatigue damage laws; industrial hardware evaluation; investigation of jet exhaust noise.

OPERATIONAL LOADS AND LIFE OF AIRCRAFT STRUCTURES

Instrumentation of aircraft for the measurement of flight loads and accelerations; fatigue life monitoring and analysis of load and acceleration spectra; full-scale fatigue spectrum testing of airframes and components.

ELECTRON FRACTOGRAPHY

Qualitative determination of fracture mechanisms in service failures; fractographic studies of fatigue crack propagation rates and modes.

METALLIC MATERIALS

Structure-property relationships in cast and wrought nickel-base superalloys. Studies of the consolidation and TMT processing of superalloy powders and compacts by hot isostatic pressing, hot extrusion and upset forging; studies on mechanical properties. Mechanics of cold isostatic compaction of metal powders, properties of hydrostatically extruded solids and compacts, extruded at pressures up to 1600 MN/m^2. Studies of the oxidation/hot corrosion behaviour of coated and uncoated refractory metals and superalloys.

MECHANICS AND THEORY OF STRUCTURES

Stresses in multi-cell caissons for marine structures. Stress concentrations at corners of box structures. Behaviour of plates under high-speed impact, with reference to bird resistance of aircraft windshields.

FLIGHT IMPACT SIMULATOR

Simulator developed and calibrated to capability of accelerating a 4-lb. mass to velocity of 1000 ft./sec. and an 8-lb. mass to velocity of 760 ft./sec.; operation on year-round basis achieved and includes use of temperature controlled enclosure from −40° to +130°F; in addition to airworthiness certification program includes assessment of resistance to impact for materials and structural design for most types of viewing transparencies.

CALIBRATION OF FORCE AND VIBRATION MEASURING DEVICES

Facilities available for the calibration of government, university, and industrial equipment include deadweight force standards up to 100,000 lb., dynamic calibration of vibration pick-ups in the frequency range 10 Hz to 2000 Hz.

COMPOSITE MATERIALS

Studies of composites including resins, crosslinking compounds, polymerization initiators, selection of matrices and reinforcements, application and fabrication procedures, material properties, and structural design.

FINITE ELEMENT METHODS

Development and application of finite element methods to structural problems. Development of refined elements with curved edges. Development of methods for non-linear problems. Studies on the analysis of cracked members.

MOTOR VEHICLE SAFETY

In collaboration with Ministry of Transport, Road and Motor Vehicle Traffic Safety Branch, studies to determine the performance of headlights in the driver passing task are being carried out. Work is continuing on a system for studying driver performance and traffic quality by the analysis of automatically recorded vehicle control input and response data.

POLICE EQUIPMENT STANDARDS

The NRC/CACP Technical Liaison Committee on Police Equipment is a bilateral arrangement for bringing together police and government personnel to review police equipment requirements, equipment performance specifications, and conformance testing procedures. Work of the Committee is expedited by a permanent Secretariat which has a primary responsibility for continuity in the activities of a number of Sections, each dealing with a particular area of expertise, and for co-ordinating work and specialist contributions from various participating Departments and organizations.

UNSTEADY AERODYNAMICS LABORATORY

DYNAMIC STABILITY OF AIRCRAFT

Development of a forced-oscillation rolling apparatus.

Development of a translational-oscillation apparatus.

Vertical acceleration experiments.

Measurements of cross-coupling derivatives at high angles of attack.

Studies of the sensitivity of aircraft motion to aerodynamic cross coupling.

Development of hydraulic drive systems for high-load oscillatory apparatuses.

ATMOSPHERIC DISTRIBUTION OF POLLUTANTS

Instrumentation of a small mobile laboratory to measure airborne particulates and of an aircraft to detect atmospheric tracers.

Exploratory field studies of the windborne loss of insecticide from the spruce budworm aerial spray program in New Brunswick. This project performed in partial co-operation with the Forest Protection Ltd., Fredericton, N.B.

Analysis of the downwind vertical spread and turbulent deposition of gaseous and aerosol pollutants from sources near the ground, with special emphasis on the effect of droplet evaporation.

TRACE VAPOUR DETECTION

Development of highly sensitive gas chromatographic techniques for detection of trace quantities of vapours of pesticides, explosives and fluorocarbons.

Sensitivity evaluation of commercially available explosive detectors.

Development of stopped-flow and continuous-flow vapour concentrators.

