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Force Instrumentation For Cryogenic Wind

Tunnels Using One-Piece Strain-Gage Balances

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FORCE INSTRUMENTATION FOR CRYOGENIC WIND TUNNELS
USING ONE-PIECE STRAIN-GAGE BALANCES

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SUMMARY

NASA LaRC has developed one-piece strain gage force balances for use in cryogenic wind tunnel applications. This was accomplished by studying the effect of the cryogenic environment on materials, strain gages, cements, solders, and moisture-proofing agents and selecting those that minimized strain gage output changes due to temperature. Wind tunnel results obtained from the Langley 0.3-Meter Transonic Cryogenic Tunnel were used to verify laboratory test results.

INTRODUCTION

The National Transonic Facility will impose rather severe requirements on the measurement of aerodynamic forces and moments. Not only does the cryogenic environment present an unusual surrounding for the force balance, but also, because of the tunnel's high density capability, the magnitude of the load to be measured can be much greater than that of a conventional tunnel of the same size. Although pushing the state of the art, initial studies indicate that one-piece, high-capacity strain-gage balances can be built to satisfy cryogenic requirements.

This paper will outline the work that has been accomplished at Langley Research Center while investigating the effects of the cryogenic environment on one-piece multicomponent strain-gage balances for use in the National Transonic Facility (NTF) at the National Aeronautics and Space Administration (NASA), Langley Research Center (LaRC), Hampton, VA. The NTF is scheduled to begin operation in mid-1982.

BALANCE LOAD CONSIDERATIONS

Since the aerodynamic forces and moments will be much higher in the NTF as compared to a conventional tunnel of the same size, the balance load carrying capacity for a given size diameter becomes quite important. Design studies and experimental results have indicated to what degree the load carrying capacity can be increased and still meet existing rigid balance performance criteria. Figure 1 indicates the loads that can be carried by balances that range in size from 2 cm (1 inch) to 10 cm (3.5 inches) in diameter. A typical ratio of simultaneous loads on a six-component balance is presented in the table in the upper left of the figure. The lower curve was empirically derived from LaRC's existent balances which fall on or below this curve. It was found that the load-to-diameter ratio could be increased to that of the middle curve without degrading performance. Three balances have been constructed with this increased load capacity with good results. These balances, hereafter called high-capacity balances, are shown as the shaded circles on the middle curve. Three high-

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capacity balances are shown on the figure as unshaded circles. The upper circle indicates that a balance will have to have a diameter of approximately 9 cm (3.4 inches) to carry the maximum loads expected in the NTF. A mid-range balance, designated NTF-101, has been fabricated and is currently being calibrated. This balance was designed for use in initial tunnel tests in the "pathfinder" model.

The maximum load carrying capacity for a given diameter can be increased further by using a three-component balance when this is appropriate. The maximum load carrying capacity of three-component high-capacity balances is depicted by the upper curve.

Two immediate consequences of going to high-capacity balances can be increased balance deflections and more critical or demanding calibration procedures. With increasing deflections, second-order interactions become more pronounced making it imperative that crossload combinations be applied in the calibration procedure. Evaluation of all second-order terms have long been an LaRC policy so this presents no new requirement.

The basic design of a balance for LaRC cryogenic applications will not differ significantly from that of LaRC conventional balances. Figure 2 is a drawing of NTF-101. The major design difference is that of minimizing areas of high stress concentrations, such as threads, and finding model and sting attachment methods that will maintain a good fit throughout the cryogenic temperature range and under large temperature gradients. Figure 2 shows the model and sting attachment designs chosen for NTF-101. Additional design work is continuing in this area.

A survey was conducted to find suitable balance materials for cryogenic use. If a balance is allowed to follow the wind tunnel operating temperature, the balance material must meet yield strength, fracture toughness, and impact strength requirements at temperatures down to 77 K (139°R). Figure 3 presents information on two materials for LaRC conventional balances and three others being considered for cryogenic use.

The maraging steels, developed by International Nickel Company, are so named from the fact that the alloy is martensitic in the annealed condition and attains its ultra-high strength by a simple aging treatment. The numbers 200, 250, and 300 correspond to the typical yield strengths developed after aging (in English units).

The HP 9-4-25 steel is a member of a family of steels developed by Republic Steel Company to improve impact strength while maintaining high yield strengths.

A chromium-nickel-copper alloy developed by Armco Steel Company, 17-4 PH, achieves its strength and hardness through a combination of a martensitic transformation and precipitation hardening.

In-house testing is currently in progress to confirm these physical characteristics obtained from manufacturer's brochures and to obtain the fracture toughness at 77 K (139°R) which is not now available. As anticipated, the change in yield and ultimate strength of balance materials at 77 K (139°R) was

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not a problem since most materials tend to be stronger at lower temperatures; however, they also tend to become brittle. The significant decrease in impact strength of the conventional balance materials at 77 K (139°R) indicates that these materials become quite brittle at cryogenic temperatures.

A criteria was established for NTF that required materials used at cryogenic temperatures to have impact strengths that meet or exceed the room temperature impact strength of conventional materials for that application. This criteria should insure that impact failures should not be any more of a risk in NTF than in a conventional wind tunnel. However, the number of metals that have both high yield strength and high impact strength at cryogenic temperatures is very limited.

Of the three candidate cryogenic materials, Maraging 200 has been chosen over Maraging 250 because of its higher impact strength at cryogenic temperatures and chosen over the HP 9-4-25 because it has a much simpler heat treatment procedure and is available in the smaller quantities we use. HP 9-4-25 must be bought in quite large lots.

Since the selection of Maraging 200, the shortage of cobalt, one of the constituents of the maraging steels, has seriously impacted the availability of this material. A survey of various steel companies' stock has disclosed a limited supply of Maraging 225 and a steel developed for the B-1 Project, Af1410. Both of these materials are being evaluated as to their suitability for cryogenic balance applications. Evaluation of other materials will continue until a satisfactory "backup" material is found or the maraging steels become more plentiful.

TEMPERATURE CONSIDERATIONS

Because of the wide operating temperature range of the NTF, it is necessary to have a balance that either has well-behaved, definable, and minimized temperature-induced output over the entire temperature range or has temperature control to hold the surrounding environment of the balance to a known, stable condition. Both approaches are being evaluated. Since the preliminary wind tunnel studies, conducted in 1974, used a "standard" type balance and placed the most emphasis on thermal control; an evaluation program was undertaken in 1975 to see if improved strain gage technology could be used to produce a balance that would operate satisfactorily at cryogenic temperatures.

Cryogenic Strain Gage Application Development

Comprehensive tests were made using test beams to determine the best combination of strain gages, adhesive, solder, wiring, and moisture-proofing on each of the candidate balance materials. This program was designed to define, and minimize where possible, the effects of the cryogenic environment on strain gage output when compared to its output at room temperature.

A Karma (K-alloy), SK-11, strain gage was made to our specifications for the selected balance material, Maraging 200. This gage with its self-temperature-compensation factor of 11 minimized the apparent strain output (no-load output due to temperature variation) over the entire cryogenic temperature range. Also, the change in gage factor (sensitivity shift) of the SK-11 gage was most nearly equal and opposite to the change in modulus of the Maraging 200, thereby minimizing sensitivity shift vs. temperature (1.1% shift 297 K (540°R) to 77 K (139°R)).

Adhesive

Various adhesives were subjected to thermal shocks and large strains while the output was checked for evidence of permanent zero shifts or hysteresis under load. The selected epoxy-based adhesive that met these tests was M-610, a product of Micro-Measurements.

Solder

Solder connections were subjected to a number of thermal cycles from 394 K (710°R) to 77 K (139°R). Three of the tested solders maintained their electrical integrity throughout the tests. However, the two solders containing antimony showed a tendency to become brittle and crystallize after long-term cryogenic exposure. A solder containing 1.8% silver, 570-28R, did not exhibit this tendency. Therefore 570-28R, marketed by Micro-Measurements was selected for cryogenic balance applications. The only undesirable characteristic of this solder is its high melting point 570 K (1030°R) that requires that greater care must be exercised when applying this solder to the small wiring and solder dots of the bridge wiring.

Wiring

The wiring used for cryogenic applications is silver-plated copper wire with Teflon insulation. It was discovered during tests of connectors for cryogenic applications that a thermocouple effect was evident on one lead. A 15 μV (0.3% F.S.) shift over a temperature change of 180 K (325°R) was generated at the junction of one of the balance wires and one of the lead-in wires. This finding indicates that it may be necessary to check all wiring junctions in cryogenic balances for thermocouple effects that will introduce errors into balance output.

Moisture Proofing

No moisture-proofing compound has been found that does not have some effect on apparent strain when applied over the strain-gage grid, although some were found that were much better than the standard ones previously used.

While research is continuing in this area, a rubber-based moisture-proofing compound, Micro-Measurements M-coat B, is being applied only to exposed terminals and wiring.

BALANCE HRC-2

A balance designed specifically for evaluation was fabricated and gaged in accordance with the information obtained from the aforementioned testing and evaluation program. This balance, designated HRC-2, is shown in figure 4. It is a three-component balance (normal, axial, pitch) that is 2.54 cm (1.0 inch) in diameter and 21 cm (8.352 inches) long and is suitable for use in the Langley 0.3-Meter Transonic Cryogenic Tunnel. It is made of Maraging 200 steel and has SK-11 Karma gages that are installed using M-610 adhesive and 570-28R solder. M-coat B is applied to all exposed wires and terminals. In addition, HRC-2 has Minco thermofoil resistance heaters for thermal control and type T (copper-constantan) thermocouples for temperature readout.

The balance is wired as a "moment" balance. The sum of the outputs of the forward and aft bridges is proportional to the total moment applied to the balance while the difference of the two outputs is proportional to the applied normal force. Existing LaRC balances are wired to produce outputs that are directly proportional to normal force and pitching moment by having half of each bridge located in both the forward and aft cages. Since temperature gradients are most likely to occur along the length of the balance, a "moment" balance will more nearly result in having all four gages of a specific bridge at the same temperature, thus minimizing gradient effects and simplifying temperature compensation and data reduction.

CALIBRATION

As previously mentioned, the high-capacity balances require extra precautions during calibration because of increased deflections. A second calibration requirement is that of calibrating at cryogenic temperatures. The test beam studies indicated that the output of a bridge designed for cryogenic use gives predictable and repeatable output at cryogenic temperatures. However, until a large number of balances have been calibrated at cryogenic temperatures to verify that the change in output due to temperature can be mathematically determined and expressed, it will be necessary to calibrate cryogenic balances over the entire temperature range.

As a preliminary attempt to obtain calibration data on HRC-2, the balance was mounted inside a cryogenic chamber and loads were applied to weight-pans that extended outside the chamber. While this method did not permit a full simultaneous loading of all components, it did provide enough data to show that the sensitivity change with temperature was within 0.05% of that predicted by the test beams. The interaction coefficients showed less than 0.1% full scale change with temperature in all but two coefficients (these differed by 0.4% F.S.). The apparent strain output of the balance

was nonlinear with temperature and appears to be a function of how well the four gages are matched. In addition, the forward and aft gage apparent strain output was very repeatable under steady state conditions while axial apparent strain showed more variation from test to test. Further testing is planned with both balances and test beams to determine the factors affecting apparent strain output. These calibration curves are presented in figures 5 and 6.

The selected approach for calibration makes use of a cryogenic calibration fixture that will replace the normal loading fixture. The fixture shown in figure 7 is being readied for checkout. Liquid nitrogen passages and electric resistance heaters built into the fixutre will allow normal calibration procedures and equipment to be used over the entire calibration load and temperature range.

THERMAL CONTROL

Thermal control of a force balance is difficult since the insulators or heaters must not interfere with the transmission of the forces and moments across the measuring beams and, in addition, since the balance is constructed of a poor thermal conductor it is difficult to distribute heat evenly or contrive an effective heater control feedback circuit. At present, a cantilever convection shield extends forward over the balance acting as a baffle to reduce heat losses due to convection, resistance heaters are attached directly to the balance at several locations, and bakelite insulator inserts can be installed at the forward and aft attachment points.

Research is continuing in this area to reduce conduction and convection losses, to improve heat distribution, and to optimize the heater control feedback circuit.

LANGLEY 0.3-METER TRANSONIC CRYOGENIC TUNNEL TESTS

Test Setup

To verify and pull together the data and information developed in the laboratory, tests were conducted in the Langley 0.3-Meter Transonic Cryogenic Tunnel in July 1979 using balance HRC-2. The model and balance are shown in figure 8. The test conditions were chosen to give the same Reynolds number and thus the same aerodynamic input at two different temperatures, 300 K (540°R) and 110 K (198°R). The tests were made at Mach numbers of 0.3 and 0.5. Aerodynamic data were taken only after the tunnel and balance temperatures had stabilized. However, transient data were obtained while tunnel conditions were being changed from one test condition to another to get a feel for stabilization times for a balance of this size. It must be noted that stabilization time is dependent not only on the absolute temperature change but also on the tunnel conditions that alter convection cooling (i.e., pressure, Mach no., etc.). As shown in figure 8, a model-balance interface and a convection shield made of bakelite could be used to reduce heat loss

when the balance was heated. They would, however, also affect stabilization time when the heaters are off. Therefore, the transient data obtained represents only a small portion of the entire spectrum of possibilities generated by combinations of tunnel and model conditions.