Testing of biosensors.

WORK FOR OUTSIDE ORGANIZATIONS

Damping and cross-coupling experiments for NASA.

Feasibility and design studies for NASA.

Aircraft-security feasibility studies and development projects for Transport Canada.

Feasibility studies for DSMA, Toronto.

Development project for The Aerospace Corporation, USA.

Experimental assistance to RCMP.

WESTERN LABORATORY (VANCOUVER)

PRACTICAL FRICTION AND WEAR STUDIES

Various laboratory simulations of practical tribological systems to study friction, wear and lubrication behaviour of lubricants and bearing materials in response to specific external requests. For example, related studies of methanol lubricity and wear in fuel pump gears with methanol as the working fluid are in progress.

FUNDAMENTAL STUDIES IN TRIBOLOGY

A special rolling contact apparatus is being built that will allow experimental studies of rail and wheel wear, and lubrication to be made in the laboratory.

LUBRICANTS

Various load capacity and endurance (wear) tests have been made on both fluid and solid lubricants at the request of local and national organizations.

PRACTICAL STUDIES OF BEARING AND SEALS

The recently constructed locomotive traction motor bearing apparatus is now being used to test the effectiveness of the wick lubrication system at temperatures down to −40°.

Another study of the leakage paths in a rotary marine steering gear has been carried out and recommendations made for reducing leakage and extending seal life.

INSTRUMENTATION

Work is continuing on the design of a computer based data logging and control system for use on the new rail-wheel wear test apparatus now under construction.

Spectral analysis of gear fuel pump vibrations are being made on the methanol lubricity experiments to monitor any wear or deterioration of the gear teeth.

NUMERICALLY CONTROLLED MACHINING

Technical assistance on this subject is being provided to firms and other institutions in Western Canada which are considering the purchase of numerically controlled machines to improve their production efficiency. Seminars are held to explain the fundamentals of numerical control and programming, and the laboratory's 3-axis NC milling machine is used to machine demonstration batch quantities of typical components for interested companies. A newsletter 'NC and the Small Shop' has been published describing this assistance in more detail.

Use is being made of computer-assisted programming and punched-tape preparation as a means of reducing manual programming time for items requiring a large number of geometrical statements. Seminars are held to demonstrate the principles and features of this method of NC part programming.

APPROPRIATE TECHNOLOGY

Up until now the laboratory has been monitoring the progress of this new technological movement towards smaller scale, environmentally and socially appropriate decentralized industrial development. In 1979 the laboratory will undertake one or two small projects on the development of appropriate but economic small scale products or processes. Enquiries regarding these developments and proposals for co-operative projects are welcomed.

LOW TEMPERATURE TEST FACILITY

The refrigeration plant of the test facility has been replaced to increase its low temperature capacity to −45°C.

PUBLICATIONS

National Aeronautical Establishment

LR-596 **CALCULATION OF THE POTENTIAL FLOW PAST MULTI-COMPONENT AIRFOILS USING A VORTEX PANEL METHOD IN THE COMPLEX PLANE.**

Mokry, M., National Aeronautical Establishment, November 1978.

An efficient algorithm for a vortex panel method in the complex plane is developed to compute the potential flow past multi-component airfoils in free air and a porous-wall wind tunnel. The theoretical foundations of the method – the properties of the source and vortex density functions, the relationship between the exterior and interior flows, and the general Kutta-Joukowski condition for a trailing edge with crossflow – are derived from the theory of the Cauchy type integral. The method utilizes flat panels with linear vortex and source densities, the latter being used to simulate the displacement effect of boundary layers. The airfoil boundary condition is satisfied at all panel midpoints and the overdetermined system of linear algebraic equations solved as a least squares problem, in the L_1 norm, or in the L_∞ norm. The wind tunnel wall interference problem is treated using the concept of the Green's function in the complex plane. Examples are worked out for some theoretical airfoils and extensive tables of exact and computed pressure distributions are given.

LABORATORY TECHNICAL REPORTS

National Aeronautical Establishment

LTR-HA-33 Cox, E.J., Piper, R.H.

The Manufacture of Turbulence Screens to Replace Original Equipment in the NAE 5′ X 5′ Blowdown Wind Tunnel Tooling Assembly Drawing No. B47320.
October 1978.

LTR-HA-35 Galway, R.D.