In addition to the original test conditions, runs were made at an intermediate temperature, 200 K (360°R), and at 300 K (540°R) and 110 K (198°R) at a constant dynamic pressure instead of Reynolds number. See figure 9. (The delta wing model configuration chosen is relatively insensitive to Reynolds number effects.)

Test Results

On-line data were obtained using a programmable desk-top calculator interfaced to a 10-channel scanner, voltmeter, clock, and plotter. The 10 channels of data were: Tunnel temperature, four balance temperatures, two angle-of-attack transducers, and three balance components (pitch forward, axial, pitch aft). Nominal tunnel conditions were keyed in manually. Limited corrections were applied to the data including temperature corrections, interactions, tare loads, and sting bending. Figures 10 and 11 show examples of the preliminary data obtained using this system. The agreement shown at the three different test conditions for C_n and C_m is very good. The axial loads of this test were quite low compared to the design full-scale load of the axial component. Even so, the C_A-α data shown in figure 11 are still within the quoted $\pm0.5\%$ full-scale accuracy of the axial component. Several runs made using a blunt body that deliberately loaded the axial component to its design load capacity shows agreement much like that shown in figure 10.

It was hoped that the balance output could be corrected to account for both the sensitivity change and the zero load output change with temperature based on the laboratory tests. It was apparent quite early in the wind tunnel test series, however, that axial zero-load output variation with temperature was not following the predicted curve even though pitch forward and pitch aft were. Therefore, all data were reduced using a wind-off zero taken after stable tunnel conditions were reached. Sensitivity corrections were applied as determined from the laboratory tests.

The heater control instrumentation had no difficulty heating the balance bridges to 300 K (540°R) at any tunnel condition or model insulator configuration. It was quite apparent, however, that the convection shield improved the stability of the output signal and reduced the power required to heat the balance. The front insulator had a much smaller effect as indicated by the following data:

Tunnel Conditions
M = 0.5 P = 1.2 bar T = 110 K (198°R)

Convection shield and front insulator	Convection shield only	No insulators
130 watts	138 watts	195 watts

The heater feedback control circuit was not satisfactory. As mentioned previously, because the balance material is a poor conductor, the feedback sensor must be located near the resistance heater to minimize lag time in the control circuit. However, this arrangement means that the temperature control set point had to be set above the desired 300 K (540°R) in order to maintain a 300 K (540°R) reading at the bridge location. At each tunnel condition the heater control set point had to be manually adjusted until the required gage temperature was reached. Also, because of the rapid change in convection cooling, getting a heated-balance wind-off zero was very difficult since the balance temperature rose rapidly if the heater control set point was not adjusted manually to compensate for decreased thermal losses.

Transient data was taken on strip chart recorders. From these records it was determined that it took the tunnel approximately 40 minutes to go from the 300 K (540°R) operating conditions to the 110 K (198°R) operating conditions. The balance temperature tended to lag behind the tunnel temperature by about 10 minutes (see fig. 12). When the tunnel and balance temperatures are changing, as in the previous example, the stabilization time is a function of both the tunnel and balance heat transfer characteristics. In an effort to isolate only the balance heat transfer characteristics, the tunnel conditions were held at a constant 110 K (198°R), P_t = 1.2 bar, M = 0.5 and the balance heaters that had been holding the balance temperature at 300 K (540°R) were turned off. In this test it took the balance 15 minutes to stabilize to tunnel temperature as shown in figure 13. To obtain another data point, the tunnel operating temperature was changed 30 K (50°R) (120 K (220°R) to 90 K (170°R)) as rapidly as allowed by operation specifications to check how the balance reacted to relatively small temperature changes. The tunnel took 3 minutes to stabilize at the new conditions and it took the balance 10 minutes to stabilize (fig. 14). These stabilization times are too large to meet NTF requirements. The effect of temperature transients results in undesirable and currently uncorrectable time dependent no-load zero shifts (or drift). This indicates that while balance temperature is changing it is not possible at this time to get accurate force data. Basic strain gage research utilizing test beams and small balances is currently underway to pinpoint the cause of these time dependent output shifts so they may be minimized or eliminated if possible. This effect will be investigated further with the cryogenic calibration fixture which allows independent control of the front and rear temperature inputs. This will allow us to deliberately introduce transients in order to determine the correction factors that must be applied to data obtained during transient temperature conditions. If this approach fails and test procedures cannot be modified to allow adequate stabilization time, thermal control will be a necessity.

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CONCLUDING REMARKS

One-piece multicomponent strain-gage balances have been designed to meet the requirements imposed by the NTF cryogenic environment. These balances are a result of extensive studies in the areas of design, balance materials, strain gages (including application techniques), and cryogenic calibration.

The laboratory and wind tunnel results indicate that these balances will yield reliable, repeatable, and predictable data from 300 K (540°R) to 110 K (198°R) under steady-state conditions.

Work is continuing in a number of areas to reduce the effect of the cryogenic environment even further where possible and to study the problems associated with transients and thermal gradients.