A General Procedure for the Reduction of Calibration Data from Wind Tunnel Balances.
December 1978.

LTR-HA-36 Galway, R.D.

A General Approach to the Application of Force Balance Tares in Wind Tunnel Testing.
December 1978.

LTR-UA-45 LaBerge, J.G., Davie, S.J.

Explosives Testing of Bomb Shields and Mk II Protective Suit.
November 1978.

Division of Mechanical Engineering

LTR-HY-67 Mansard, E.P.D., Ploeg, J.

Model Tests of Sines Breakwater.
October 1978.

LTR-IN-395 Dukkipati, R.V., Watson, W.J.

Freight Car Truck Evaluation Tests.
October 1978.

LABORATORY TECHNICAL REPORTS (Cont'd)

Division of Mechanical Engineering (Cont'd)

LTR-IN-396 Dukkipati, R.V., Watson, W.J.

Impact Tests on Container Cars for CP Intermodal Services.
October 1978.

LTR-IN-398 Dukkipati, R.V.

Dynamics of Independently Rotating Wheelsets – A Survey of the State-of-the-Art.
November 1978.

LTR-LT-91 Timco, G.W.

Morphological Characteristics of Ice Growth from an Impure Melt.
June 1978.

LTR-LT-92 Stallabrass, J.R.

An Appraisal of the Single Rotating Cylinder Method of Liquid Water Content Measurement.
November 1978.

LTR-WE-13 Hawthorne, H., Lowe, J.

Friction and Wear Behaviour of Some High Temperature Bearing Alloys at 700°C (1400°F).
September 1978

MISCELLANEOUS PAPERS

Bhat, M.V.*, Dukkipati, R.V. Analysis of Periodic Systems with Aperiodic Loads. Paper presented at the 2nd International Symposium on Large Engineering Systems, University of Waterloo, Waterloo, Canada, May 15-16, 1978. Also appeared in the *Proceedings of the Conference.*

Bosik, A.J., Heath, J.B.R., Gould, R.W. A Study of Bird Impacts on Monolithic Aircraft Windshields. Paper presented by A.J. Bosik at the Conference on Aerospace Transparent Materials and Enclosures, Long Beach, Calif., 24-28 April 1978. To be published in Proceedings.

Cooper, K.R., Garner, G.J.** Reducing the Aerodynamic Drag of Logging Trucks. Paper No. 78-1574 presented at the 1978 Winter Meeting American Society of Agricultural Engineers, Chicago, Illinois, U.S.A., 18-20 December 1978.

Deneeve, P.F.W.***, Dukkipati, R.V. A Procedure for Axial Blade Optimization. Paper presented at the ASME Winter Annual Meeting, San Francisco, December 10-15, 1978. Also accepted for publication in the Transactions of the ASME. ASME Paper No. 78-WA/GT-15.

Dukkipati, R.V. Kinematic Analysis of a Seven-link Mechanism. Paper presented at the ASME Design Engineering Technical Conference, Minneapolis, Minnesota, September 24-27, 1978. ASME Paper No. 78-DET-55.

Dukkipati, R.V. Number Synthesis of Multi-loop Mechanisms. Paper presented at the 9th Southeastern Conference on Theoretical and Applied Mechanics Conference, Nashville, Vol. 9, May 1978, pp. 29-38.

Dukkipati, R.V., Sankar, S.***, Osman, M.O.M.*** On the Use of Complex Method of Constrained Optimization in Linkage Synthesis. Paper accepted for presentation at the Fifth World Congress on Theory of Machines and Mechanisms Conference, Montreal, July 8-13, 1979. Also accepted for publication in the Proceedings of the Conference.

Elias, L. Recent Projects at National Research Council of Canada Related to Explosives Detection. Presented at New Concepts Symposium and Workshop on Detection and Identification of Explosives, 30 October - 1 November 1978, Reston, Virginia, U.S.A. To be published in the Proceedings.

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* Pratt & Whitney Aircraft of Canada Limited
** Forest Engineering Research Institute of Canada
*** Concordia University

MISCELLANEOUS PAPER (Cont'd)

Galway, R.D. A Means of Assessing the Overall Accuracy of Multi-Component Wind Tunnel Balances. National Research Council Canada, Lab Memo HSA-171, January 1979.