In addition, new and improved methods of thermal control are being studied to improve heat distribution, heater control, and insulators.
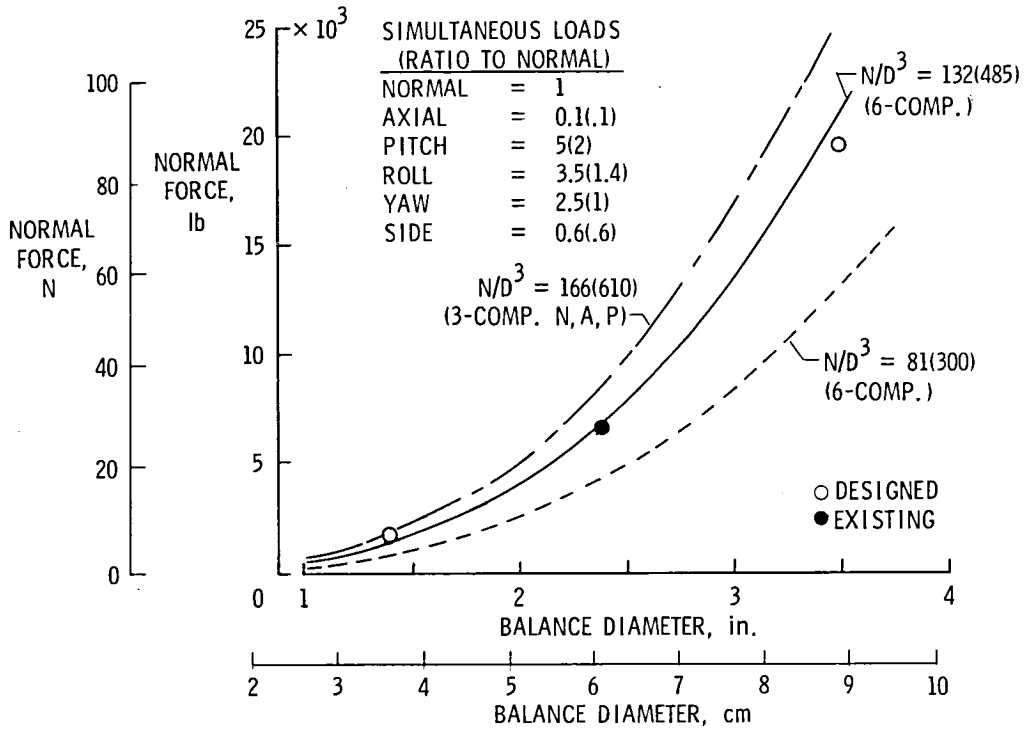
Figure 1.- Relationship between load carrying capacity (N) and diameter (D).

29 000 N (6500 lb) NORMAL
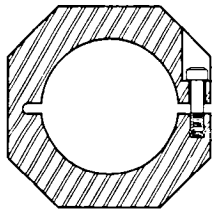
TYPICAL MODEL
ADAPTOR FOR
NTF-101 BALANCE
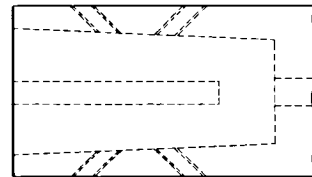
TYPICAL STING
ATTACHMENT FOR
NTF-101 BALANCE
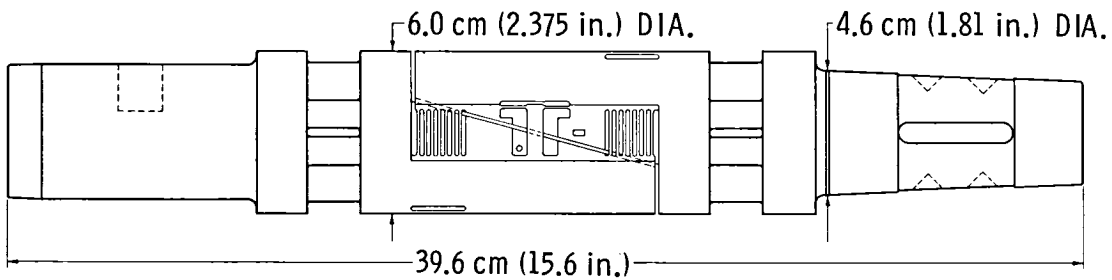
Figure 2.- Drawing of prototype balance NTF101.

CRYOGENIC MATERIALS

MATERIAL	TENSILE STRENGTH GPa (ksi)		IMPACT STRENGTH CHARPY-V J (ft-lb)	
	YIELD ROOM TEMP	ULTIMATE ROOM TEMP.	ROOM TEMP.	139°R
MARAGING 200	1.46 (212)	1.49 (216)	49 (36)	38 (28)
MARAGING 250	1.79 (260)	1.86 (270)	27 (20)	18 (13)
HP 9-4-25	1.28 (185)	1.38 (200)	57 (42)	34 (25)

CONVENTIONAL MATERIALS

17-4 PH	1.21 (175)	1.31 (190)	27 (20)	4 (3)
MARAGING 300	2.00 (291)	2.06 (299)	34 (17)	15 (11)

Figure 3.- Strength and impact characteristics of balance materials.
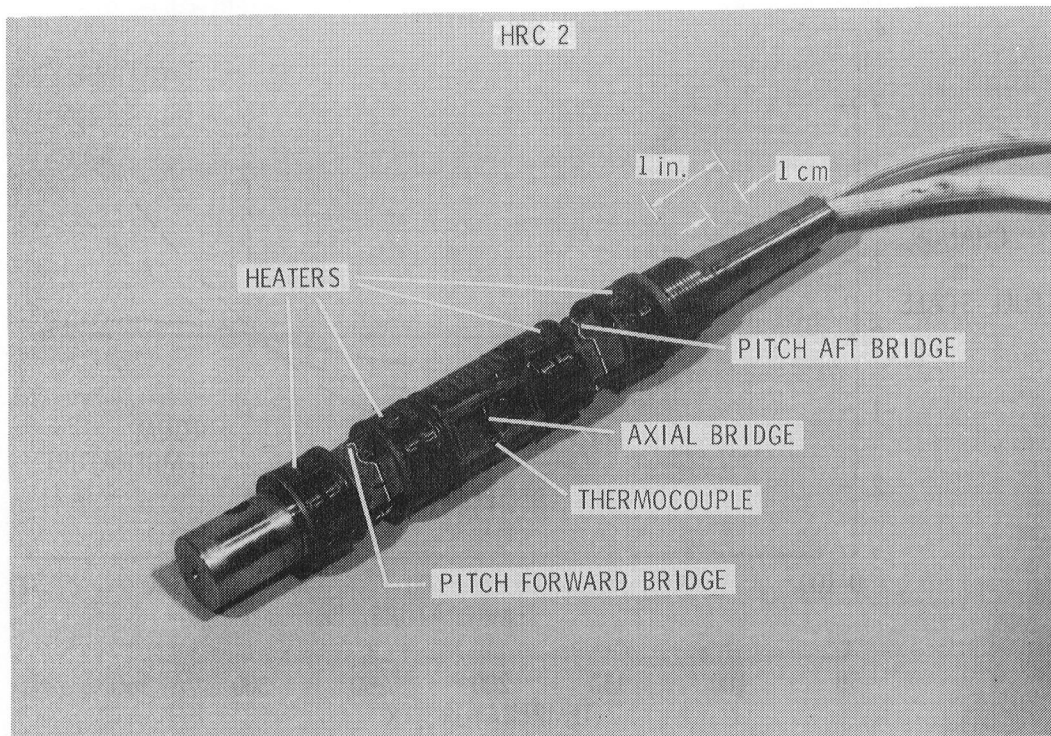
Figure 4.- Evaluation balance HRC-2.
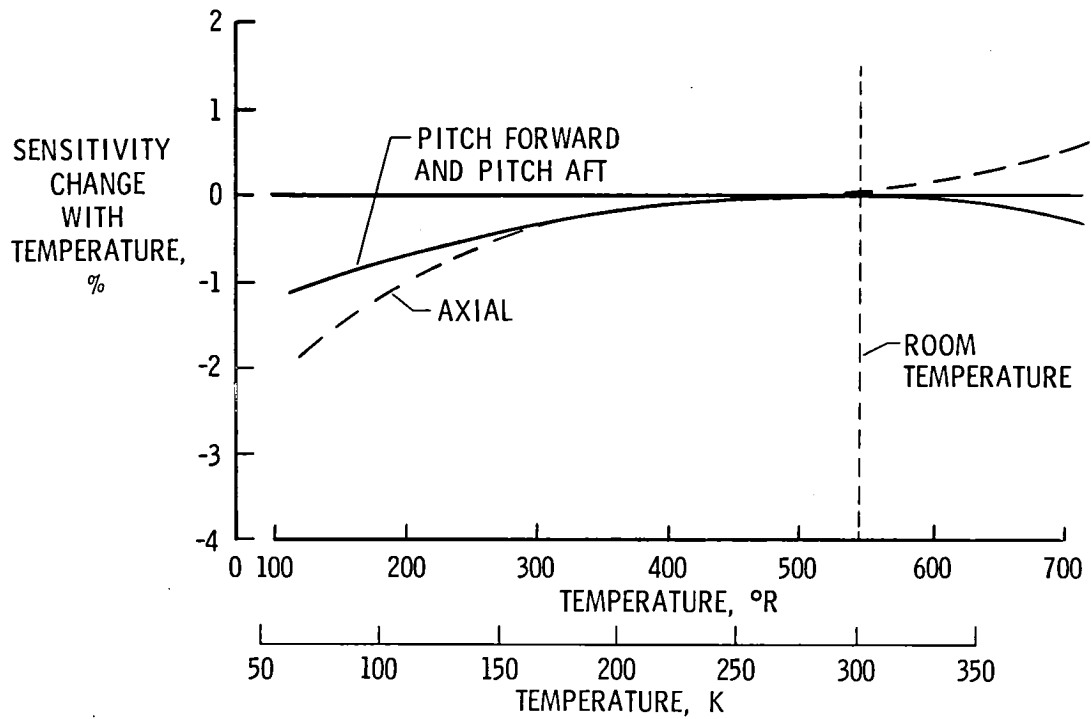
Figure 5.- Sensitivity change with temperature of evaluation balance.
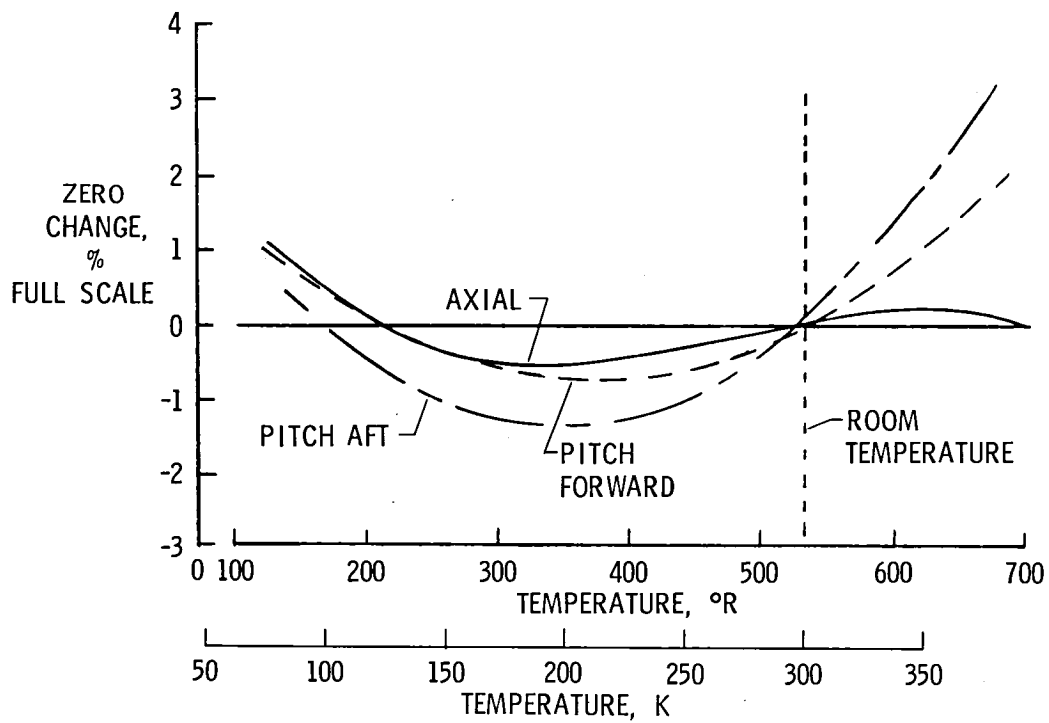