Graefe, P.W.U., Crate, G.F., Chan, A.W. Operations Study of an Intermediate Capacity Transit System on a Hybrid Computer. Proceedings of the 1978 Joint Automatic Control Conference, Philadelphia, PA., October 18-20, 1978, pp. 271-280.

Gupta, R.P., Panarella, E. Quantum Electrodynamics of High Intensity Laser Beams. Bulletin of the American Physical Society, Vol. 23, 1978, p. 858.

Orlik-Rückemann, K.J. Effect of High Angles of Attack on Dynamic Stability Parameters. Presented at the AGARD FDP Symposium on High Angles of Attack Aerodynamics, Sandefjord, Norway, 4-6 October 1978. Paper 1 in AGARD CP 247.

Osman, M.O.M.*, Bahgat, B.M.*, Dukkipati, R.V. Kinematic Analysis of Spatial Mechanisms Using Train Components. Paper accepted for publication in the transactions of ASME, Journal of Mechanical Design, 1979.

Panarella, E. The REXIMPLO (Repetitive-Expolosion-Implosion) Experiment – Conversion from Cylindrical to Spherical Geometry. Bulletin of the American Physical Society, Vol. 23, 1978, p. 876.

Panarella, E. Single-Photon Mechanism of Laser-Induced Gas Ionization. Bulletin of the American Physical Society, Vol. 23, 1978, p. 914.

Rudback, N.E., Hayes, W.F., Eastham, E.R. Status of High Speed Magnetically Levitated Transportation Research in Canada. (In. English and Japanese.) Transportation Development Centre, Transport Canada, Montreal, Quebec, November 1978. (Presented at International Seminar on Superconductive Magnetic Levitated Train, Miyazaki, Japan, November 9, 1978.)

Venter, R.D.**, Hewitt, R.L., Johnson, W.*** Application of the Matrix Inversion Technique to Extension and Drawing Problems. Paper presented by R.L. Hewitt at the Winter Annual Meeting of the American Society of Mechanical Engineers, San Francisco, Calif., December 10-15, 1978. Published in 'Applications of Numerical Methods to Forming Processes', AMD Vol. 28, pp. 143-154.

Venter, R.D.**, Hewitt, R.L. An Introduction to the Matrix Operator Technique for Solving Plane Strain Metal Forming Problems. Paper presented by Prof. R.D. Venter at 4th Symposium on 'Engineering Applications of Solid Mechanics', held at Ontario Research Foundation, September 25-26, 1978, in Toronto. To be published in Proceedings.

Weigert, A.W. Continuously Adjustable Digital Waveform Generator. National Research Council Canada, Lab Memo HY-99, December 1978.

UNPUBLISHED PAPERS

Crabbe, R.S. Report to the Meeting on Calculation of Long Range Drift of Insecticide from Spruce-Budworm Spraying Operations in New Brunswick, Toronto, 4 December 1978.

Hayes, W.F. Suspension System Dynamics for Canadian Maglev Vehicle Conceptual Design. Lecture given at International Seminar on Superconductive Magnetic Levitated Train, Miyazaki, Japan, November 10, 1978.

Immarigeon, J-P., Floyd, P.H. Structural Instabilities During Superplastic Forging of Nickel-Base Superalloy Compacts. Paper presented by J-P. Immarigeon at Symposium on Flow and Fracture during High Temperature Forming; TMS/AIME Fall Meeting, October 1978, in St. Louis, Missouri. Also presented at the 17th Annual Conference of Metallurgists of the CIM held in Montreal, Que., August 27-31, 1978.

Irwin, H.P.A.H. Wind-Induced Dynamic Instablities of Civil Engineering Structures. Presented to McGill University, Department of Mechanical Engineering, Montreal, 14 November 1978.

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* Concordia University
** University of Toronto
*** University of Cambridge, England

UNPUBLISHED PAPERS (Cont'd)

Orlik-Rückemann, K.J. Dynamic Stability Parameters at High Angles of Attack. Seminar at the Royal Institute of Technology, Stockholm, Sweden, 10-11 October 1978.

Orlik-Rückemann, K.J. Dynamic Stability Parameters at High Angles of Attack (Part 1: Brief Review, Part 2: Related Work at NAE). Presented at the 5th Meeting of TTCP Technical Panel W-2, DREV, Valcartier, Quebec, 23-27 October 1978.