Figure 6.- Zero change with temperature of evaluation balance.
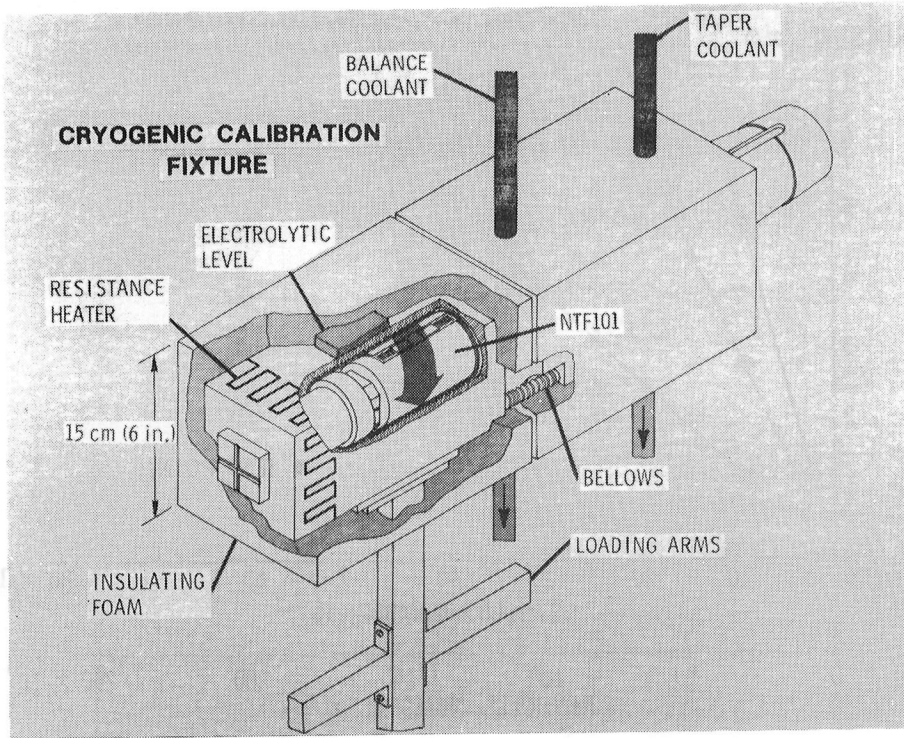
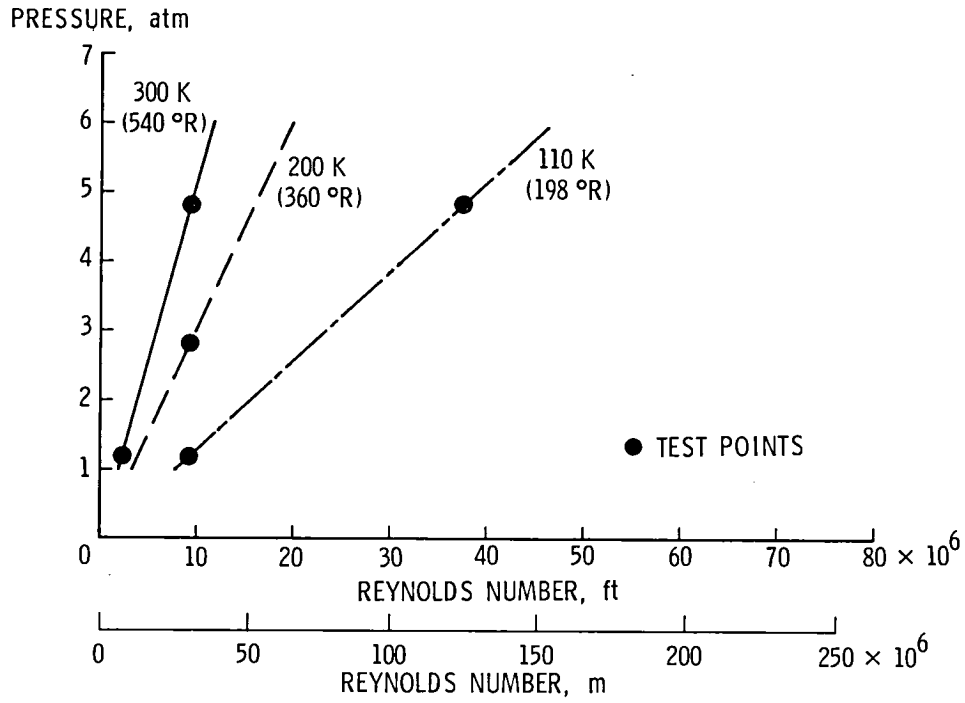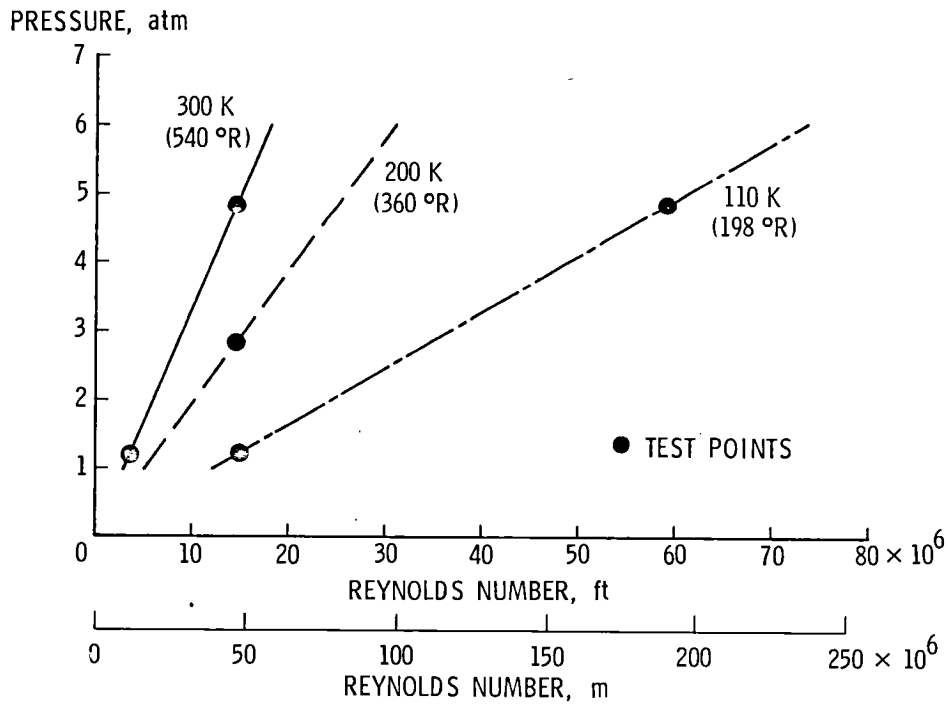Figure 7.- Drawing of cryogenic calibration loading fixture.
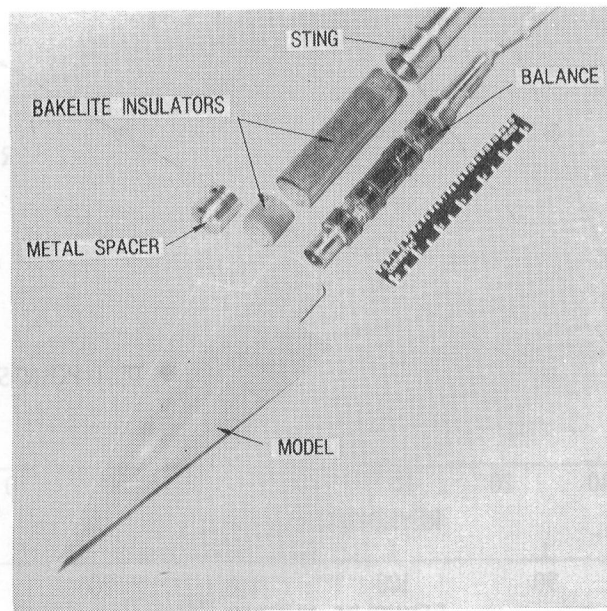
Figure 8.- Evaluation balance with model.