Stallabrass, J.R., Lozowski, E.P. Ice Shapes on Cylinders and Rotor Blades. Presented at NATO Panel X Symposium on Helicopter Icing, London, England, 6-7 November 1978.

Wallace, W. Materials Work of the Structures and Materials Laboratory of NAE. Talk given to the Canadian Steel Industries Research Assoc., Ottawa, Ont., September 19, 1978.

Wardlaw, R.L. Sectional Versus Full Model Wind Tunnel Testing of Bridge Road Decks. 1978 FCP Research Review Conference, U.S. Department of Transportation, Federal Highway Administration, University of Maryland, 3-6 October 1978.

PATENT

Tucker, H.G., Tanney, J.W., Hayes, W.F. Apparatus for Measuring the Flow Rate and/or Viscosity of a Fluid. United States Patent No. 4,118,973, October 10, 1978.

PROPRIETARY PROJECTS DURING 1978

Part of the work of the two Divisions covers proprietary projects, and, for this reason, has not been reported in these Bulletins.

Following is a list of Industrial Organizations, Government Departments and Universities for whom work was done during 1978.

INDUSTRIAL ORGANIZATIONS

Ackurst Machinery Ltd., Vancouver, B.C.
A.C. Sprayers Inc., Hamilton, Ontario
Aerophoto Ltd.
A.F. Lehman Associates Inc., Centerport, N.Y.
Albion Industries Ltd., Kitimat, B.C.
Allied Chemical Canada Ltd., Amherstburg, Ontario
Aluminum Company of Canada Ltd., Montreal, P.Q.
Anaconda Cable T.V. Ltd., Vancouver, B.C.
Analytical Systems Ware Ltd., Vancouver, B.C.
Andrew Antenna Company Ltd., Whitby, Ontario
ASTM Committee D-2, Philadelphia, PA
Atlantic Bridge Co., Plastics Division, Mahone Bay, Nova Scotia

B.C. Hydro and Power Authority, Vancouver, B.C.
Beavers Dental Products, Morrisburg, Ontario
Bingham-Wilamette Ltd., Burnaby, B.C.
Bohm, C., Ottawa, Ontario
BP Canada Ltd., Montreal, P.Q.
BP Refinery, Oakville, Ontario
Brabazon Assoc. of Canada Ltd., Ottawa, Ontario
Bradley Air Services Ltd., Carp, Ontario
Bristol Aerospace Ltd., Winnipeg, Manitoba
Buckland and Taylor Ltd., Vancouver, B.C.
Burke Machine Works Ltd., Vancouver, B.C.

CAE Morse Ltd., Vancouver, B.C.
Canada Cement Lafarge Ltd., Montreal, P.Q.
Canadair Ltd., Montreal, P.Q.
Canadian Aircraft Products Ltd., Richmond, B.C.
Canadian Air Vehicles Ltd., Ottawa, Ontario
Canadian Aviation Electronics
Canadian Enterprise Development Corp., Vancouver, B.C.
Canadian Fram Ltd., Chatham, Ontario
Canadian General Electric, Peterborough, Ontario
Canadian Institute of Guided Ground Transportation, Kingston, Ontario
Canadian International Paper Co., Hawkesbury, Ontario
Canadian Marconi Ltd., Montreal, P.Q.
Canadian Marine Drilling Ltd., Calgary, Alberta
Canadian Ski Team
Canadian Thin Films Ltd., Burnaby, B.C.

Canron Ltd.
Chemoleums Private Ltd., Madras, India
Chrysler Canada Ltd., Windsor, Ontario
CIL Industrial Chemicals, McMasterville, Ontario
City of Ottawa Police Department, Ottawa, Ontario
Civic Hospital, Ottawa, Ontario
C.N.C. Precision Machinery Ltd., North Vancouver, B.C.
CN Rail, Montreal, P.Q.
Computing Devices of Canada Ltd., Ottawa, Ontario
Conair Aviation, Abbotsford, B.C.
CP Air, Vancouver, B.C.
CP Rail, Montreal, P.Q.
CTF Systems Inc., Port Coquitlam, B.C.