(a) M = 0.3.

(b) M = 0.5.

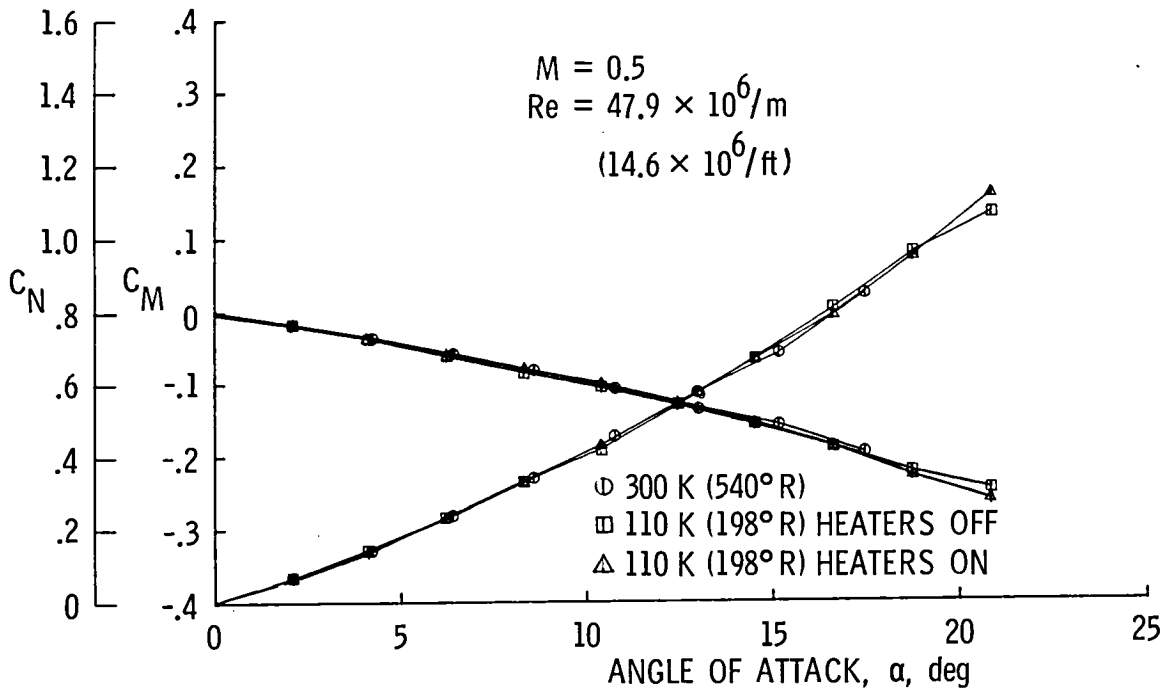Figure 9.- Tunnel conditions for balance evaluation tests.

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Figure 10.- Force balance data from tests in Langley 0.3-Meter
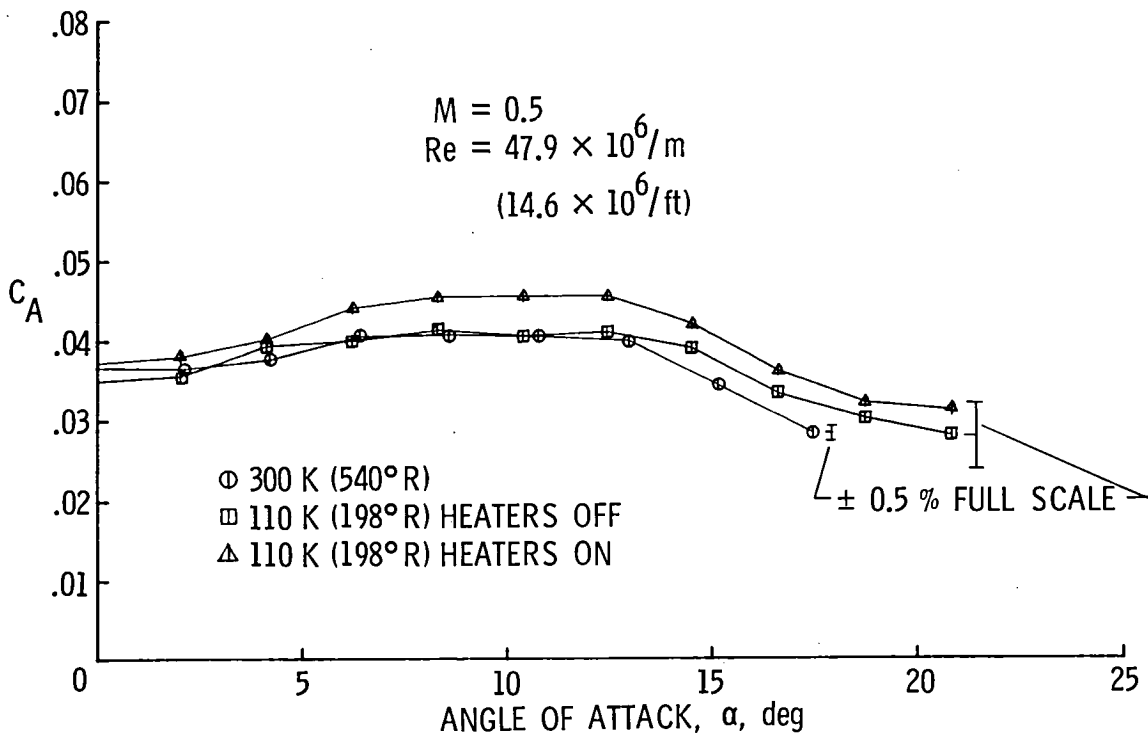Transonic Cryogenic Tunnel.