Davis, Eryou and Assoc. Ltd., Ottawa, Ontario
DeHavilland Aircraft of Canada Ltd . Downsview, Ontario
Deloro Stellite, Div. of Canadian Oxygen Ltd., Belleville, Ontario
D.G. Instruments Ltd., Kanata, Ontario
Dilworth, Secord, Meagher and Associates Ltd., Toronto, Ontario
Dominion Bridge Co. Ltd., Ottawa, Ontario
Dominion Cutout Ltd., Scarborough, Ontario
Dominion Engineering Works Ltd., Montreal, P.Q.
Dow Chemical of Canada Ltd., Sarnia, Ontario

E.F. Barnes Ltd., St. John's, Newfoundland

Ferritronics Ltd., Richmond Hill, Ontario
Firestone Canada Ltd., Hamilton, Ontario
Fleet Industries, Fort Erie, Ontario
Fluidynamic Devices Ltd., Mississauga, Ontario
Forest Engineering Research Institute of Canada, Pointe Claire, P.Q.
Foster-Wheeler Co. Ltd., St. Catharines, Ontario

Gearmatic Co. Ltd., Surrey, B.C.
General Behaviour Systems Inc., Toronto, Ontario
General Motors Corp. of Canada
Geoterrex Ltd., Ottawa, Ontario
German & Milne, Montreal, P.Q.
G. Kelk Ltd., Don Mills, Ontario
Goldblatt, Larry, Hamilton, Ontario
Golden Eagle Canada Ltd., Ottawa, Ontario
GTE Automatic Electric (Canada) Ltd., Brockville, Ontario

H. Aass Aero Engineering Ltd., Ottawa, Ontario
Harley-Davidson Motor Co. Ltd.
Hawker Siddeley Canada Ltd., Canadian Car (Pacific) Division, Vancouver, B.C.
Hawker Siddeley Canada Ltd., Orenda Div., Toronto, Ontario
Heatex Ltd., Toronto, Ontario

Heatex Radiators Ltd., Rexdale, Ontario
Hermes Electronics
Hoverlift Systems Ltd., Calgary, Alberta
Hovey & Associates Ltd., Ottawa, Ontario
Hussman Store Equipment Ltd., Brantford, Ontario

Imperial Oil Enterprises Ltd., Dartmouth, Nova Scotia
Imperial Oil Enterprises Ltd., Montreal, P.Q.
Imperial Oil Enterprises Ltd., Edmonton, Alberta
Imperial Oil Ltd., Toronto, Ontario
Industrial High Pressure Systems Inc., Markham, Ontario
Innotech Aviation Ltd., Dorval, P.Q.
Institute of Aviation Medicine, Bangalore, India
International Nickel Co., Copper Cliff, Ontario
International Nickel Co. Ltd., Sudbury, Ontario
International Submarine Engineering Ltd., Port Moody, B.C.

Keith Philpott Consulting Ltd., Thornhill, Ontario
Kenting Earth Sciences

Leigh Instruments Ltd., Avionics Div., Carleton Place, Ontario
Leigh Instruments Ltd., Carleton Place, Ontario
Lloyds Registry of Shipping, Montreal, P.Q.

MacLean Hunter Ltd., Willowdale, Ontario
MacMillan-Bloedel Ltd., Vancouver, B.C.
Magnum Oil Co., Saskatchewan, Sask.
Mar Kee Distributors (Alberta Ltd.), Edmonton, Alberta
Martec Ltd., Halifax, Nova Scotia
McGregor Enterprises
McRostie, Genest, Middlemiss & Associates Ltd., Ottawa, Ontario
Mechron Engineering Co., Ottawa, Ontario
Melville Shipping Ltd., Montreal, P.Q.
Mental Health Institute, Montreal, P.Q.
Metco Inc., Westbury, New York
Metropolitan Toronto and Region Conservation Authority, Toronto, Ontario
Mirolin Industries Ltd., Toronto, Ontario
Mitchell, Robert, Pownal, P.Q.
MLW Industries Ltd., Montreal, P.Q.
Montreal Neurological Institute, Montreal, P.Q.
Morris Industries Ltd., North Vancouver, B.C.
Morrison, Hershfield, Theakston and Rowan Ltd.

New Brunswick Electric Power Commission, Fredericton, N.B.
New Brunswick Task Force on Long-Distance Drift of Forest Insecticides, Fredericton, N.B.
Newfoundland and Labrador Hydro
Nicholson Murdi e Machines Ltd., Victoria, B.C.
Noranda Mines Ltd., Toronto, Ontario

Noranda Mines Ltd., Noranda, P.Q.
Nordair Ltd., Dorval, P.Q.
Nortec Air Conditioning Industries Ltd., Ottawa, Ontario
Northwest Hydraulics Consultants, Edmonton, Alberta
North Wind Power Co.

Olympic Installation Board
Onex Industries Ltd., Ottawa, Ontario
Ontario Hydro, Toronto, Ontario
Ontario Hydro, Research Div., Ottawa, Ontario

Petrofina Canada Ltd., Montreal, P.Q.
Petrofina Canada Ltd., Pointe-Aux-Trembles, P.Q.
Petrostable Inc., Montreal, P.Q.
Philbrooke's Shipyards Ltd., Sydney, B.C.
Photosur Ltd.
Placer Development Ltd., Vancouver, B.C.
Popular Shoe Co. Ltd., Contrecoeur, P.Q.
PPG Industries Inc., Huntsville, Alabama
Pratt & Whitney Canada Ltd., Longueuil, P.Q.
Production Supply Co., Vancouver, B.C.
Pullman Trailmobile Canada Ltd., Brantford, Ontario

Quebec Iron and Titanium Corp., Sorel, P.Q.
Queensway Tank Lines, Ottawa, Ontario
Quest Engineering Ltd., Halifax, Nova Scotia

Rama Stone Quarries, Willowdale, Ontario
Rite Manufacturing Ltd., Montreal, P.Q.
Riverside Hospital, Ottawa, Ontario
R.L. Crain Ltd., Ottawa, Ontario
Rolls-Royce (Canada) Ltd., Montreal, P.Q.
Royal Aircraft Establishment, Farnborough, England
Royal Alexandra Hospital, Edmonton, Alberta

S. Albert Co. Ltd., Montreal, P.Q.
Sandia Corporation, Albuquerque, New Mexico
Saskatchewan Power Corporation
saTel Consultants Ltd., Ottawa, Ontario
Seagold Industries Corp., Richmond, B.C.
Selkirk-Metalbestos, Brockville, Ontario
Shell Canada, Oakville, Ontario
Shell Canada, Pointe-Aux-Trembles, P.Q.
Shell Canada, Toronto, Ontrio
Singer Valve Ltd., Surrey, B.C.
Ski-Doo Division, Bombardier Ltée
Society of Automotive Engineers
Souque, Guy, Haywood, Manitoba

Spar Aerospace Products Ltd., Kanata, Ontario
Spar Aerospace Prdocuts Ltd., RMS Design Group, Toronto, Ontario
Standon, Neil (Consultant), Ottawa, Ontario
Steel Co. of Canada, Hamilton, Ontario
St. Vincent's Hospital, Ottawa, Ontario
Surgeson Electric Ltd., Cornwall, Ontario
Sutton-Perry, Buckingham, P.Q.
Syncrude Canada Ltd., Fort McMurray, Alberta
Systems Technology Inc.

Teleflex (Canada) Ltd., Vancouver, B.C.
T.E. Rody Ltd.
The Aerospace Corporation, Washington, D.C.
The Lubrizol Corp., Wickliffe, Ohio
Thermo-King Corporation
Tornado Manufacturing Corp., Ville d'Anjou, P.Q.
Toronto Harbour Commissioners, Toronto, Ontario
Tricil Ltee, Ville Ste Catherine, P.Q.
Turbo Refineries Ltd., Edmonton, Alberta
Tuuk Sports Ltd., Ville St. Laurent, P.Q.

Union Carbide Canada Ltd., Toronto, Ontario

Vancouver Gear Works Ltd., Vancouver, B.C.
Volcano, Ottawa, Ontario

Wagner Engineering Ltd., North Vancouver, B.C.
Warnock Hersey Professional Services Ltd., Vancouver, B.C.
Western Canada Hydraulics Laboratories Ltd., Port Coquitlan, B.C.
Westinghouse Canada Ltd., Hamilton, Ontario
Worthington Pump Co. Ltd., Brantford, Ontario

GOVERNMENT DEPARTMENTS AND AGENCIES

Aeroplane and Armament Experimental Establishment, England
Agriculture Canada, Ottawa, Ontario
Air Canada, Montreal, P.Q.
Atomic Energy of Canada Ltd., Chalk River, Ontario
Atomic Energy of Canada Ltd., Mississauga, Ontario

Consumer and Commercial Relations, Toronto, Ontario
Consumer and Corporate Affairs Canada, Fraud Protecton Branch, Hull, P.Q.
Consumer and Corporate Affairs Canada, Vancouver, B.C.