Figure 11.- Force balance data from tests in Langley 0.3-Meter
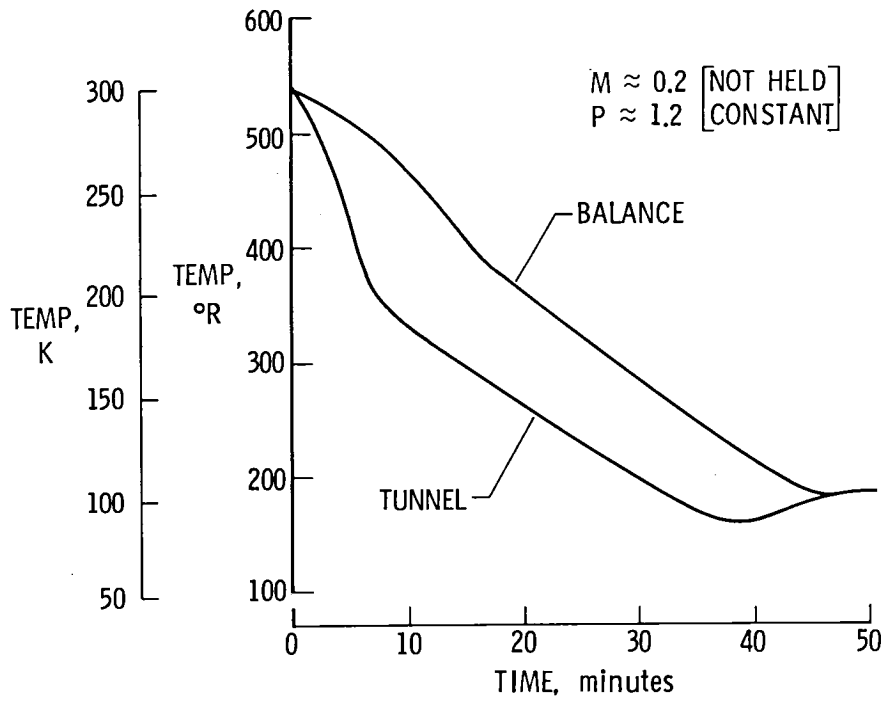Transonic Cryogenic Tunnel.

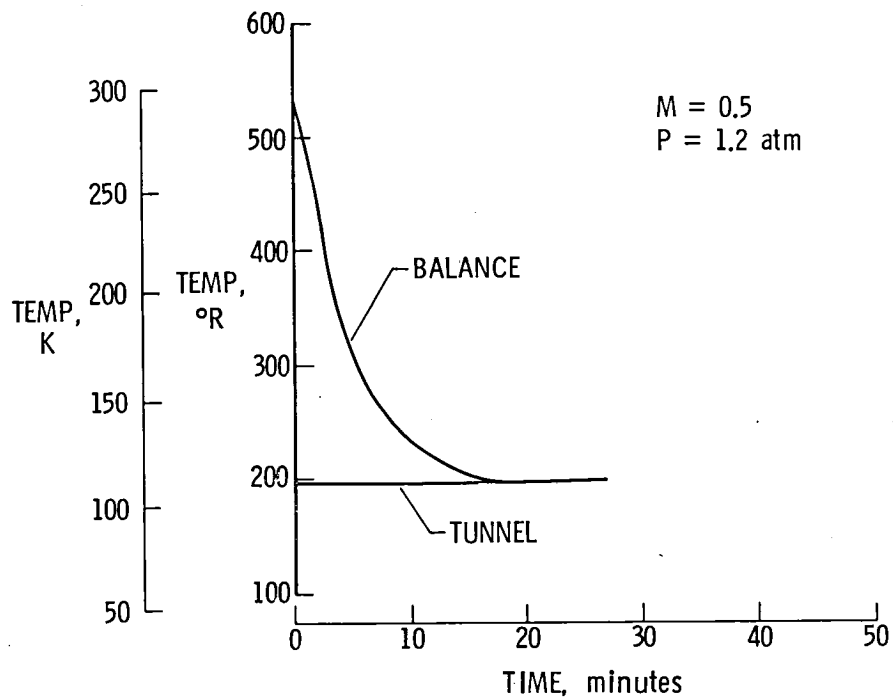Figure 12.- Temperature response of balance and tunnel.
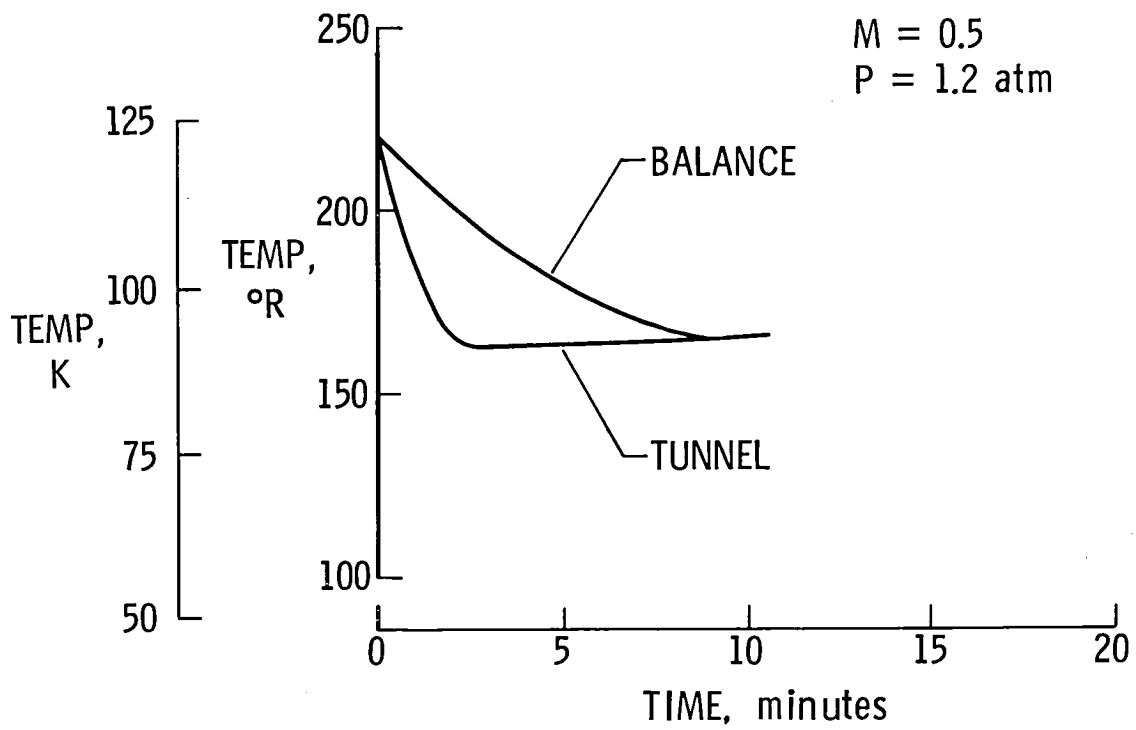

Figure 13.- Balance temperature response.

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Figure 14.- Temperature response of balance and tunnel to small changes.

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15. Supplementary Notes

16. Abstract

The use of cryogenic temperatures in wind tunnels to achieve high Reynolds Numbers has imposed a harsh operating environment on the force balance. Laboratory tests were conducted to study the effect cryogenic temperatures have on balance materials, gages, wiring, solder, adhesives, and moisture proofing. Wind tunnel tests were conducted using a one-piece three-component balance to verify laboratory results. These initial studies indicate that satisfactory force data can be obtained under steady state conditions.

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