Defence Research Establishment Atlantic, Dartmouth, Nova Scotia
Defence Research Establishment, Ottawa, Ontario
Defence Research Establishment Pacific, Victoria, B.C.
Department of Communications, Communications Research Centre

Department of Lands and Forests, Quebec, P.Q.
Department of National Defence, Ottawa, Ontario
Department of National Defence, Canadian Armed Forces
Department of National Defence, Directorate of Aeronautical Engineering and Simulators, Ottawa, Ontario
Department of National Defence, Directorate of Maritime Engineering and Maintenance, Ottawa, Ontario
Department of National Defence, Land Engineering Test Establishment, Ottawa, Ontario
Department of National Defence, DGMS/DMES 4, Ottawa, Ontario
Department of National Defence, QETE, Hull, P.Q.

Federal Aviation Administration, Washington, D.C.
Fisheries and Environment Canada, Atmospheric Environment Service, Downsview, Ontario
Fisheries and Environment Canada, Chemical Control Research Institute
Fisheries and Environment Canada, Great Lakes Forest Research Centre
Fisheries and Environment Canada, Forest Management Institute, Ottawa, Ontario
Fisheries and Environment Canada, Forest Pest Management Institute, Sault Ste Marie, Ontario
Fisheries and Environment Canada, Ottawa, Ontario
Fisheries and Environment Canada, Small Crafts Harbours Branch, Ottawa, Ontario
Fisheries and Environment Canada, Emission Testing Laboratory, Ottawa, Ontario
Fisheries and Environment Canada, Fisheries and Marine Service, Ottawa, Ontario

Government of Alberta, Consumer and Corporate Affairs Branch
Government of Alberta, Transportation Department

Health & Welfare Canada, Ottawa, Ontario

Industry, Trade and Commerce, Ottawa, Ontario

Laurentian Forest Research Center, Ste Foy, P.Q.

Ministry of Defence, Aeroplane & Armament Experimental Establishment, Boscombe Down, England
Municipality of Metro Toronto, Department of Roads and Traffic, Traffic Control Centre, Toronto, Ontario

NASA Ames Research Center, Moffett Field, California
National Research Council Canada, Committee on Aviation Security, Ottawa, Ontario
Naval Engineering Testing Establishment, Lasalle, P.Q.
New Brunswick Research & Productivity Center, Fredericton, N.B.
Newfoundland Department of Consumer Affairs & Environment, St. John's, Nfld.

OC Transpo, Ottawa, Ontario
Ottawa Board of Education, Ottawa, Ontario

Public Works Canada, Ottawa, Ontario
Public Works Canada, St. John, N.B.
Public Works Canada, Research & Development Laboratories, Ottawa, Ontario

Royal Canadian Mounted Police, Ottawa, Ontario

St. Lawrence Seaway Authority, St. Lambert, P.Q.

Transport Canada, Ottawa, Ontario
Transport Canada, Air Traffic Control Simulation Centre, Ottawa, Ontario
Transport Canada, Canadian Coast Guard
Transport Canada, Research & Development Centre, Montreal, P.Q.
Transport Canada, Road and Motor Vehicle Traffic Safety, Ottawa, Ontario
Transport Canada, Telecommunications and Electronics, Air, Resolute Bay, N.W.T.
Transport Canada, Waterways Development, Ottawa, Ontario
Transport Canada, Marine Regulation, Ottawa, Ontario
Transport Canada, Flight Services Branch, Ottawa, Ontario
Transport Canada, ASE, Ottawa, Ontario
Transport Canada, Winnipeg, Manitoba

U.S. Army Research & Technology Laboratories, Fort Eustis, Virginia

UNIVERSITIES

British Columbia Institute of Technology, Department of Mechanical Engineering, Burnaby, B.C.

Carleton University, Division of Mechanical Engineering, Ottawa, Ontario

McGill University, Montreal, P.Q.

Queen's University, Kingston, Ontario

University of Calgary, Calgary, Alberta
University of Guelph, Department of Family Studies, Guelph, Ontario
University of New Brunswick, Fredericton, N.B.
University of Sherbrooke, Sherbrooke, P.Q.
University of Toronto, Institute of Aerospace Studies, Toronto, Ontario
University of Washington, Seattle, Washington, D.C.